THE SPECTROSCOPY OF NUCLEAR GAMMA-RAYS.

by

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Presented as a thesis for the degree of Ph.D.
in the University of Glasgow.
April, 1950.

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P R E F A C E.

In this thesis I have tried to show how the method of Gamma-Ray Spectroscopy is used as a tool in obtaining information about the stationary states of nuclei. Part I, in which I have drawn freely from Devons (Excited States of Nuclei), deals with the general argument and with the techniques available in the application of the method.

Part II contains an analysis of the relative merits of the various types of spectrometer employing magnetic resolution, and leads to the choice and design of the inst-:ruments built here and used in the experiments described later. The analysis and designs are in general original; the principles involved are not. I might mention here Appendix I, which contains a design for a new type of beta-ray spectrometer of very high intensity factor. This work has been placed in an appendix solely because the instru-:ment is not suitable for use as a gamma-ray spectrometer, but the design, which is a development of an idea suggested by Dr. S.C. Curran, may prove to be important in the separation of complex beta-ray spectra by the method of beta-gamma coincidences.

Parts III and IV describe the experimental work and the significance of the results obtained; the matter here is original, all the work having been carried out solely by myself with the exception of the experiment on $F^{19} + p$, (111,2). This/

This experiment, which involved the use of the proton accelerator, was suggested by Mr. J.G. Rutherglen, and was carried out in collaboration with him and with Mr. R.D. Smith, these workers being responsible for the preparation of the targets, and for the satisfactory performance of the accelerator and its auxiliary equipment.

I must thank Professor P.I. Dee and Dr. S.C. Curran for their sustained interest and encouragement throughout the work, also Dr. B.F.X. Touschek and Mr. D.L. Pursey for helpful discussion on several points of theory, and finally Mr. H.W. Wilson for permission to reproduce the spectrum of the gamma-rays from Hg^{203} which he observed with one of the spectrometers mentioned above.

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PART I. - GENERAL INTRODUCTION.

I.1. The purpose of Gamma-Ray Spectroscopy: its capabilities and limitations.

It might be stated that gamma-rays are the light of the atomic nucleus since they are the electro-magnetic radiation emitted by the nucleus during a change from one state to another in the absence of particle emission. Now it is well known that the intensive study of optical spectra which took place towards the end of the nineteenth century, and the general empirical laws which were found to govern the spectra emitted by hydrogen and a few other elements, laid the basis for the theories which were later to explain not only the emission of optical spectra, but the whole electronic structure of the atom. Consequently it might seem not unreasonable to suppose that the study of the nuclear gamma-rays would lead to a similar collection of data concerning nuclear spectra, which must lead in the end to the formulation of empirical rules and so to a better understanding of the structure of the atomic nuclei.

While it is arguments of this kind which provide the main justification for the study of gamma-ray spectroscopy, it must be clearly understood that the analogy between optical and gamma-ray spectroscopy is only a very loose one, for the following reasons. Firstly, in the atomic case it is com-
:paratively easy to excite the whole spectrum, and measurements
of/

of the energy (or wavelength) of each line can be made with a very high degree of precision, while in the nuclear case excitation is only possible through specific nuclear reactions or through radioactive decay,+ and apart from the low energy region (up to about 1 M.E.V.) where optical diffraction techniques can be used, the precision available in gamma-ray energy measurement is normally only about 1%. In the second place the observation of atomic spectra represents, if not the only way, certainly the most accurate way in which information can be obtained about the energy levels in the electronic structure of the atom: in the nuclear case however, the measurement of gamma-ray energies is only one of several tech-:niques for obtaining information about nuclear levels, and while it is the most general method available, there are certainly others with limited applications which provide a much higher degree of precision.

It is however this feature of generality which makes the method of gamma-ray spectroscopy so attractive and potentially so important in the study of nuclear structure, for although it is possible by the study of excitation curves due to bombard-:ment by protons and neutrons, to obtain very accurate and detailed/

+ Excitation by collision is of course possible using beams of fast particles, but is very difficult compared with the methods applicable to the excitation of atomic spectra.

detailed information concerning a small part of the energy level diagram of the compound nucleus formed, and although it is possible in particle-particle reactions, by observing the energy of the outcoming particle, to obtain information about the absolute position of the levels in the residual nucleus, each of these methods is limited in principle, and both can be made to yield still more information by combining with their results, measurements of the energies of the gamma-rays pro-:duced in the reactions concerned. A limitation to the former of the techniques mentioned above is that the capture of a nucleon by the nucleus of a light element always produces a compound nucleus which is in a highly excited state, and so this method cannot be used to explore the region near the ground state; for instance it could not be used to find the first excited state of such a nucleus. A limitation which applies to both of the above techniques is that it may not be possible to isolate the desired reaction because the target nucleus may be radioactive with a short half-life. The important point is that these limitations in the applicability of two of the best techniques for the study of nuclear levels are limitations which depend on the nature of matter. The limitations in the use of gamma-ray spectroscopy however, the difficulty in exciting the nuclei and in achieving a high degree of precision, are rather limitations in technique, which suggest that the study of this method may be very much worth/

worth while.

One further general feature of gamma-ray spectroscopy must be mentioned before we proceed to discuss in rather more detail the kind of work that has been done in this field up to the present, and that is that in the examination of gamma-ray spectra with magnetic spectrometers, it is possible to obtain information, not only about the energy of the gamma-ray lines observed, but also about the multipole order of the transitions giving rise to those lines. The reason for this is that the emission of a photon by a nucleus always takes place in competition with the emission of an electron (Internal Conversion) or of a positron-electron pair (Internal Pair--Creation) the excess energy appearing as kinetic energy of the electron or pair. Now the probability of occurrence of these phenomena is a function of the multipole order of the nuclear transition concerned, and so a determination of this probability (Internal Conversion Coefficient, or Internal Pair-Creation Coefficient) yields information about the multipole order of the transition, and so about the spins of the nuclear levels involved.

I.2. Techniques in Gamma-Ray Spectroscopy.

(a) Diffraction.

If we now consider in more detail the problem of the measurement/

measurement of gamma-ray energies, it is clear that since gamma-rays react with matter in a number of different ways, there are correspondingly many ways in which their energies may be deduced. Certainly the most fundamental and precise method of measurement is that afforded by diffraction at a glancing angle in a crystal. This method, which is really an extension of the optical technique, is of course capable of great accuracy since it measures wavelength in terms of the crystal lattice spacing; it has also been improved lately by the use of curved crystals to produce a focussing effect and in this form has been used, among other things, to determine the wavelength of the two-quantum positron annihilation radiation (Du Mond, Lind and Watson, 1949). The limitations of this method are that it demands a very strong source and also that there is an upper limit to the energy at which it can be used on account of the very small angles involved, which diminish with increasing energy. Du Mond et al. used sources of the order of 1 Curie to obtain their accuracy of 1 part in 10,000, and the highest energy line they have investigated appears to be the 1.3 M.E.V. line from radio-cobalt (Lind, Du Mond and Brown, 1949). Thus for energies much in excess of 1 M.E.V., and for all cases where only small sources are avail-:able, indirect methods must be used, such as the measurement of the absorption coefficient of the rays in different materials, and measurements on secondary particles produced by the/

the gamma-rays.

(b) Simple Absorption.

The first of these methods, that of determining the absorption coefficient of the gamma-rays in various materials, is useful in the determination of the energy of soft gamma--radiation. The measurements must however be carried out with great care if errors due to scattering are to be avoided, and the method should preferably be used only empirically, that is where gamma-rays of known energy are available for calibration purposes. Where more than one gamma-ray is present in the same energy region, the method breaks down completely, and it is also made difficult at energies much in excess of 1.5 M.E.V. by the fact that at high energies the absorption coefficients change too slowly with energy to provide much information. There is also the difficulty that since the absorption coefficients have a minimum value, it is necessary to determine the coefficient in more than one material to avoid ambiguity. An example of the errors involved in this method is given in the published results on the radiations of Pr^{142} quoted in III.1.

In comparison with the limited applicability of the method of simple absorption, measurements on the secondary particles produced by gamma-rays have provided useful information through-:out the entire observed gamma-ray spectrum. The secondary particles may be further subdivided into light and heavy particles/

particles, the former, electrons and positrons, originating in the photo-electric effect, the Compton effect and pair production, and the latter, protons and neutrons mainly, in the nuclear photo-effect.

(c) Nuclear Photo-Effect.

While all these effects have been utilised in the deter-:mination of gamma-ray energies, the use of the nuclear photo-effect has of necessity been rather limited. It is limited on the low energy side by the fact that the nucleus most commonly used (Deuterium) requires the threshold energy of 2.2 M.E.V. before the effect can be observed, while on the high energy side the use of the technique is made difficult by the fact that the cross-section for the effect falls off, and also at high energies (above 10 M.E.V.) other nuclei start to dis-:integrate which confuses the interpretation of the observed data. The method used by Gibson, Green and Livesey (1947) was to impregnate an Ilford Nuclear Plate with heavy water, expose it to the gamma-rays, then develop it and examine the proton tracks. In this way they were able to measure the energy of the 6 M.E.V. gamma-rays from the F(p,α) reaction. Here the use of the method is certainly restricted at high energies by the photo-disintegration of other materials in the photographic plate.

Another useful application of the nuclear photo-effect to the measurement of gamma-ray energies was that of Baldwin and Koch/

Koch (1945). These authors made up a list of elements in which the (γ,n) reaction left a radioactive nucleus with a half-life of at least several minutes and their thresholds range from 9.3 M.E.V. for Ag^{109} to 19 M.E.V. for C^{12}. With this list it is theoretically possible to determine the end point of a gamma--ray spectrum by a "Bracketing" process, and this method was used recently by Devons and Hereward (1948) to demonstrate the existence of proton capture gamma-rays from Fluorine, using Cu^{63} as detector. The method is of course rather crude, but has the great advantage that it makes it possible to detect a very weak high energy radiation in the presence of intense radiation of a lower energy, as in the example quoted where the high energy radiation had not previously been observed by any other method. It is however clear from the above, that the use of the nuclear photo-effect does not provide a method of gamma-ray spectroscopy capable of very general application since it can only be used at rather high energies, and even then the most convenient method of using it, the deuterium loaded plate, breaks down at much higher energies because of the disintegration of other materials in the plate.

(d) Coincidence Absorption.

It remains then to discuss the use of the light secondary particles in techniques for the measurement of gamma-ray energies. The simplest method here is to measure the range of the secondaries by the coincidence absorption method. In this method/

method the secondary particles produced in a "Convertor" are caused to pass right through one thin walled G.M. counter and enter a second counter. The range of the particles is then found by placing sheets of absorber between the counters and plotting the coincidence counting rate against the absorber thickness. When the absorber thickness is greater than the range of the secondary particles, no further drop in the coincidence counting rate can take place. This method, in the hands of experienced workers, is capable of determining the energy of a single gamma-ray line to a few per cent, over a very wide range of energies (Curran, Dee and Petrizilka, 1938); but it breaks down when it is necessary to discriminate between two lines of comparable energy because it has very bad resolution. It may also give trouble if two gamma-rays are present in coincidence, (in cascade) or if the energy of the gamma-ray is very high so that pair production and bremsstrahlung become important. Consequently this method is only used now for rough survey work, or with very weak sources, where its extreme simplicity and its high sensitivity outweigh its disadvantages.

(e) Magnetic Analysis.

In all accurate work however, (except at very low energies where the proportional counter technique developed recently by Curran and his co-workers (Curran, Angus and Cockroft, 1949), has proved a very powerful tool), the technique used has been to analyse, in a magnetic resolver of some kind, the light secondary/

secondary particles produced by the gamma-rays. A critical discussion of the various methods of resolution and their use to determine gamma-ray energies will be given in the next chapter; it is sufficient to note here that with good modern techniques it is possible to measure gamma-ray energies in the range 50 K.E.V. to 20 M.E.V. and probably higher, with an accuracy of 1%, and to resolve lines separated by 10% of their energy (Siegbahn, 1946; Walker and McDaniel, 1948). This latter figure can be greatly improved upon where strong inter-:nal conversion occurs in the source (Ellis and Skinner, 1924), or where very strong sources are available, so that very thin convertors can be used and beta-rays from the source suppressed magnetically (Latyshev, 1947).

I.3. Survey of Work Done.

(a) Classification.

As was remarked in an earlier paragraph, one of the main limitations to the use of gamma-ray spectroscopy is the difficulty of exciting the nuclear spectra. This difficulty at once provides a way of classifying the work done by the various workers in the field, since all must have used one of two methods of excitation, either excitation by radioactive decay, or else by collision or through a nuclear reaction, each of which processes require the use of a source of bombard-:ing particles. The first of these groups may be further subdivided/

subdivided into work done on the "Natural" radioactive elements, and that done on the more recently available "Artificial" elements. Since the work done on the natural radioactive elements includes some of the earliest measure-:ments made on the nuclear gamma-rays, (and also some of the best), we shall consider this group first of all.

(b) Natural Radioactive Elements.

The early investigations of the gamma-ray spectra of the natural radioactive bodies were really investigations of their beta-ray spectra; indeed the work of Von Baeyer, Hahn and Meitner (1911) was carried out in order to determine whether or not the beta-ray spectrum of a radioactive element was continuous. With the introduction of semi-circular focussing by Danysz in 1913, the modern technique of deriving gamma-ray spectra from photographs of the internal conversion spectra of the heavy radioactive elements was virtually complete, and in the intervening years the spectra of most of the natural radio-:active bodies have been thoroughly investigated, many by Ellis whose results have since been used as standards for the calibration of magnetic resolvers. The accuracy of Ellis's best work (Ellis and Skinner, 1924) is quoted as 1 part in 500, which is remarkable since it was carried out as long ago as 1924. One reason for the high accuracy obtained is that the sources used were chemically separated and of very high specific activity so that they were very thin, and straggling

of/

of the internal conversion electrons was negligible; also the internal conversion coefficients were high on account of the high nuclear charge of the elements investigated. Hence it was possible and profitable to work with a spectrometer of high resolving power. Even so the accuracy obtained was remarkable, since it was not merely the relative position of the lines which was determined (this was quoted to 1 part in 1,000) but the absolute value, which involved a measurement of a magnetic field to 1 part in 1,000. (This introduced also the question of the uniformity of the field.) More recent work on the natural radioactive elements has been concerned mainly with questions of the relative intensity of the lines, with the determination of the multipole order of the transitions, and with the sorting out of complex beta-ray spectra by the method of beta-gamma coincidence measurements. (If this can properly be regarded as gamma-ray spectroscopy.) In other words, most of the experi-:ments in gamma-ray spectroscopy that can be done on the natural radioactive elements with the techniques available at the moment, have already been done; and while, on account of their complexity, the level schemes of these nuclei are by no means complete, there does not seem at the moment to be much opportunity for the application of our method of investigation. The results of recent work on the natural radioactive elements have been well summarised in review articles by Latyshev (1947) and Feather (1949).

(c) Artificial Radioactive Elements.

The position with regard to the study of the gamma-rays from the artificial radioactive elements is very different. Here it is not possible, in general, to obtain strong sources of high specific activity and so the use of the photographic technique is made difficult. It has however been used, notably by Helmholtz (1941) and Cork (1949), the latter author employ-:ing Alnico permanent magnets and making exposures of sometimes several weeks. Even so this technique, while very powerful in determining the energy of soft radiation from the heavier elements, has been very little used on elements with an atomic weight of less than 50, and is of course useless for determin-:ing the energy of the harder gamma-rays (say over 1 M.E.V.) on account of the rapid drop in the internal conversion coefficient with increasing energy. For the measurement of the energy of the harder gamma-rays, it has been necessary to find a detector of much greater sensitivity than the photographic plate. This has been provided by the G.M. counter, which not only provides the increased sensitivity, but also makes possible the counting of the individual secondary electrons, thus greatly simplifying the problem of determining relative intensities. The disadvantage of the G.M. counter is that it can only record the integral of a small part of the spectrum at one time, and so to obtain the complete spectrum the magnetic field must be varied and a large number of such observations/

observations made. It may be that the recent development of a photographic plate which can detect single electrons (Berriman, 1948) will provide the advantages of both methods, but this is by no means certain as such a plate would have to be subjected to long and tedious microscopic examination after exposure. In any case the problem of obtaining a sensitive detector is only one part of the difficulty in making observations on the artificial radioactive elements; there remains the difficulty that in the case of the light elements, and for energetic radiation from the heavier nuclei, the internal conversion coefficients are so small that with the resolution attainable it becomes impossible to detect the internal conversion lines against the background of the continuous beta-ray spectrum.. In this case it is necessary to use a convertor and make observations on the secondary electrons from this. In this connection the technique originated by Siegbahn (1946a) has become standard practice. This consists in placing the source inside a hollow copper container with walls thick enough to absorb all the beta-rays from the source. (Copper is chosen as it is dense and therefore can be made reasonably thin, and yet has a low enough nuclear charge to make the photo-electric effect in it small for most radiations.) Round the copper container is placed a very thin lead foil (This may be of gold or platinum leaf if necessary) in which photo-electrons of nearly homogeneous energy are produced. When the secondary electrons from this convertor are examined in a magnetic spectrometer/

spectrometer, the photo-electrons from the lead foil can be clearly seen against the background of Compton electrons from the copper. At energies of a few hundred Kilovolts, peaks can be observed due to conversion of the gamma-rays in the K, L, and M shells of the lead while even at energies as high as 2.76 M.E.V. (the high energy line from Na^{24}) the K conversion peak still shows quite plainly. With the use of this technique, Siegbahn was able to make measurements of energies up to the order of 3 M.E.V. to better than 1%, with sources of the order of a few microCuries, the great improvement being due to the suppression of the intense beta-ray spectrum which normally accompanies the gamma-ray secondaries. The use of this tech-:nique by many different investigators has supplied a large body of experimental results on the energy and relative inten-:sity of the gamma-rays from many of the artificial radioactive elements. Since these are so numerous however, there is still a great deal of work of this kind to be done, to provide accurate data where at present the only information available is derived from very rough absorption experiments. On the question of the determination of multipole order, very little work has been done, but this question will be discussed more fully later.

(d) Nuclear Reactions.

With regard to the study of the gamma-rays emitted by nuclei/

nuclei excited by nuclear reactions, little work of a precise nature has been published. This is largely attributable to the technical difficulties involved in setting up and using a magnetic spectrometer in the vicinity of the source of the bombarding particles, especially since in this case the radiation is likely to be much more energetic than in the case of radioactive decay. This fact makes necessary the use of large and expensive resolving equipment, and also new techniques depending on pair-production, since measurements based on the observation of photo-electron peaks begin to fail above about 3 M.E.V. Most of the work done on the radiations from the light elements under proton and deuteron bombardment has therefore been accomplished by the use of absorption techniques (Curran, Dee and Petrizilka, 1938; Fowler, Lauritsen and Lauritsen, 1948) which may be, as discussed earlier, subject to serious errors at high energies, and which have poor resolution.

The achievement of good resolution and accuracy in measurements on high energy radiations was only made possible when the pair production mechanism was utilised by the observation of the tracks of pairs produced in a thin lead foil in the gas of a Wilson chamber placed in a strong magnetic field; here the momentum, and hence energy of each component of the pair could be measured, and so the energy of the gamma--ray inferred. Using this method, Delsasso, Fowler and Lauritsen (1937) were able for the first time to show that the hard gamma-radiation resulting from the bombardment of Li^7 with

protons/

protons consisted of a strong line at 17 M.E.V. together with a weaker broad component in the region of 14 M.E.V. This method has been used to investigate the radiations from a few nuclear reactions, but it suffers from the disadvantage that a great deal of time and effort has to be expended in obtaining and analysing a large number of photographs if good statistics are to be obtained. Furthermore great care must be taken to avoid spurious results owing to accidental superposition of tracks. These difficulties were partly overcome by the use of two semi-circular magnetic resolvers fitted with G.M. counters, to analyse the pairs produced in a foil, the emission of a pair of the appropriate energy causing a coincidence between the two counters (McDaniel, von Dardel and Walker, 1947); it was however the multi-counter type of pair spectrometer used by Walker and McDaniel in 1948 which finally overcame this difficulty and made possible the obtaining of good statistics on the high energy gamma-rays in hours instead of weeks. The Walker and McDaniel instrument consists essentially of a number of semi-circular resolvers set on either side of the foil being irradiated, the outputs from all of these units being combined in a large multiple coincidence circuit which obtains the maximum amount of information from the signals from the counters and displays this information on a row of mechanical registers from which a number of points in the energy distribution of the pairs can immediately be plotted. (A detailed description of the design and operation of an instrument of this type/

type will be given in the next chapter.) With the aid of this instrument Walker and McDaniel were able to produce curves showing the high energy gamma-ray spectra of Fluorine and Lithium when subjected to proton bombardment. They were also able to show the variation in the energy of the Lithium radiation with change in bombarding energy. Apart however from these measurements and from some unpublished observations on neutron capture radiation by Kinsey, the precision study of high energy nuclear gamma-rays has hardly yet been begun. Determination of the multipole order of these radiations has scarcely been attempted at all.

I.4. Opportunities for Useful Research

(a) The General Field.

Summing up the various points discussed in the course of this chapter, it would seem that while a great deal of work is still being carried out on the radiations from the naturally radioactive elements (Latyshev, 1947; Feather, 1949), this work can no longer be described as simple gamma-ray spectro-:scopy, and indeed there does not seem to be much opportunity of adding significantly to the information already available concerning the level schemes of these elements, by the application of our method.

In the study of the radiations from the artificial radio-:active elements, however, a great deal of useful work remains to be done in determining accurately the energy and intensity of/

of the gamma-rays emitted by these elements. In addition to the determination of the energy of the various levels in these nuclei, another feature which is of great theoretical interest is the determination of the spins of these levels. This is a subject on which very little experimental work has been done (Latyshev, 1947; Helmholtz, 1941), but one on which the study of gamma-ray spectra in conjunction with measurements of the probability of internal conversion and internal pair creation, can throw much light.

If we go back for a moment and consider the loose analogy between gamma-ray and atomic spectra, it will be remembered that the first advances in the understanding of atomic structure came through the study of the spectrum of Hydrogen. Hence it seems reasonable to suppose that a fruitful field of study in nuclear spectroscopy will lie in the examination of the spectra of the light elements. Of course there are certain statistical properties of nuclei, such as level densities, which can be better studied in the heavier elements, but to the use of the method of gamma-ray spectroscopy, which is capable of giving detailed information about the energy and spin of individual levels, the light elements undoubtedly provide a strong chal-:lenge. It will of course be appreciated that very few of the light nuclei can be excited by radioactive decay, because most of the decay processes take place with very short half-lives. Hence the main method of excitation must be by nuclear reactions, and here, fortunately, the gamma-ray spectra of

many of the light elements can be easily excited by proton or neutron capture, or by the equivalent deuteron reactions, (d,n) or (d,p). These spectra demand the best modern techniques for their investigation, since they extend to high energies, and they also demand new techniques for the determination of the multipole order of the transitions observed.

(b) The Present Research.

It is clear from the above summary that the field of opportunity presented in the study of gamma-ray spectroscopy is very wide, especially when it is considered that after nearly 40 years of investigation, the study of the radiations from the natural radioactive elements is not yet complete. Nevertheless, since we, in Glasgow, were in the fortunate possession of a source of high energy protons and deuterons, and since there was also available an electromagnet of dimensions suitable for the resolution of electrons up to 30 M.E.V. in energy, it was decided that techniques should be developed for the investigation of gamma-rays from the artificial radioactive elements, and from excited states of the light elements caused by particle bombardment. These techniques were then to be used to collect data in this field, leading to the construction of energy level diagrams, and if possible to the determination of the spins of some of these levels. The remainder of this thesis is concerned with the execution of this programme, Part II dealing with the techniques developed, and Parts III and IV with several investigations/

investigations in which these techniques have been employed in the study of the gamma-ray spectra of particular nuclei, and the results obtained used to construct an energy level diagram, or else to verify or augment an existing diagram. In Part IV the use for the first time of the internal pair creation effect to determine the multipole order of a gamma-ray line from a light element is described, and tentative spin values are assigned to two levels in the Mg^{24} nucleus.

PART II. - INSTRUMENTATION.

II.1. Comparison of Different Types of Magnetic Analysers.

In order to carry out the desired programme of experiments, it was necessary to provide an instrument or instruments capable of analysing the secondary electrons and positrons from gamma--rays in the energy range say 100 K.E.V. to 20 M.E.V. With this requirement in mind let us consider briefly the advantages and limitations of the various types of analyser that have been described in the literature. These instruments can be brought roughly under three heads;

(a) Semi-circular resolvers,

(b) Magnetic lenses,

(c) Double focussing spectrometers utilising circular trajectories.

Various other types of instrument have been proposed from time to time (Korunsky, 1945; Richardson, 1947), but for practical reasons all the instruments to date with which serious work has been done have belonged to one or other of these classes, and their development has taken place in the order in which they have been listed.

(a) Semi-circular Resolvers.

The semi-circular analyser is of course the device introduced by Danysz (1913) and depends on the fact that if a plane pencil of charged particles of homogeneous energy and diverging with an angle 2θ are subjected to the action of a uniform/

uniform magnetic field acting perpendicularly to the plane of the pencil, then they are brought back to a focus after they have described approximately a semi-circle. Figure 1 illustrates the geometry of this process, the magnetic field

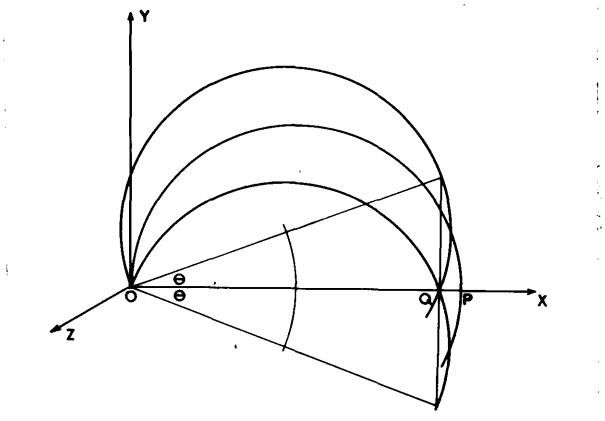


Figure 1. Semi-Circular Focussing.

acting along OZ, and the particles being emitted from O in the X-Y plane into a pencil of half-angle θ surrounding OY. Since the trajectory of each particle is a circle, it is clear that particles emitted along OY intersect OX again in the point (2R,0,0) where R is the radius of curvature. Those emitted at an angle A, say, to OY, intersect OX again in the point (2R.cosA,0,0). Hence it follows that all the particles in the pencil intersect OX again between the points P (2R,0,0), and Q (2R.cosθ,0,0); i.e., the point O forms an image PQ of length 2R(1-cosθ).

If we now consider the case of a particle emitted in the plane/

plane OYZ, so that its direction of emission makes an angle B with OY, its momentum, p, can be resolved into a component p.sinB along OZ, which is unaffected by the magnetic field, and a component p.cosB in the X-Y plane, which is rotated by the field. The particle therefore moves in a helix on the surface of a right circular cylinder of radius 2R.cosB with its axis parallel to OZ, and intersects the X-Z plane again in the point S, (2R.cosB,0,πR.sinB). Hence if B is allowed to vary so that $-\phi/2 \leqslant B \leqslant \phi/2$, S will trace out a portion of the ellipse

$$x^2/(2R)^2 + z^2/(\pi R)^2 = 1,$$

$$y = 0$$

lying between the points (2R.cosϕ/2,0,πR.sinϕ/2) and (2R.cosϕ/2,0,$-\pi$R.sinϕ/2). Thus where, for rays lying in the X-Y plane, the image of the point O was a sequence of points on the X-axis between the points P and Q, the corresponding image for rays which are allowed to emerge in a rectangular pencil of half-angle θ in the X-Y plane, and ϕ/2 in the Y-Z plane, surrounding OY, is given if each of the points in the line image is expanded into a portion of an ellipse in the X-Z plane, as shown above. The image of a point source is thus a section of the above ellipse, of length approximately 2πR.sinϕ/2, and thickness 2R.(1-cosθ), as shown in Figure 2 (a).

The image of a broad line source can be inferred from the above analysis, for if θ and ϕ are both made very small, every point (x,z) in the source will produce an image point (x+2R,z), thus producing an exact image of the source displaced/

displaced a distance 2R in the direction of OX. The effect of allowing finite but small values of θ amd ϕ, is to turn each point image into a portion of the characteristic ellipse. Hence if we let the source have length $\pi R\phi$ and thickness t, and if we restrict the image length to $\pi R\phi$, we produce a figure of the general shape shown in Figure 2(b), the overall

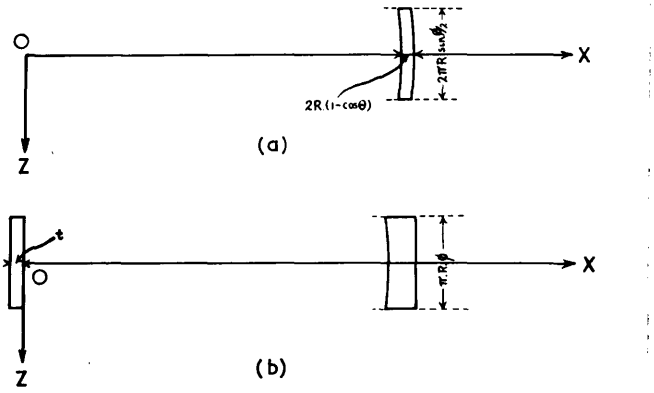


Figure 2. Images of point and line sources.

width, w, of the image, being given by;

$$w = t + 2R(1 - \cos\theta.\cos\phi)$$
$$= t + R(\theta^2 + \phi^2)$$

This quantity, w, is called the "Full Line Width" of the spectrometer, and if the mean intensity of the image is plotted as a function of x, the "Line Shape" obtained is roughly triangular (Cork, 1949) with the maximum near the high energy side. Hence the "Half Width", or width of the line at half maximum intensity, is given approximately by w/2.

Now/

Now we have discussed above the image formed by a line source of homogeneous electrons, in a uniform magnetic field, and have deduced its half width. It is, of course, formed at a distance from the source which is proportional to the momentum p, of the electrons from the source. Hence, if the source is emitting several groups of electrons of different momenta, each group will produce its own image, at a distance from the source proportional to its momentum, and so if there are two groups of nearly equal momentum, their images will just be resolved when their distance apart is equal to their half width. If the momentum difference in this case is δp, and if the mean momentum of the two lines is p, then we can define the "Resolving Power" of the spectrometer as;

$$P = p/\delta p = 2R/(w/2) = 4R/w.$$

This then gives a measure of the resolving power of the semi-circular spectrometer as used to form images of the source, say on a photographic plate. If now we consider its use with a G.M. counter as detector, then we must place a slit of suitable dimensions in the X-Z plane with its length at right angles to the X-axis, and at a suitable distance from the source, and then cause each line of the spectrum to be focussed, in turn, on to the slit, by adjusting the value of the magnetic field. In this case, obviously an infinitely narrow slit would give the same resolving power as the photographic plate, but a slit of finite width would integrate the photographic spectrum over a momentum range/

range corresponding to its own width. Hence the line width for a slit of finite width w_o is given by:

$$w = (t + w_o + R(\theta^2 + \phi^2))$$

and the resolving power is altered accordingly.

If now we consider a spectrometer in which the various sources of line width are made to contribute equally to this width, i.e.:

$$t = w_o = R\theta^2 = R\phi^2, \text{ then,}$$

$$w = 4R\theta^2$$

and the resolving power is given by:

$$P = 4R/w = \theta^{-2}$$

Also the solid angle into which the particles are projected is given approximately by $2\theta\phi$, or $2\theta^2$, and the source area is $\pi R\theta.R\theta^2$, or $\pi R^2\theta^3$.

Now the desirable qualities in a magnetic resolver which has to be used for gamma-ray spectroscopy are, in the first instance, large collecting angle, large source area, and good resolution. The first two criteria are particularly important when weak sources have to be studied. If the sources have a low specific activity, then their strengths are limited, for internal conversion measurements, by the surface area that can be exposed, and for external conversion, by the volume that can be contained within a copper vessel of appropriate dimensions to suit the spectrometer source holder. In the case of targets being bombarded by a beam of particles, since this beam is normally of finite cross-section, it is again clear

that/

that the strength of source available will depend on its area. Hence in every case the intensity of the secondary radiation to be studied depends on the source area. The intensity observed at the detector is also proportional to the collecting solid angle, and so, as suggested by Persico (1949), a convenient measure of the intensity observed at the detector of a magnetic resolver is afforded by the product of the source area and the collecting angle. This figure, which we shall call the intensity factor, F, together with the corresponding resolving power, P, determines the performance of the spectrometer.

To return to the case of the semi-circular resolver, it was shown that for the case of equal contributions to the line width of each of the independent variables, the resolving power, solid angle of collection, and source area, could all be expressed as simple functions of the aperture angle, θ. Hence we can write:

$$P = \theta^{-2}$$

$$F = (\text{source area})(\text{solid angle})$$

$$= \pi R^2 \theta^3 . 2\theta^2$$

$$= 2\pi R^2 \theta^5$$

and we thus have the relation:

$$F = 2\pi R^2 P^{-5/2}$$

Thus with the two variables R and θ at our disposal, it is clear that for good design we must make R as large as possible, and choose θ in such a way as to give a good compromise between high/

high resolving power and high intensity. In practice, the value of θ is limited by the geometry of the electromagnet used, since a large value of θ involves the use of a wide gap between the poles, which interferes with the uniformity of the magnetic field.

(It is to be noted that the above calculations, carried out by the author, are not rigorous. An exact theory of the semi-circular spectrometer has been carried out very recently by Geoffrion (September, 1949) who derives optimum conditions of operation, which are slightly different from those chosen above (equal contributions to the line width.) With the optimum conditions, however, the same fundamental relationship between F and P is derived, the only change being in the value of the numerical constant.)

(b) Magnetic Lenses.

The term magnetic lens is normally used to describe any magnetic focussing arrangement where the field possesses axial symmetry. The simplest case of this is, of course, that of a uniform axial field, such as is conveniently obtained by the use of a long solenoid. In this case, particles of the same energy and emitted from a point source at the same angle to the magnetic field, describe helices of the same dimensions and are brought back to a focus in a point at the same distance from the axis as was the point of emission. The method of use is to

place the source and the detector at points on the axis of the solenoid, and to interpose between them a baffle which transmits only those particles which pass through an annular aperture whose dimensions and position control the collecting solid angle, and resolution of the instrument. This method was first suggested by Kapitza and investigated by Tricker (1924) using the photographic plate method of detection which was not very suitable for use with this technique. The first spectrometer using this method with a G.M. counter was constructed by Witcher (1941) and achieved a solid angle of 0.126 steradians and a source area of 3.14 cm^2 with a resolving power of 16.7. This performance can theoretically be equalled by a semi--circular resolver of 12 cm radius, with an aperture angle θ of 0.245 radians. The solenoid used by Witcher, which contained about 360 lbs of copper, was 60 inches long, had an internal diameter of 10.5 inches and was water-cooled so that it could dissipate a power of 18 kW. The maximum energy of electron that could be focussed was 4.4 M.E.V. It will be observed that from this point of view the solenoid is a very inefficient instrument when compared with a semi-circular resolver, which, with the same amount of copper on a 12" magnet would focus electrons of 30 M.E.V. with the expenditure of only one third of the power.

Recently, however, a great deal of attention has been paid to the design of the solenoid spectrometer, and an excellent paper/

paper by Persico (1949) considers this design problem not only from the point of view of optimum geometrical performance, but also bearing in mind the question of economy of copper and power. Persico claims that with a solenoid of the size used by Witcher, optimum design could give four times the intensity factor for the same resolving power, or twice the resolving power for the same value of F. A better comparison between the best design of solenoid and of semi-circular type resolvers is, however, available since Persico gives the relationship between the intensity factor and resolving power for the solenoid as:

$$F = 5.4D^2.P^{-5/2}$$

where D = 2p/eH, e being the electronic charge in e.m.u. This length determines roughly the dimensions of the solenoid, being of the order of its diameter.

It will be observed that the relationship is similar to that governing the performance of the semi-circular resolver, the area $5.4D^2$ being substituted for $2\pi R^2$. It is thus clear that there is no essential difference between the performances of the two instruments, since either type can be made to give any desired performance by suitable choice of dimensions. It is clear, however, that in practice the solenoid type is superior where a large solid angle is essential, as where a source is limited in total strength but can be concentrated into a small area. Here a large source area is pointless, while the largest possible solid angle is desirable, and in this case/

case the semi-circular type is not suitable, since large solid angles mean wide gaps, and hence difficulty in maintaining the uniformity of the field. This advantage of the solenoid for weak sources of small size, is however quite outweighed by its limitation in the energy range that can be focussed by a solenoid of reasonable dimensions; and where a spectrometer is desired which will provide good intensity and resolving power for work on sources of low specific activity and very high energy, as in the present case, there is little doubt that the semi-circular resolver provides a better instrument.

The above criticisms of solenoid type lenses apply equally to lenses of other types. Of these the short coil type (Deutsch, Elliott and Evans, 1944) is more economical than the solenoid, but provides an inferior performance. Recent designs of lenses having small spherical aberration (Richardson, 1949; Slätis and Siegbahn, 1949) promise to provide extremely large solid angles for the study of weak sources, but are rather specialised instruments using point sources and would not be applicable to our problem.

(c) The Double Focussing Spectrometer.

In 1946, in a letter to Nature, Svartholm and Siegbahn described a new type of analyser in which the particles move approximately in circles, but undergo second order focussing both in the median plane of the instrument, and in their motion at/

at right angles to this plane. This type of instrument, which has since come to be known as the Double Focussing Spectro-:meter, depends on the principle that had already been used in Betatron design, that a magnetic field with axial symmetry, which diminishes with increasing radius, tends to produce focussing in a beam of particles moving in approximately circular orbits round the central axis. A full theory of the effect has since been published by Shull and Dennison (1947), and they treat the motion of the particles as due to small perturbations of the central circular equilibrium orbit, and show that for a certain law of variation of the field, which corresponds very closely to $H \propto R^{-\frac{1}{2}}$, the "Wavelengths" of the perturbations, in the median plane and normal to it, are equal and correspond to an angular distance of $\pi\sqrt{2}$.

From the equations of Shull and Dennison, it is possible to arrive at a relationship between F and P for this type of resolver as well as for the other two which we have considered. In this case, if θ or ϕ are linearly related, we once again obtain $F = (\text{const}).R^2P^{-5/2}$, only this time the constant may be made several times as large as for the semi-circular instrument, since by a suitable choice of the second order coefficient in the radial variation of the field, it is theoretically possible to achieve third order focussing in the median plane and so achieve comparatively large collecting angles in this plane. ($\theta = k\phi$, say, where k is a design parameter). This advantage is/

is only realizable in practice, however, if the angles concerned are small, since the perturbation theory breaks down for large displacements. For this reason, the use of this type of spectro-:meter has been restricted to the case of high resolution (Kurie, Osoba and Slack, 1948; Shull, 1948) (Resolving power of several hundreds), for which case it can provide a higher intensity than either of the other types of comparable size.

Summing up this short discussion of the relative merits of the three main types of magnetic analysers, then, we must observe that the intensity factor, which we defined earlier, is in each case proportional to the 5/2 power of the inverse of the resolving power, and to the square of the linear dimensions of the apparatus. Hence, for the purpose of gamma-ray spectro-:scopy, there is no fundamental virtue in one type rather than another, since any one can be made to equal the performance of another by making it large enough. In practice, however, those instruments using iron magnets are more economical for use at high energies, while the lenses are capable of providing larger solid angles than the other types, though usually at the expense of source size. They are most useful then, at low energies, and with weak sources of high specific activity. Where high resolution is essential, the double focussing type of instrument is capable of providing the largest intensity of the three types. It shares with the semi-circular type the advantage of using an iron magnet which enables it to be used

at/

at relatively high energies, but suffers from the practical difficulty that it requires a shaped field.

In view of arguments of the above type, and also of the important fact that an electromagnet of suitable dimensions was available in the Department, it was decided (early in 1948), to concentrate on the use of spectrometers employing an electro-:magnet to provide the field. Furthermore, since it was realized that in the study of the energies of very hard gamma radiations the only way to achieve good resolution was to observe simultaneously the energies of the positrons and electrons produced as pairs by the gamma-rays, (see I,3,(d)) it was decided to concentrate initially on the simplest possible type of resolver, namely the semi-circular type. The idea, then, was to construct a simple spectrometer of this type for the investigation of Compton and photo-electrons produced by gamma-rays in the energy range 100 K.E.V. to 3 M.E.V. using the well established technique of Siegbahn, and further, to construct a double semi-circular resolver for the simultaneous analysis of the positrons and electrons ejected from a thin foil by hard gamma-rays in the energy range 3 M.E.V. to 20 M.E.V. The former of these projects was carried through as originally planned, but the latter was altered after the publication of Walker and McDaniel's paper in August, 1948, and the pair spectrometer finally built was a multiple resolving chamber of the type described by these authors.

II.2. The Semi-Circular Resolver.

(a) The Electromagnet.

The design of this instrument was naturally, to some extent affected by the electromagnet which was available, and so it would perhaps be wise to begin with a short description of this apparatus. The electromagnet of which a photograph is shown in Figure 3, has circular pole pieces of twelve inches in diameter,

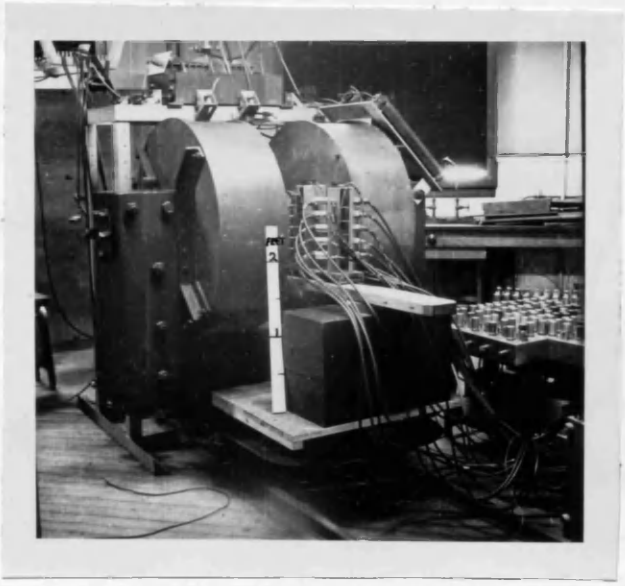


Figure 3. The Electromagnet.

and a gap which is adjustable in quarter inch steps, from one quarter inch to eight inches. With a gap of two inches, the fifteen hundredweights of copper in the windings enable a field of ten thousand gauss to be obtained with a current of thirty--five amperes, which represents a dissipation of the order of twelve hundred watts. The gross weight of the magnet is about four tons. It will be observed from the photograph that in its present position, in the beam room of the particle accelerator, it/

it is mounted on a bogie which enables it to be moved out of the way along the rails provided, when not in use.

(b) The Spectrometer.

To return then to the design of the semi-circular resolver, this is essentially similar to the numerous examples of the type described in the literature, except possibly that more care than usual was taken in its design in order to achieve high intensity. Most earlier designs were essentially for two dimensional instruments, and not until the publication of Geoffrion's paper in September 1949 was the exact calculation of the optimum relation between the various design parameters carried out. The present author, however, with the aid of the calculations described in II,1,(a) had already constructed an instrument of good design, and a diagram of the internal structure of the spectrometer is shown in Figure 4. It will be observed from the diagram that the vacuum tank, which is the structural basis of the apparatus, consists of two half-inch steel plates fourteen inches in diameter, separated by a hollow copper cylinder of quarter-inch wall thickness, to give a space two inches deep. One steel plate is soldered to the copper cylinder, while the other is attached with a number of steel screws, and sealed with a rubber gasket. The steel plates were deliberately made larger in diameter than the magnet poles, in order to reduce the fringing field effect inside the/

the tank. Three of these tanks were constructed, one being used for each of the resolvers discussed above, and the third being kept as a spare.

To return to the diagram of the semi-circular resolver,

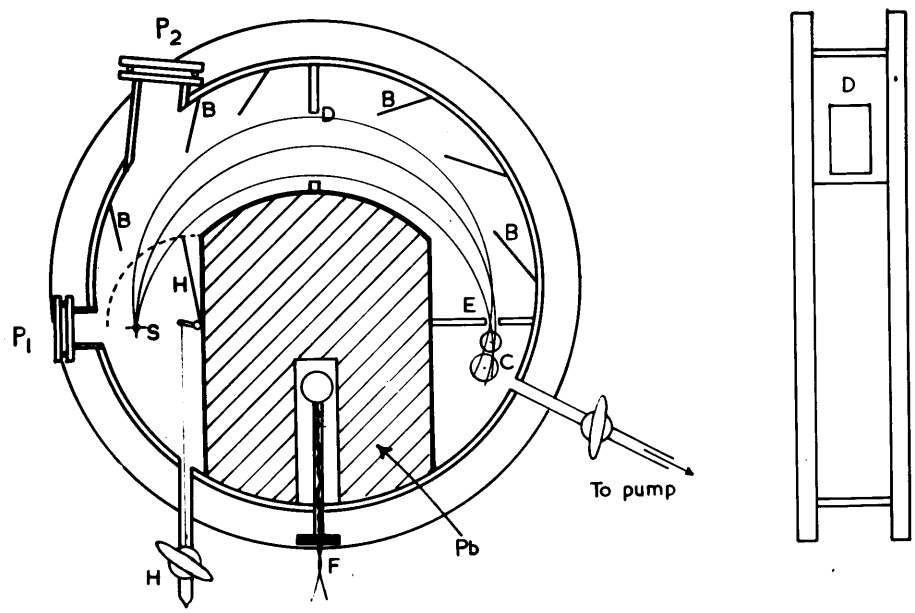


Figure 4. The Semi-Circular Spectrometer.

S is the position of the source which is mounted through a hole in the lid of the vacuum tank. C is the position of the counter which also mounts through a hole in the lid, and D is an aluminium plate in which is milled the aperture which defines the values of θ and ϕ utilised. Several of these plates are available, providing a variety of solid angles, and a corresponding/

corresponding set of plates E is available, with slits milled in them to suit the values of solid angle available with D. The baffles B are fixed and have no part in defining the beam of particles, but they help to suppress unwanted particles which might otherwise enter the counter after scattering at the walls of the apparatus. All exposed surfaces in the spectro-:meter are covered with aluminium sheeting to reduce such scattering to a minimum. Of the remaining features of the apparatus, F is a flip coil which is used, in conjunction with a Cambridge Fluxmeter, to determine the value of the magnetic field, and P_1 and P_2 are ports which respectively enable a beam of protons or deuterons to be directed on to a target situated at the source position, and a proportional counter to be fitted to the apparatus in order to detect heavy particles emanating from the target. H is a small shutter which can be operated from outside the vacuum, and to which can be attached a convertor which can thus be placed in front of the source during an experiment, if desired. All of these features have either been used already in experiments with this spectrometer of else their use is planned in future experiments.

(c) The Counters.

One of the small double G.M. counters used with the instrument is shown in Figure 5. These counters are made as small as possible in order to reduce their background, but the/

the smallest background obtained in this way with a single counter was about ten counts per minute. With the use of two

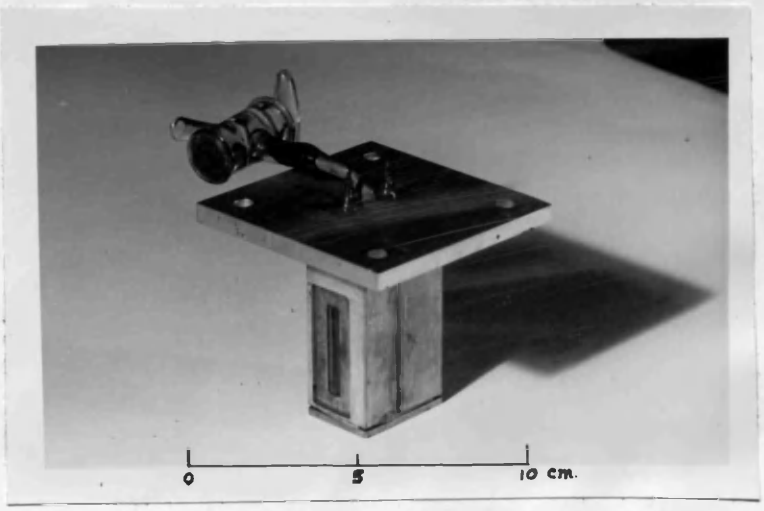


Figure 5. The Double Counter.

small counters in coincidence however, the background was finally reduced to 1.5 counts per minute, this reduction being highly important in the study of weak effects like internal pair-creation, which, with the intensity factor available, may yield a counting rate of only a few times this figure, and certainly less than ten per minute. The window between the two counters is of aluminium leaf, and is equivalent to only one or two mm. of air, while the outer window, which has to withstand atmospheric pressure when the spectrometer is opened to the atmosphere, is normally of mica and of thickness equivalent to one or two cm. of air.

(d) Calibration of the Spectrometer.

In order to test the working of the instrument, and also

to/

to obtain a calibration of the flux-measuring system, a short study was made of the radiations of ThB and its products. The source used was a piece of fine tinned copper wire on which a very thin layer of ThB had been deposited from the emanation of RaTh by the action of an electric field. This provided a source of negligible width, which emits a well known series of internal conversion lines which extend over the entire range of energies for which the spectrometer was designed, and the results of the runs taken on this source are shown in Figures 6 and 7. Figure 6

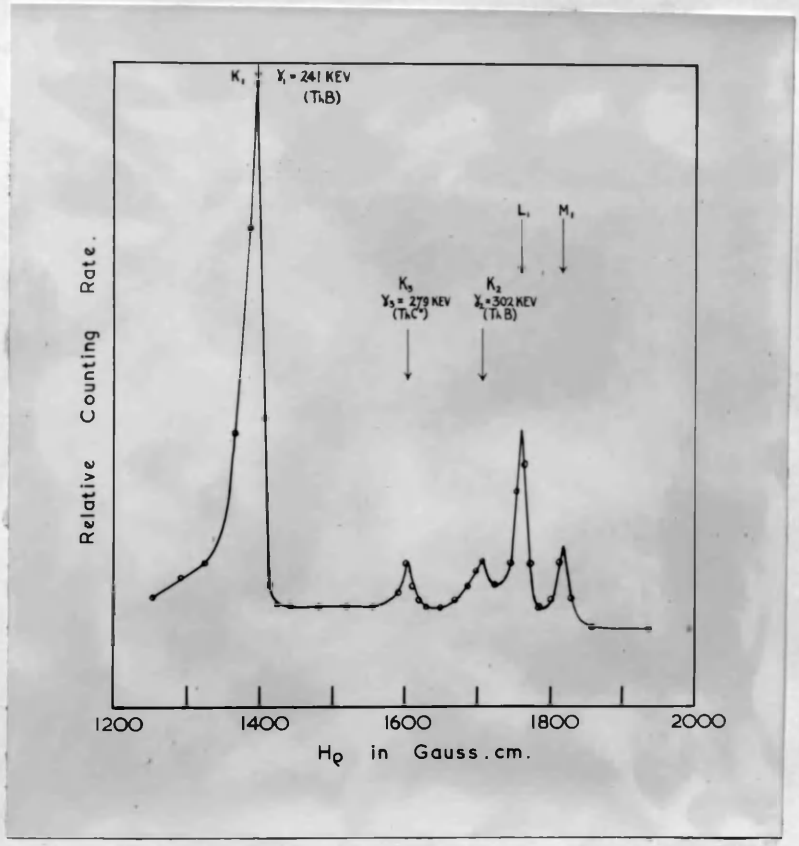


Figure 6. Low Energy Beta-ray Spectrum of Th(B+C+C")

shows the low energy region of the beta-ray spectrum when examined with a nominal resolving power of 200. The largest peak is the well known "F-line" whose momentum value has been measured/

measured very accurately (to at least 1/500) by Ellis and others (Rutherford, Chadwick and Ellis, 1930, pp.369-370), and the determination of the fluxmeter reading for this peak alone is theoretically sufficient to calibrate the instrument for all energies. It was decided, however, that a check on the calibration at high energies would be advisable, in order to be certain of the linearity of the fluxmeter, and so a record was taken of the beta-ray spectrum of the source, near its end-point, with a resolving power of 50, with a view to observing the internal-conversion (K) line of the 2.62 M.E.V. gamma-ray from ThC". This line, though feeble, was observed, and found to

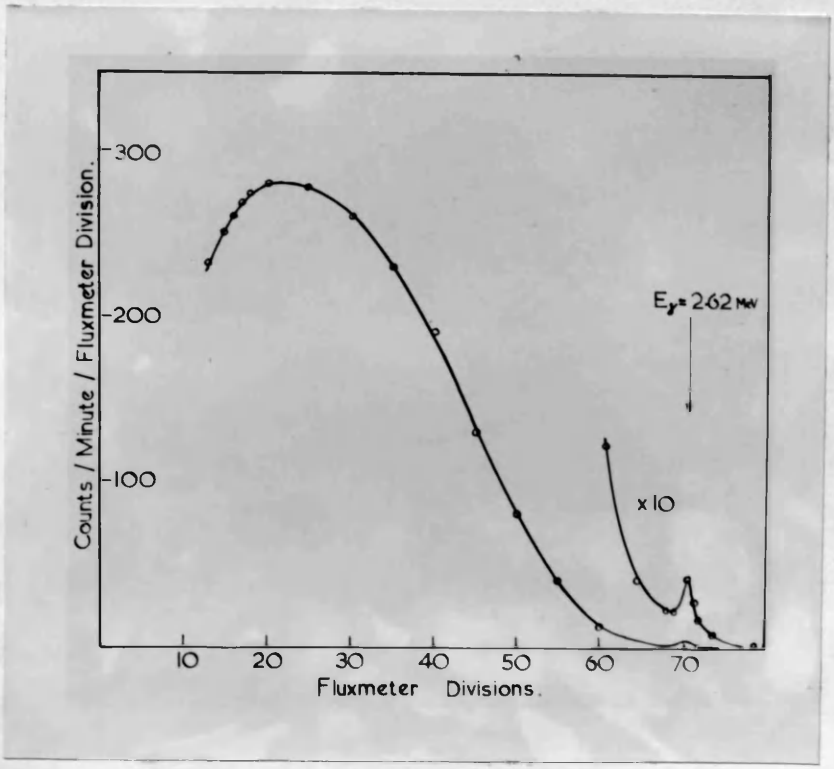


Figure 7. High Energy Beta-ray Spectrum of Th(B+C+C")

yield a calibration of the instrument in good agreement with that/

that obtained from the F-line of ThB. The spectrum obtained is shown in Figure 7, and the calibration curve of the spectro-:meter, based on the F-line is shown in Figure 8, with the point due to the 2.62 M.E.V. gamma-ray also shown.

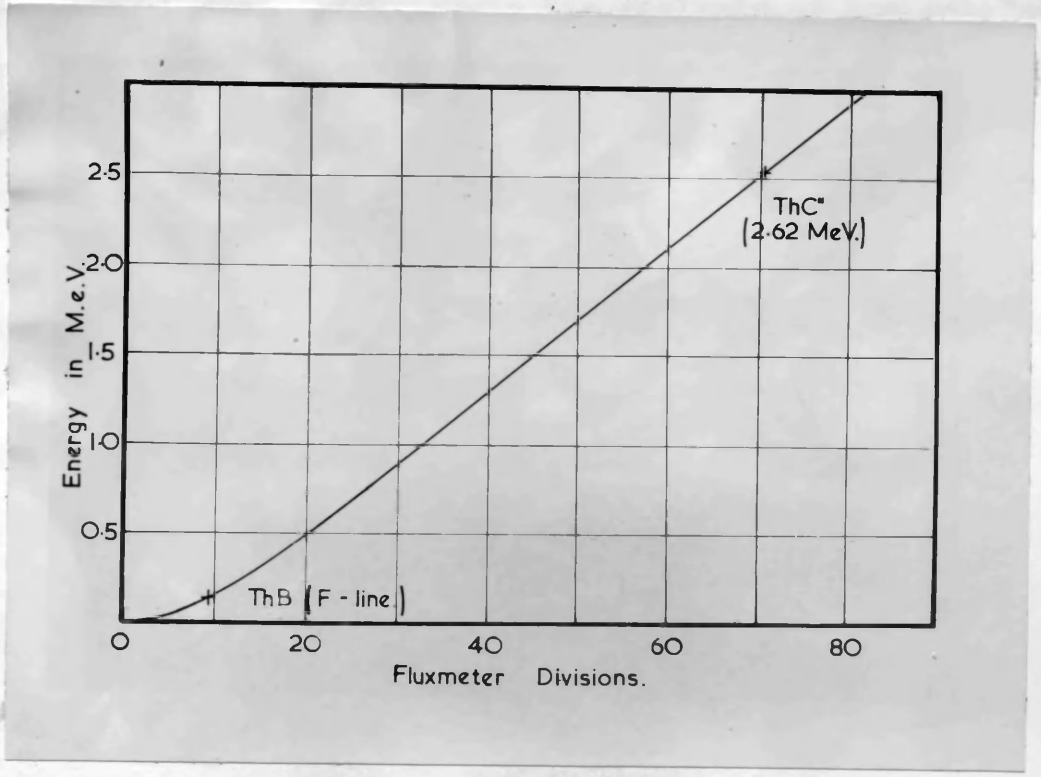


Figure 8. Calibration Curve of Spectrometer.

(It may be noticed in Figure 6 that the F-line actually has a half-width of about 1.5% despite the high resolving power used. This is due to the source mounting, since the use of lower resolving powers did not increase greatly the width of the line, and is caused by scattering in the heavy copper and tin of the mounting, and also by self absorption of those electrons which come from the sides of the wire and so emerge nearly tangentially/

to its surface. The problem of source mounting is one of the main difficulties in the use of magnetic analysers for the study of low energy beta-ray spectra.)

While Figure 6 shows very clearly the order of resolution provided by the spectrometer in the analysis of the internal-conversion electrons from a soft gamma-ray (241 K.E.V.) and a heavy nucleus, it is interesting to observe the order of resolution possible with the use of Siegbahn's technique. Here ThB and its products do not provide a very suitable source since they emit a large number of gamma-rays, and with the diminished resolution obtainable by external conversion, it becomes difficult to interpret the results obtained. A very good

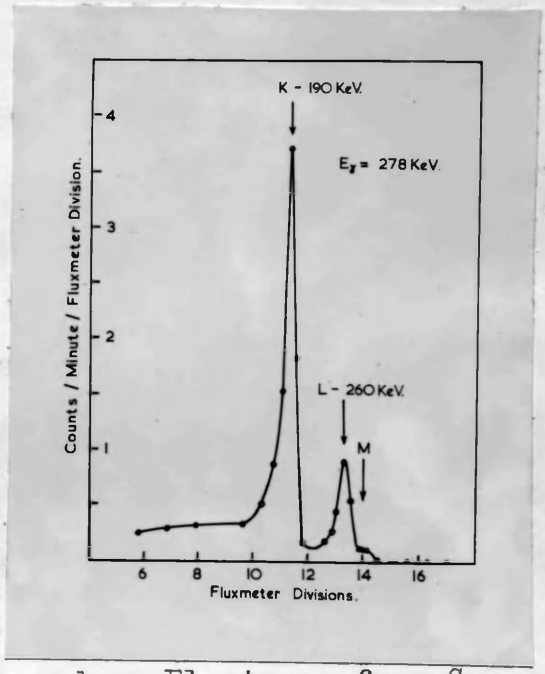


Figure 9. Secondary Electrons from Gamma-Rays of Hg^{203}

example of the resolution obtainable with the instrument is however shown in Figure 9. This is the spectrum of the secondary electrons/

electrons ejected from a glass tube covered with several thicknesses of platinum leaf, by the 270 K.E.V. gamma-rays from Hg^{203} and was obtained by Mr. H.W. Wilson during the course of his work on this source. It will be observed that at this energy the Compton effect in the (thick) glass produces comparatively few electrons, while the photo-electric effect in the very thin platinum is so strong that the peaks due to conversion in the K and L shells of the platinum are clearly seen, and traces of the M-conversion electrons are also visible. Since the mercury source was weak ($\sim 80\mu C$), it is clear that the spectrometer provides a good method of investigating the energies of gamma-rays in this energy region.

II.3. The Pair Spectrometer.

(a) An Early Idea.

In 1947, the author was working with Dr. S.C. Curran on the properties of G.M. counters with beads of conducting or insulating materials on the wire. (Curran and Rae, 1947) Out of this work arose an idea of Dr. Curran's to utilise this effect in the design of a spectrometer, in particular a pair spectrometer, and a model was constructed, of which a schematic diagram is shown in Figure 10. The plan was to surround the source of particles with a ring shaped G.M. counter having its axis lying along the direction of the magnetic field, and to divide/

divide this counter into a large number of independent sections, by means of beads, or their equivalents, placed at regular intervals on the wire. Then a particle emitted by the source in

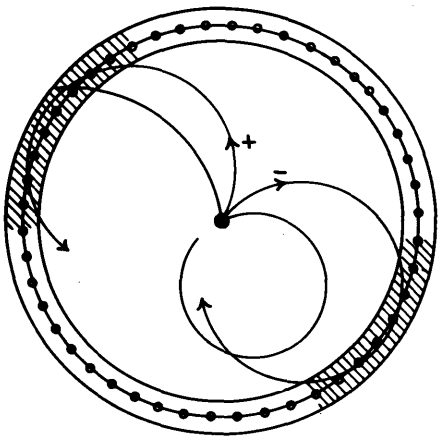


Figure 10. The 360° Spectrometer.

the plane of the paper will, in general, intersect only one or two sections of the counter, and will produce a pulse of corresponding size in the output. If, however, the particle is emitted with a momentum such that its radius of curvature will cause it to describe a path tangential to the outer wall of the counter, then this particle will trigger some five or six sections of the counter and produce a correspondingly larger pulse. Hence if the source consists of a quantity of some material emitting hard gamma-rays (energy much greater than 1 M.E.V.), surrounded by thin lead foil, it is clear that positron-electron pairs ejected from the foil by the gamma-rays, for the correct/

correct value of the magnetic field, and for the case of equi-partition of energy between the two components of the pair, could produce pulses corresponding to the triggering of ten or twelve sections of the counter.

This was, in essence, the idea behind the first pair spectrometer constructed in the laboratory, and a considerable amount of effort, on the part of the author, was applied to its development. Unfortunately, for a number of technical reasons, the instrument in its original form did not prove suitable for use as a pair spectrometer. The basic idea, of a 360° semi-circular focussing spectrometer, has however been developed by the author, by the analysis of the general case where the particles are not confined to the neighbourhood of the median plane, and an instrument of this type would seem to be particular-:ly suited to certain branches of beta-ray spectroscopy. In particular, the very large solid angle of collection, which may approach 50% of 4π, would make such an instrument ideal for the study of complex beta-ray spectra by the method of beta-gamma coincidences. (See Part III.1.(d).)

Despite the importance of this development of the idea of the 360° spectrometer, it was felt that a detailed discussion of the subject at this point might interfere with the logical development of the main theme of this thesis. Consequently such a discussion has been omitted from the main body of the text, but a full account has been prepared and accepted for publication/

publication (Rae, 1950,c) and this is given in Appendix I.

(b) The Double Semi-Circular Resolver.

In November 1947 McDaniel, von Dardel and Walker published a letter in the Physical Review giving the results of an experiment in which the pairs produced by the 17 M.E.V. gamma-rays from the proton bombardment of lithium were analysed by means of two G.M. counters placed on either side of a lead foil which was being irradiated by the gamma-rays. By this means they obtained a curve which resolved the 17 M.E.V. component of the radiation quite clearly, and suggested the presence of lower energy radiation. This demonstrated the feasibility of studying high energy gamma-ray spectra by analysing the pairs produced, in a double semi-circular resolver, at least in the 17 M.E.V. energy region. Since however the cross-section for pair production falls off with decreasing energy, and since thinner convertors must also be used on account of increased scattering and relative loss of energy in the convertor, it was by no means certain, from the data of McDaniel and his co-workers, that this method would be practicable at energies much below 17 M.E.V.

For this reason a very crude model was constructed using two bell type G.M. counters sunk in a lead block as shown in Figure 11. This lead block was fixed between the poles of the electro-magnet, and the whole surrounded by a thin brass strip, sealed with Q-compound and evacuated. Gamma-radiation from

10 mC/

10 mC of RaTh was then caused to fall on the thin lead foil,

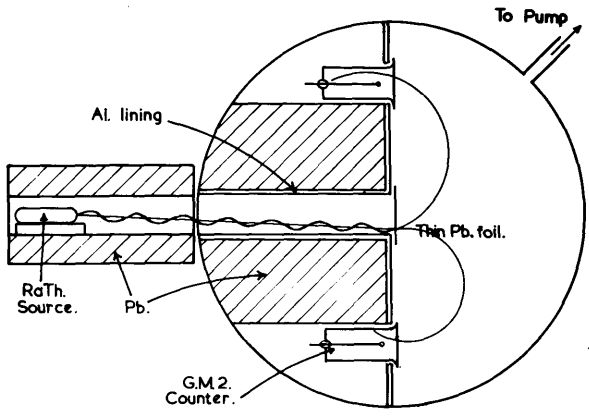


Figure 11. Experimental Pair Spectrometer.

as is shown in the diagram, and the coincidence rate between the two counters plotted against the magnet current. This gave the curve shown in Figure 12, indicating that even at 2.6 M.E.V.,

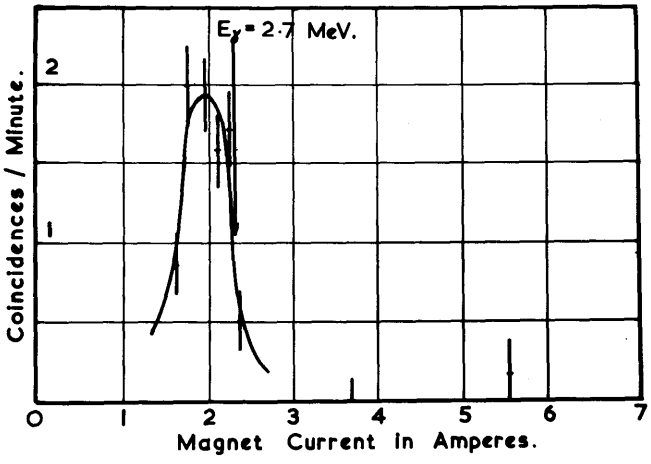


Figure 12. Gamma-Ray Spectrum of ThC"

the pair-production cross-section was still high enough to make the/

the method usable.

(c) The Multi-Channel Pair Spectrometer.

When this fact had been established, drawings were made for the construction of a properly designed double resolver, but before work had actually started on this spectrometer, McDaniel and Walker (1948) published their later paper describing their multi-channel instrument, and as this represented such an obvious advance on the single-channel type, it was at once decided to build such an instrument here. A schematic diagram

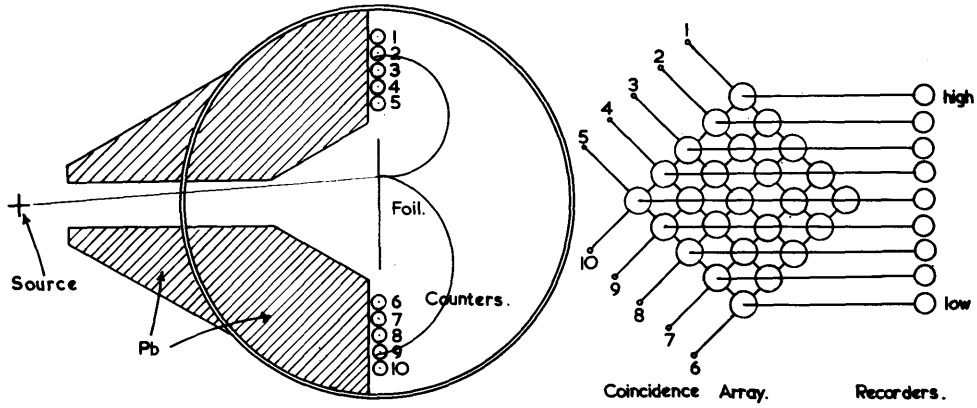


Figure 13. The Multi-Channel Pair Spectrometer.

of the apparatus is shown in Figure 13, and it will be observed that the foil irradiated by the gamma-rays is very wide. The ability/

ability to use a wide foil and so place a large quantity of converting matter in the path of the gamma-rays, without using a thick convertor, was one of the great advantages of this type of spectrometer pointed out by McDaniel et al. This can be tolerated because at relativistic velocities the energy of a particle is proportional to its momentum, and so the sum of the energies of the positron and the electron in a pair, which is a measure of the energy of the gamma-ray producing the pair, is also proportional to the sum of their momenta, and so to the sum of their radii of curvature in a uniform magnetic field. Now, if a particle is ejected in a direction nearly normal to the plane of the counters and the foil, it is brought back to the counter plane at a distance from its point of emission equal to twice its radius of curvature in the field. (This follows from the properties of semi-circular focussing). Hence if a positron and electron in a pair are ejected nearly normal to the counter plane, they are brought back to the plane at a distance apart equal to twice the sum of their radii of curvature. If now each of these particles enters and triggers a counter, then the distance apart of the two counters is a measure of the energy of the gamma-ray concerned, and this is independent of the point of emission of the pair, and of the absolute position of the counters. Hence if a large number of counters is used, as in the diagram, a coincidence between the triggering of any counter on one side of the foil and one on the other, gives a measure of the energy of the gamma-ray which produced the pair. If further

the/

the outputs of all the counters are connected as shown to a multiple coincidence circuit which registers all such possible combinations of counters, and adds together all the combinations corresponding to the same counter separation, then the outputs from the coincidence circuit give a number of points on the spectrum of the gamma-rays which are under observation. It is clear that with the aid of such a circuit, the information that can be obtained in a given time from any source, is proportional to the number of pairs of counters in use; but if there are n counters on each side of the foil, then the number of such pairs is n^2. Hence, though the use of four or five counters on each side of the foil makes the necessary coincidence circuit very large, (the size of the circuit is also proportional to n^2) the increase in speed in taking spectra with the instrument, which is the great advantage it enjoys over the cloud-chamber, makes this expenditure worth while.

(d) Considerations in the Design of a Multi-Channel Instrument.

In the above description of the action of the pair spectro-:meter, no account has been taken of the various factors which operate to reduce its efficiency and resolution. These have been discussed at length by Walker and McDaniel, and it will suffice here to mention the main difficulties, and the limitations they impose on the use of the instrument. It was assumed in the above discussion that the pair particles were projected/

projected forward at right angles to the plane of the foil and counters. In practice this is not so because the pair particles are in fact projected in such a way that the majority of them are contained within a cone of solid angle $m_o c^2/h\nu$ surrounding the direction of the gamma-rays, where m_o is the rest-mass of an electron. (Heitler, 1936; p.198) At an energy of 3 M.E.V. this solid angle is of the order of 1/6 and the corresponding semi-circular line-width is 17%. There is also the fact that the gamma-ray beam is diverging and so the axes of the cones of particles are inclined to the normal to the counter plane. This is only a small effect provided the source of the gamma-rays is sufficiently far from the foil. Even if, however, the particles commence their motion nearly perpendicularly to the counter plane, it is essential that they should not be scattered through large angles in emerging from the converting foil. It might be thought that this criterion would make the selection of a foil material easy, since one desires the highest pair production cross-section for a given amount of nuclear scattering. This is not, however, the case, since both phenomena increase in the same way, (proportional to z^2) with Z, (Heitler, 1936, p.200; Rutherford, Chadwick and Ellis, 1930, p.225) and so it is equally possible to use aluminium or lead convertors, and indeed Walker and McDaniel did use both. Hence the scattering effect sets a limit on the effective thickness of convertor that can be used, but/

but not on the material. It might be noted here that the loss of energy of a particle in traversing the foil is normally trivial compared with its apparent loss of energy due to scat-:tering, which causes imperfect focussing and always has the effect of making the particle intersect the counter plane at a shorter distance from the point of emission than twice its radius of curvature in the field.

It is clear then that the two main factors which control the resolving power of a pair spectrometer are the width of the counters and the thickness of the foils used. The former can theoretically be improved by the use of slits, with a correspond-:ing loss in intensity; but in practice it is extremely difficult to construct a slit to limit a beam of electrons with an energy of 10 to 20 M.E.V., on account of their very high penetrating power, and so any such increase in resolution would be more likely to come through the construction of smaller counters. The limitation in foil thickness seems to be of an absolute nature, but owing to the properties of semi-circular focussing, a thick foil produces a broadening of the gamma-ray line only on the low energy side, so that although it lowers the resolution of the instrument, it still enables the energy of a line to be accurately determined from the sharp high energy edge, and so, for a single-line spectrum, gives good intensity without much loss in accuracy.

Only one more design limitation exists for this type of instrument/

instrument, and this is in the circuit design. It is well known that if two trains of random impulses of mean recurrence rates p and q, and of duration s and t, are compared, then the number of overlaps that occur in unit time between members of the two series is given by $p.q(s + t)$. Hence if p and q represent the background rates in two of the counters of the pair spectrometer, one belonging to each set, and if s and t represent the duration of the pulses produced by the counters and their associated circuits, then the expression $p.q(s + t)$ gives the number of random coincidences occurring per unit of time. Hence the counter backgrounds must be made as small as possible, by making their physical size small, and by placing as much absorber (lead) as possible between the source and the counters; also the circuits must produce as short pulses as possible, if the number of random coincidences is to remain small in comparison with the number of real coincidences caused by the pairs.

(e) The Glasgow Pair Spectrometer.

A photograph of the pair spectrometer built at Glasgow together with its associated circuits is shown in Figure 14. The instrument is fitted with ten separate miniature G.M. coun-:ters, A, which are described elsewhere (Rae, 1950b), and are filled to a pressure slightly in excess of one atmosphere in order to provide a high efficiency, together with a stable thin window (20 cm. of air equivalent). The convertor is mounted on

a/

a thin wire frame which is pivoted so that the foil may be placed in, or removed from, the beam of gamma-rays without dis-:turbing the vacuum. Each counter is connected by a short piece of low-capacity screened cable to a cathode follower B, which in turn relays the counter impulses through a long cable to a pulse shaping circuit C. This circuit produces a pulse of duration from 0.3 to 3 microseconds whose leading edge is coincident with

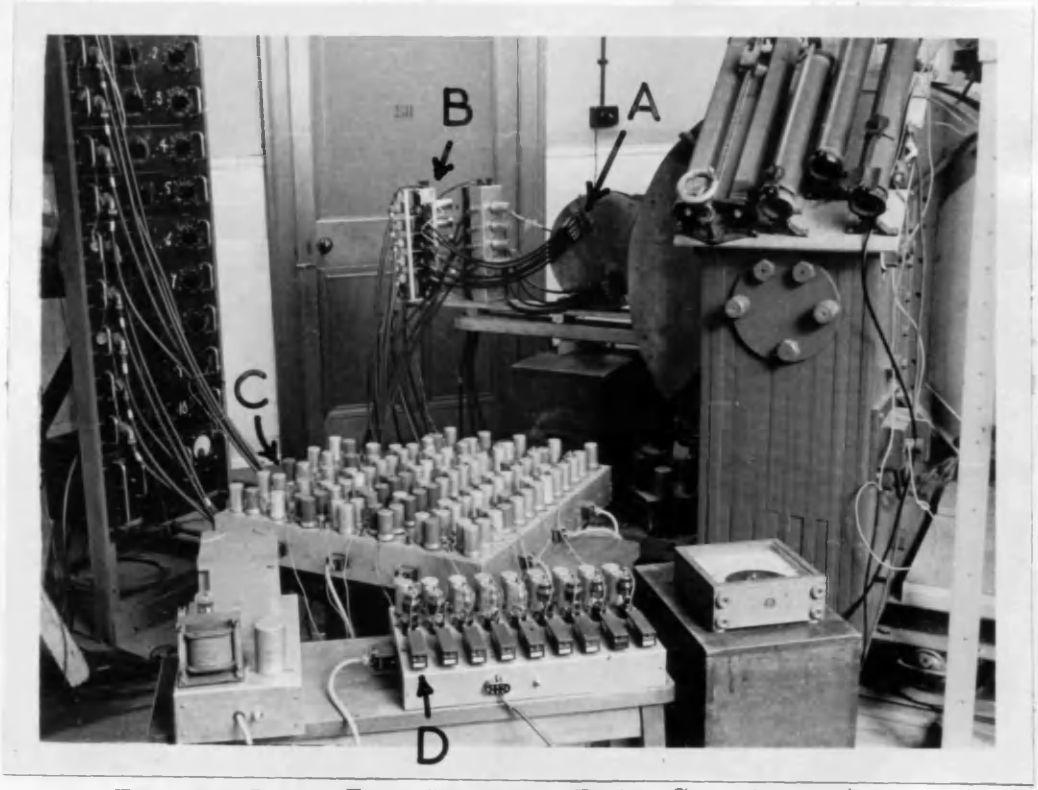


Figure 14. The Glasgow Pair Spectrometer.

the sharp rise of the counter pulse, and feeds this short pulse into a row of coincidence circuits in the coincidence circuit array. The coincidence circuit outputs are connected up diagonally, in such a way that each of the nine final outputs corresponds to a definite counter separation. The nine outputs feed/

feed into nine pulse-lengthening circuits, which produce pulses long enough to operate a post office telephone register, and the total number of pairs in each channel is recorded on these instruments D. The electrical circuits used, which were designed by the author with a view to obtaining the shortest resolving time possible with valves of the E.F.50 type, are described in more detail in Appendix II.

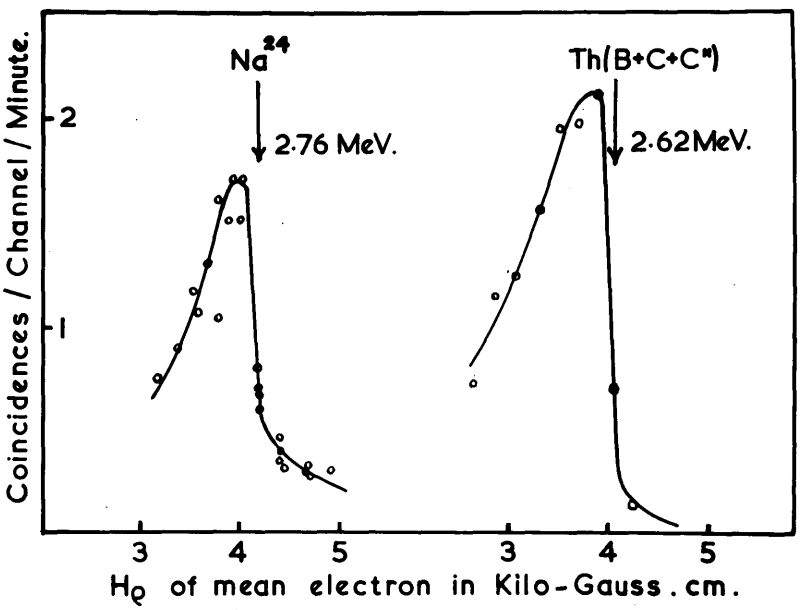


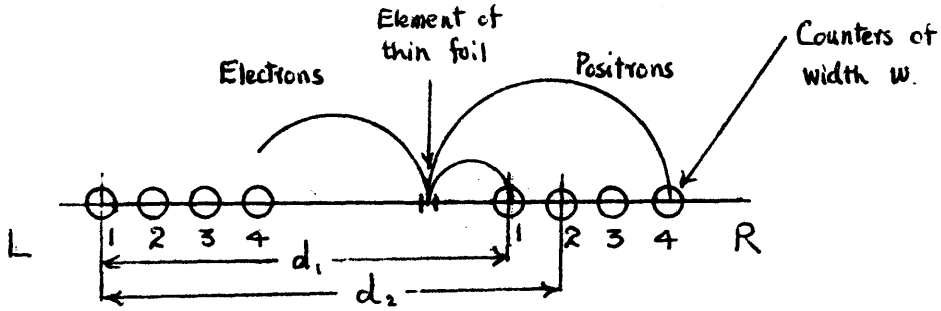
Figure 15. Gamma-Ray Spectra of Th(B+C+C") and Na^{24} - Thick Convertors.

When the spectrometer was first completed, the electromagnet was housed in a separate room from the particle accelera-:tor, and so the only sources of energetic gamma-rays available to test and calibrate it were radioactive ones. Hence the instrument/

instrument was tested using sources of Th(B+C+C") and Na^{24}, and thick convertors in order to obtain good sensitivity at the relatively low energies of the radiations provided by these sources. The spectra obtained are shown in Figure 15, and it will be observed that the lines are very broad, as expected. If however, a point half-way up the high energy edge of the lines is taken as significant, then their energies can be determined with a relative accuracy of the order of $\pm \frac{1}{2}\%$. Also the determination of these two well known spectra enables a calib-:ration to be made of the flux measuring arrangement of the spectrometer, though it will be appreciated that on account of the relatively low energy of the radiation from these sources, this determination is not as accurate as would be desired.

Note on the Normalisation of Results obtained with the Multi-Channel Pair Spectrometer.

Heitler has shown theoretically (Heitler: Quantum theory of Radiation p. 199) that for gamma-rays in the energy region covered by the pair spectrometer, say 3 to 20 M.E.V., the energy spectrum of positrons or electrons produced as pairs is roughly rectangular, provided we ignore the distortion caused by the Coulomb field of the nuclei of the material in which the pairs are formed. The effect of the Coulomb field is to raise the high energy end and depress the low energy end of the positron spectrum, with a complementary effect on the electron spectrum. This effect is however quite negligible, even in lead, except at the low end of the range of gamma-ray energies in which we are interested. These results have been confirmed by experiment. (Delsasso, Fowler and Lauritsen, 1937; Alichanov, Alichanian and Kosodaev, 1936)



Distribution of pairs among counters.

Hence if we consider the case of pairs produced by high energy photons falling normally on to a narrow element of a thin foil placed between two sets of counters in a magnetic field/

field, as shown in the diagram, then the number of positrons focussed by the magentic field into R1, will be the same as the number focussed into R2, R3 or R4, since each counter of width w represents the same fixed momentum interval Hw, and so for relativistic particles, the same energy interval. (Provided always that the value of the magnetic field has been suitably chosen). Similarly the number of electrons focussed into each of the electron counters will be constant. Hence if we take coincidences between L1 and R1, and so measure the number of pairs of total momentum $Hd_1 \pm Hw$ entering these two counters, we shall find that this is the same number as enter L2 and R2, L3 and R3, or L4 and R4. Similarly coincidences between L1 and R2, L2 and R3, or L3 and R4 will record the number of pairs of total momentum $Hd_2 \pm Hw$, and so on. In the Multi-Channel Pair Spectrometer, the output of each pair of counters appears on a register corresponding to the total momentum concerned, as shown in Figure 13, and all that is necessary to normalise the results for a single setting of the magnetic field is to divide the reading of each register by the number of channels recorded on it, and so obtain the number of coincidences per channel per momentum interval Hw. Since the above argument is true for any narrow element of foil placed between the sets of counters, it is clearly also true for the case of a wide foil.

When the magnetic field is changed to another value, say H_1, then the momentum interval is changed to H_1w, and if the results obtained have to be compared with those for the standard/

field H, then all the register readings must be reduced to a momentum interval Hw by multiplying by the factor H/H_1.

The application of this simple geometrical normalisation procedure has been found to give satisfactory results, except in those cases where relatively low energy radiations have been investigated with the use of thick lead foils (See pp. 57 and 58). In these cases the pairs are not projected normally to the foil, and severe scattering increases this effect (See p.53) so that a number of particles are deflected so far from the plane of the spectrometer that they are not recorded. In addition, the use of a lead foil at low energies causes considerable Coulomb distortion, and so it is clear that for such spectra no accurate measurement of relative intensities would be possible. In the two cases cited, however, no question of relative intensities was raised, the interest being entirely in the energy measurement. Even so, an attempt was made to correct empirically for the effect of the deflection of the particles, by multiplying the results by a factor of the form $(d/d)^n$ where n was chosen to give the best fit between sets of results obtained with different settings of the magnetic field, the various runs being normalised at some fixed value of the momentum. In practice the value n = 2 was found to yield the best results, and the curves shown in Figure 15 have been corrected using this value.

Undoubtedly good determinations of relative intensity could be obtained even in the 2.5 to 3 M.E.V. region by the use of/

PART III. - ENERGY DETERMINATION AND THE CONSTRUCTION OF ENERGY-LEVEL DIAGRAMS

As stated in the Introduction, we shall be concerned, in this chapter, with the use of the two instruments described in Part II, to make determinations of gamma-ray energies, and to use the information obtained, either to construct new energy-level schemes for the nuclei concerned, or else to verify or augment existing schemes. Two examples will be studied, the first being the radioactive decay of Praseodymium-142, which was known to emit a hard gamma-ray of energy somewhere between 1.5 and 2.1 M.E.V., and the second being the radiation emitted by Fluorine-19 when subjected to bombardment by protons. In the case of Pr^{142}, which was examined by means of the semi-circular spectrometer, using the Siegbahn technique, the spectrometer was also used to examine the beta-ray spectrum, for which purpose it is equally well suited, and an analysis of the beta-ray spectrum, together with that of the gamma-rays, enables a complete provisional scheme to be constructed for the radioactive decay of Pr^{142}. In the case of F^{19}, the proton capture radiation has been detected, and its energy and intensity measured, thereby confirming the work of Devons and Hereward (1948), which was carried out using Baldwin and Koch's (1945) ap-:plication of the nuclear photo-effect. In addition, the energy/

energy measurement suggests that the transition following proton capture is not to the ground state of Ne^{20}.

III.1. Praseodymium-142.

(a) Previous Work.

This isotope, which is a beta-ray emitter, has been examined by a number of authors who have published rather contradictory results concerning the nature of its radiations. De Wire, Pool and Kurbatov in 1942 examined the beta-ray spectrum in a semi-circular spectrometer of 16 cm radius, and found it to be simple and to have an end-point at 2.14 ± 0.02 M.E.V. They also reported the presence of a very weak hard gamma-ray, whose energy they estimated as 1.9 M.E.V. by absor-:ption in lead. Cook, Shreffler and Fowler in 1948 examined the soft end of the beta-ray spectrum with a permanent-magnet spectrometer, using a photographic plate and very long exposures, and were able to detect internal conversion lines due to gamma-rays of energies 134, 329, 490 and 624 K.E.V. They also reported the presence of a hard ray, whose energy they estimated as 2.1 M.E.V., also by lead absorption. Mande-:ville, in 1949, using the absorption technique, examined the beta-ray spectrum in coincidence with the gamma-rays and found that it was complex, having a soft component with an end-point at 0.212 M.E.V., the main beta-ray spectrum ending at 2.22 M.E.V./

M.E.V. He also gave the hard gamma-ray energy as 1.74 M.E.V., as measured by coincidence absorption, and reported the presence of some soft gamma-radiation, and some gamma-gamma coincidences. Jurney, in 1949, repeated Mandeville's experiments but gave end-points of 0.35 and 2.52 M.E.V. for the beta-ray spectra, and an energy of 1.53 M.E.V. for the hard gamma-ray, this having been obtained by coincidence absorption of Compton recoil electrons. Jurney also made a quantitative study of the gamma-gamma coin-:cidences produced by the source, and came to the conclusion that their numbers were a factor of ten too low to be due to a simple cascade process, of a soft and a hard gamma-ray being emitted after each soft beta-ray.

(b) The Beta-Ray Spectrum.

It will be clear that in late 1949, the information obtainable from the literature concerning the radiations of Pr^{142} was, to say the least, confusing, and none of the authors quoted had attempted to assign a level scheme to the decay process. It was therefore decided, since samples of Pr^{142} which had been irradiated in the Low Energy Pile at Harwell were avail-:able, that it would be worth while to re-examine its radiations and attempt to divise a level scheme. A very thin source of the Material (Pr_2O_3) was therefore made, by smearing a little of the fine black powder on a piece of paper, and mounting this on the aluminium foil source mount in the semi-circular spectrometer. The spectrometer was set for a resolving power of 50 and a first record of the beta-ray spectrum, made with a counter window of copper/

copper foil of mass 10 mg/cm^2, indicated a simple spectrum of the type found by De Wire et al.; later runs, however, taken with progressively thinner windows, showed a marked rise at lower energies, which was heightened when a single counter was used as detector thus cutting losses due to scattering in the window. When every care had been taken, a window of mica, of mass 1 mg/cm^2 being used with a single counter, the spectrum

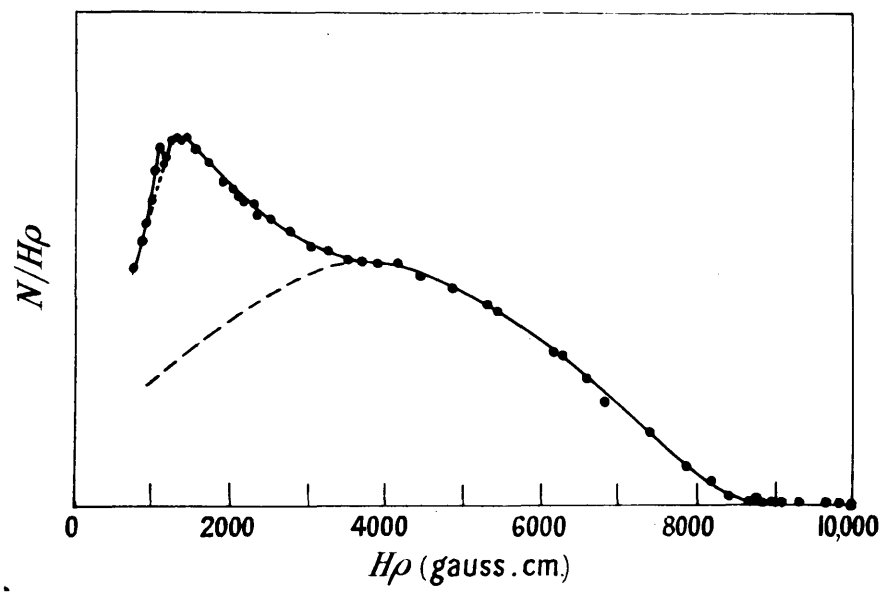


Figure 16. The Beta-Ray Spectrum of Pr^{142}.

shown in Figure 16 was obtained. It will be observed that the soft and hard components of the beta-ray spectrum appear to have end-points in the region of 0.7 and 2.2 M.E.V. respectively. It will also be observed that there is a very weak peak visible to the left of the maximum of the soft component. This can be assigned/

assigned to the internal conversion of a gamma-ray of energy 135 ±5 K.E.V. A Fermi-Plot of the beta-ray spectrum was constructed and is shown in Figure 17. This confirmed the rough estimate of the end points of the beta-ray spectra, giving them as 0.66 ± 0.02, and 2.23 ± 0.04 M.E.V. One more piece of information can be obtained from the beta-ray spectrum, and that is an estimate of the relative numbers of the soft and hard electrons. Since the source and the counter window are both thin, and since also the Fermi-Plot gives two straight lines, it seems reasonable to assume that Figure 16 is a good representation

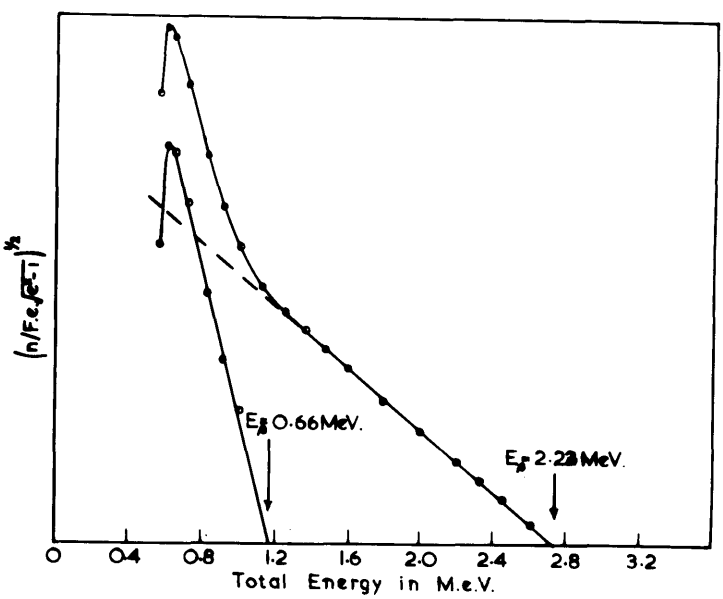


Figure 17. Fermi-Plot of the Beta-Ray Spectrum.

of the true shape of the beta-ray spectrum, and hence, if the spectrum of the hard beta-rays, as predicted by Fermi, is produced/

produced back, the difference between this curve and the total, gives a measure of the number of soft particles present. Such an analysis indicates that the hard beta-rays outnumber the soft by a factor of about four to one.

(c) The Gamma-Ray Spectrum.

The beta-ray spectrum of the source having been obtained

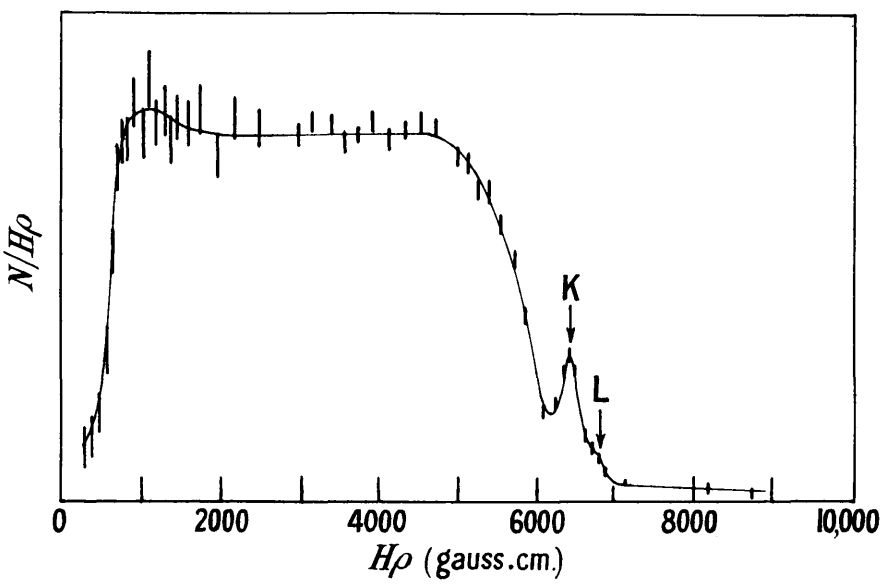


Figure 18. Momentum Spectrum of Electrons ejected by the Gamma-Rays of Pr^{142} from a thick-walled copper cylinder covered with a thin lead foil.

the gamma-ray spectrum was examined using the Siegbahn Technique. As much as possible of the source material was placed inside a hollow, thick-walled copper cylinder which was covered with a thin/

thin (0.0015") lead foil, and placed at the focus of the spectrometer. The spectrogram of the secondary electrons ejected from the copper and lead, is shown in Figure 18, and it will be seen that most of these particles are derived from a hard gamma-ray line of energy 1.59 ± 0.04 M.E.V., the K-conversion peak of this line in the lead foil being plainly visible. There is also the suggestion of the presence of a very weak soft radiation of energy about 140 K.E.V., which is doubtless identical with that causing the internal conversion peak in the beta-ray spectrum.

(d) The Decay Scheme.

An examination of these results leads to a self-consistent scheme for the beta-decay of Pr^{142}, for the sum of the energies of the soft beta-ray spectrum and the hard gamma-ray line is equal to 2.25 ± 0.06 M.E.V. which is identical with the maximum energy of the hard beta-ray spectrum. Furthermore these values are not in real contradiction with those obtained by the earlier authors, for none of them had measured the gamma-ray energy with a comparable accuracy, and the end-point obtained for the hard beta-ray spectrum is in good agreement with that obtained by Pool et al., who made the most accurate determination. As regards the soft beta-ray spectrum, Pool did not observe this because of the thickness of his counter windows, and Mandeville and Jurney were using a method which, though very powerful in demonstrating the existence of a complex spectrum, is quite unsuited/

unsuited to determining end-points. This fact is clear if we look at the experimental points from which Jurney derived his end-point of 0.35 M.E.V., as shown in Figure 19. It will be observed that a curve could easily be drawn through these points which would give an end-point considerably in excess of the present author's value of 0.66 M.E.V. This difficulty in

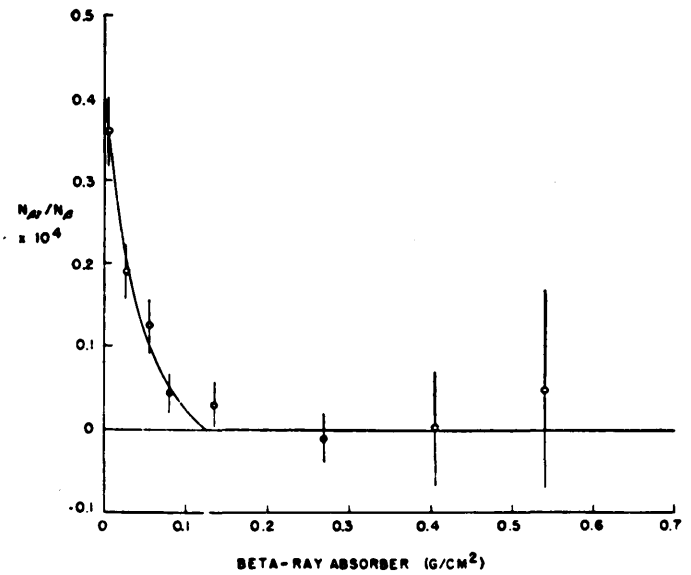


Figure 19. Beta-gamma coincidence absorption curve for Pr^{142} (Jurney).

determining the end-points of complex beta-ray spectra by the method of beta-gamma coincidences will only be overcome when a spectrometer method is used in place of the absorption method to determine the spectra. This however requires the development of a spectrometer of very large solid angle, and a scheme to provide/

provide such an instrument is put forward in Appendix I of this thesis. To return, however, to the question of the end-point of the soft component of the beta-ray spectrum of Pr^{142}, it is clear that the value of 0.66 M.E.V. is not really in contra-:diction with the observations of Mandeville and Jurney, and probably represents a good estimate of the true value.

The question of the soft gamma-rays is also capable of a satisfactory solution, because the one line observed by the present author agrees well in energy with the softest of those observed by Cook et al. Furthermore the energies of the four lines observed by those authors add up to the value of 1.58 M.E.V. which is in excellent agreement with the energy of the hard line. Hence it is reasonable to suppose that these soft radiations are due to an alternative cascade transition to the ground state of Nd^{142}, from the state at 1.59 M.E.V. The fact that the conversion peaks of the harder lines were invisible in this instance, is easily explicable in terms of their reduced conversion coefficients because of their higher energies. An estimate of the maximum possible intensity of the 135 K.E.V. line can be made from a comparison of the area under the internal conversion peak with that under the complete beta-ray spectrum. Such a comparison leads to the conclusion that even if the 135 K.E.V. line is of electric dipole origin, (which gives the smallest internal conversion coefficient), its intensity cannot exceed 20% of that of the hard gamma-ray. The

presence/

presence of these four soft gamma-rays in cascade would account for the small number of gamma-gamma coincidences reported by Mandeville and Jurney, and so it would seem that a decay scheme of the type shown in Figure 20 is in good agreement with all the information available about the radiations of Pr^{142}. The transitions actually observed are indicated by full lines, and dotted lines have also been added to show the possible subsidiary beta-ray transitions to the lower levels of the Nd^{142} nucleus.

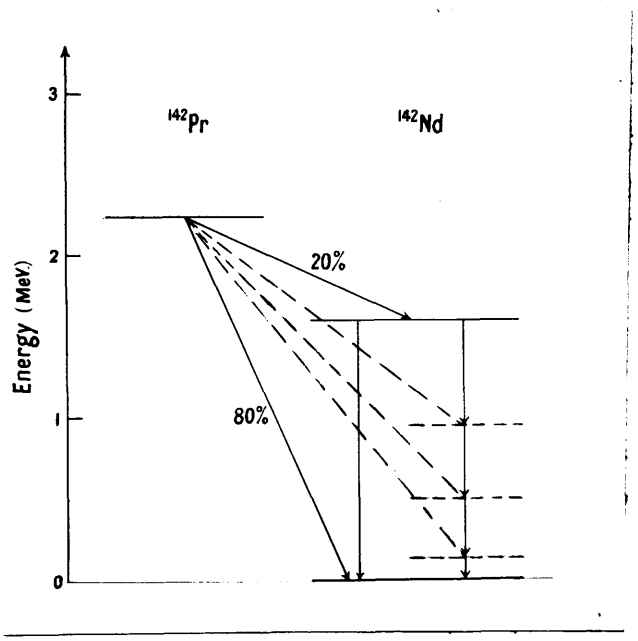


Figure 20. Energy Level Diagram for the beta-decay of Pr^{142}.

The above account serves as a good example of the way in which a few accurate measurements with a magnetic spectrometer can enable one to sift out the available information and construct/

construct an energy level scheme for the reaction, which fits all the information which is likely to be reliable. Since Pr^{142} was only one radioactive isotope chosen more or less at random, it is clear that there is a great deal of work to be done in this way, in constructing level schemes for the many artificial radioactive isotopes now available. Since, however, as discussed earlier, more information of a fundamental kind is likely to be obtained from the setting up of accurate energy-level diagrams for the light elements, the remainder of this chapter is devoted to an examination of the gamma-ray spectrum of F^{19}. A short account of the above work on Pr^{142} has recently been accepted for publication (Rae, 1950a).

III.2. Fluorine-19.

(a) Previous Work.

When fluorine, F^{19} being the only stable isotope, is bombarded with protons, it is well known (Hornyak and Lauritsen, 1948) that it can capture a proton and form an intermediate nucleus of excited Ne^{20}. This normally de-excites by the emission of an alpha-particle, giving a nucleus of O^{16} which may be excited. The latter reaches its ground state either by the emission of a gamma-ray, or, in the case of certain values of the energy of the bombarding protons, by the emission of a positron-electron pair. This reaction has been subjected to the most careful study, both by measurements on the energy of the/

the gamma-rays, and also by accurate measurements of the energy of the groups of alpha-particles emitted, but up till very recently it was not known whether the Ne^{20} could de-excite itself by direct gamma-ray emission, and go to its own ground state, Ne^{20} being a stable nucleus. Indeed, McDaniel and Walker (1948), who made the best recent study of the gamma-ray spectrum of the reaction with their pair spectrometer, looked specifically for the 13.4 M.E.V. radiation which would be expected from such a gamma-ray transition to the ground state, and stated that if such radiation exists, it represents less than 0.3% of the intensity of the 6 M.E.V. radiation, with a proton bombarding energy of 1.15 M.E.V.

Devons and Hereward (1948), however, used the photo-nuclear effect on Cu^{63} to show that for high enough energies of the bombarding protons, some gamma-radiation of energy greater than 11 M.E.V. was emitted by the fluorine. By measuring the strength of the activity induced in the copper, they were able to draw an excitation curve for the emission of the capture gamma-rays, for a thick target. This they showed to have a steep rise which corresponded with the well known resonance for the emission of gamma-rays, at a proton bombarding energy of 660 K.E.V. Beyond the resonance, the activity in the copper continued to increase slowly with increasing proton energy, thus suggesting a small probability of proton capture at energies above the resonance, or else a dirty target.

(b) The Gamma-Ray Spectrum/

(b) The Gamma-Ray Spectrum.

In view of these rather contradictory results, an attempt was made to find and identify the proton capture radiation, with the aid of the pair spectrometer. A thin target of calcium fluoride was prepared by evaporation on to a brass plate. An excitation curve was taken at the gamma-ray resonance for a proton energy of 340 K.E.V., and the width at half maximum of the curve obtained, was about 50 K.E.V. With the proton energy set to give the maximum output of gamma-rays, a

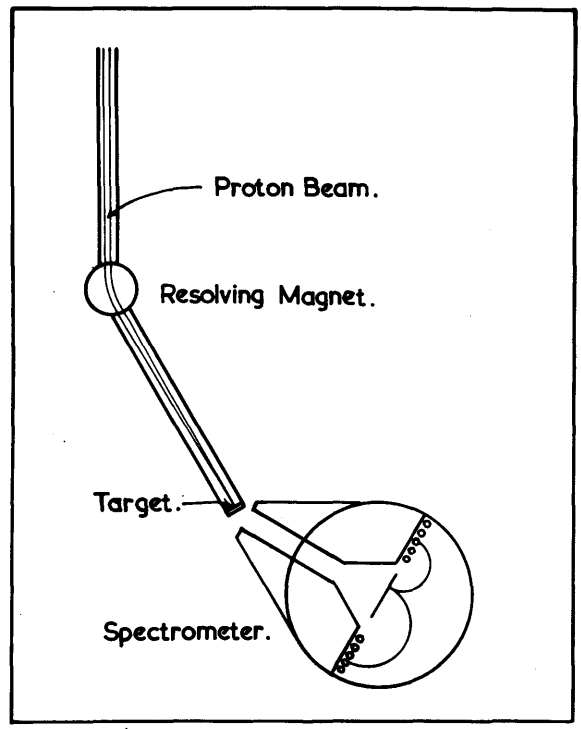


Figure 21. Experimental Arrangement.

spectrum was taken of the radiation from the target. A diagram of the experimental arrangement is shown in Figure 21, and the gamma-ray/

gamma-ray spectrum obtained is given in Figure 22. It will be observed that there is a large peak due to the 6 M.E.V.

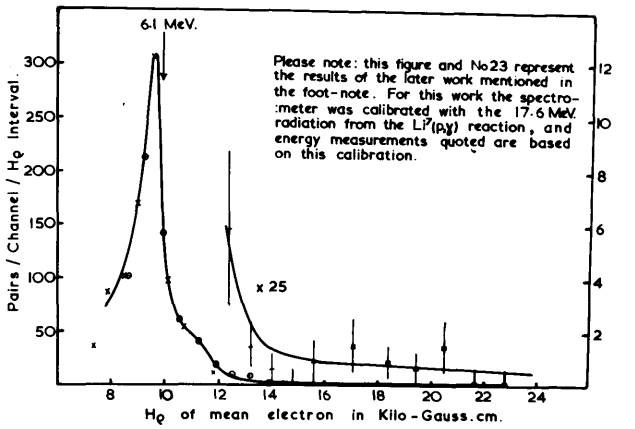


Figure 22. Spectrum of the Gamma-Radiation from F^{19} + p; 340 K.E.V. Resonance.

radiation with a small shoulder due to the 7 M.E.V. rays, but above this energy no significant number of counts is recorded

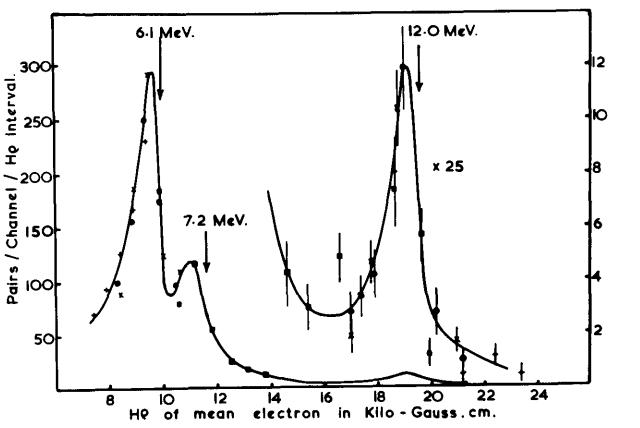


Figure 23. Spectrum of the Gamma-Radiation from F^{19} + p; 660 K.E.V. Resonance.

The proton bombarding energy was then increased to 660/

660 K.E.V. and the experiment repeated, the spectrum obtained being shown in Figure 23. It will be seen that in this case the 7 M.E.V. shoulder has increased considerably in size, and that now a small peak is visible due to some radiation of energy 12 M.E.V. This is very interesting in view of the fact that the capture radiation was expected to have an energy of 13.4 M.E.V., and suggests that the Ne^{20} nucleus does not become de-excited through a transition to the ground state,

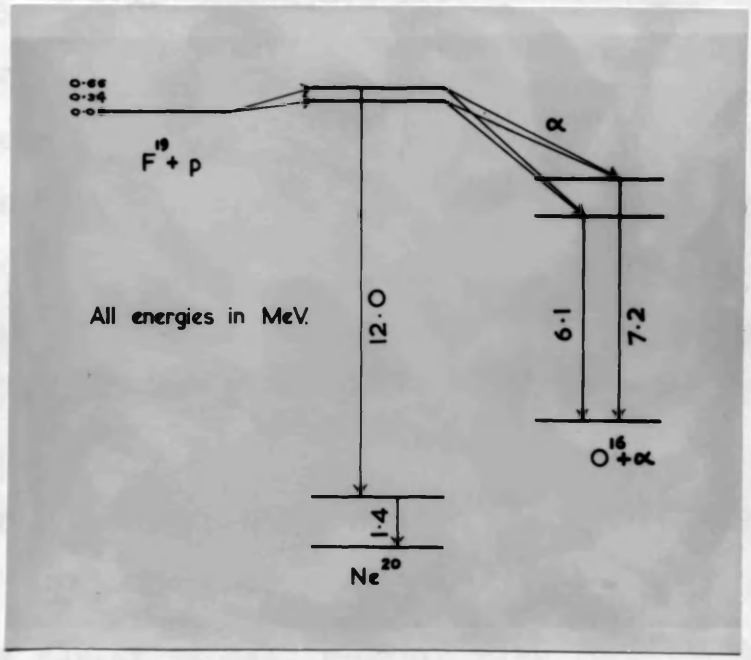


Figure 24. Energy Level Diagram of F^{19} + p.

but through a transition to a state of energy about 1.4 M.E.V. above the ground state, as shown in Figure 24. Such a state has already been detected (Curran and Strothers, 1940; Powell, May, Chadwick and Pickavance, 1940) as a result of other experiments/

experiments, and this postulate seems reasonable.

(c) Discussion.

It was intended to study this transition further and to verify the energy measurements with great care, but this has proved impossible owing to technical trouble with the high tension generator which has rendered its operation at potentials in excess of 500 K.E.V. very hazardous, and until certain modifications have been carried out it will not be possible to repeat any of this work. For this reason, the above results are put forward with some reserve,* though even if the energy measurements have not been confirmed, it can certainly be stated that proton capture radiation was found, having an intensity of the order of 2% of that of the 6 M.E.V. radiation,† a figure which is in good agreement with the value determined by Devons and Hereward, of 2.2 ± 0.8%. It should also be noted that this value is not in contradiction with the findings of Walker and McDaniel, since their value of less than 0.3% of the intensity of the 6 M.E.V. radiation was determined for a proton bombarding energy of 1.15 M.E.V. With this bombarding energy and a thick target, the intensity of the 6 M.E.V. radiation would/

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* The experiment described has recently been repeated with great care and the energy of the capture radiation determined as 12.0 ± 0.2 M.E.V., thus completely verifying the early measurement.

† See pp 58(a) to 58(d)

would be greater by a factor of 15 than it would be for a bombarding energy of 660 K.E.V. (Bonner and Evans, 1948), while the intensity of the capture radiation is known to increase very little when the bombarding energy is increased from 700 to 960 K.E.V. (Devons and Hereward). For bombarding energies between 0.96 and 1.15 M.E.V. there are only two weak gamma-ray resonances which could contribute only about 1% to the total output of gamma-rays (Bonner and Evans, 1948), and so it is clear that unless these two resonances were to produce nothing but the capture radiation, it is unlikely that the intensity of the capture radiation, for a bombarding energy of 1.15 M.E.V., would exceed the figure of 0.3% given by Walker and McDaniel.

In considering the advantages of the pair spectrometer over other methods of measuring the energy and intensity of very hard gamma-rays, it is interesting to note that in each of the spectra shown, the total counting time was less than an hour, and yet it was possible to detect and measure the energy and intensity of the very weak proton capture radiation, whose intensity was only 2% of that of the main gamma-ray spectrum. A considerable programme of work is in hand for this instrument, including investigations of the gamma-rays emitted by Li^7 and C^{13} under proton bombardment. After the completion of this work it will probably be used for the study of the gamma-rays emitted by most of the light elements under bombardment by deuterons.

PART IV. - DETERMINATION OF ENERGY AND MULTIPOLE ORDER.

THE COMPLETE SOLUTION

IV.1. Theoretical Background.

(a) General.

According to modern Quantum Theory, the spectroscopic properties of the stationary states of a nucleus can be defined in terms of three coordinates: energy above the ground state, total angular momentum (or spin), and parity. This latter quantity depends on the symmetry properties of the wave-function of the nucleus: it is two-valued, and may be either odd or even. In the last chapter, experiments were described which led to the determination of the energies of some nuclear levels (or stationary states), and to the construction of diagrams illustrating these levels and the transitions that occur between them. For a complete specification of the states described, however, it would be necessary to ascribe a spin and parity value to each level, which would then determine the "Multipole Order" of the transitions occurring. While such a complete specification of the energy levels of a nucleus has not yet been obtained, it is clear that this knowledge is desirable as a basis on which to build a general theory of nuclear structure. The need for such information is stressed in the present uncertainty concerning the selection rules for beta-decay (Fermi and Gamow-Teller selection rules) where a thorough knowledge of the nuclear levels/

levels involved in a few actual cases of beta-decay might enable a decision to be made as to the relative merits of the two sets of rules.

Now information concerning the spin and parity of nuclear levels can be obtained from transmutation experiments by measurements made on the widths of resonance curves, and on the angular distribution of the emitted particles and radiation. Information obtained in this way has, however, been very limited, and the interpretation of the experimental results very difficult (Fowler, Lauritsen, and Lauritsen, 1948; Devons and Hine, 1948) Hence it follows that the methods of determining spin and parity, based on the determination of the multipole order of radiative transitions, are very important. By this is meant determination of the multipole order of the transitions, through observations made on the internal conversion electrons and internally created pairs emitted by the radiating nuclei. Since a considerable body of experimental results has been built up by the use of this method in the study of gamma-radiation excited by radio-active decay, and since it is in this type of investigation that a magnetic spectrometer can be used to obtain information about the spin and parity of nuclear levels, let us consider briefly the use of the internal conversion and internal pair creation effects in the determination of multipole order.

(b) Internal Conversion.

Before discussing the internal conversion mechanism, let us/

us consider for a moment the exact connection between multipole order, and the spin and parity of the two states involved. Suppose we have a transition between two states of angular momentum J and J', where these quantities are both vectors, then the angular momentum carried away by the radiation will tend to be the lowest value of J - J' allowed by the parities of the two states involved. If we write $j = |J| - |J'|$, then the lowest allowed multipoles, for a given parity change, are given in the following table which is taken from Gamow and Critchfield (1949) p.190.

PARITY CHANGE	MINIMUM ALLOWED MULTIPOLE	
	for j even	for j odd
Yes	Electric 2^{j+1}-pole Magnetic 2^{j}-pole	Electric 2^{j}-pole Magnetic 2^{j+1}-pole
No	Electric 2^{j}-pole Magnetic 2^{j+1}-pole	Electric 2^{j+1}-pole Magnetic 2^{j}-pole

If, in the above table, we write m for the index of the power of 2, then for radiation to occur, m must have at least the value 1, which corresponds to the emission of dipole radiation.

To return, however, to the problem of internal conversion, this is said to happen when the energy of the transition, instead of appearing as radiation, is concentrated on one of the extra-nuclear electrons of the atom, which is then emitted from/

from the atom with an energy equal to $h\nu - E_K$, $h\nu - E_{LI}$ etc. where $h\nu$ is the energy of the transition, and E is the binding energy of the atomic electron, the suffix indicating the atomic shell involved. The Internal Conversion Coefficient (I.C.C.) for the K-shell, α_K, is then defined as being the ratio of the probability of the emission of a K-electron to the total probability of occurrence of the transition concerned. The total I.C.C., α, is thus defined as the sum of $\alpha_K, \alpha_{LI}, \alpha_{LII}$, and so on.

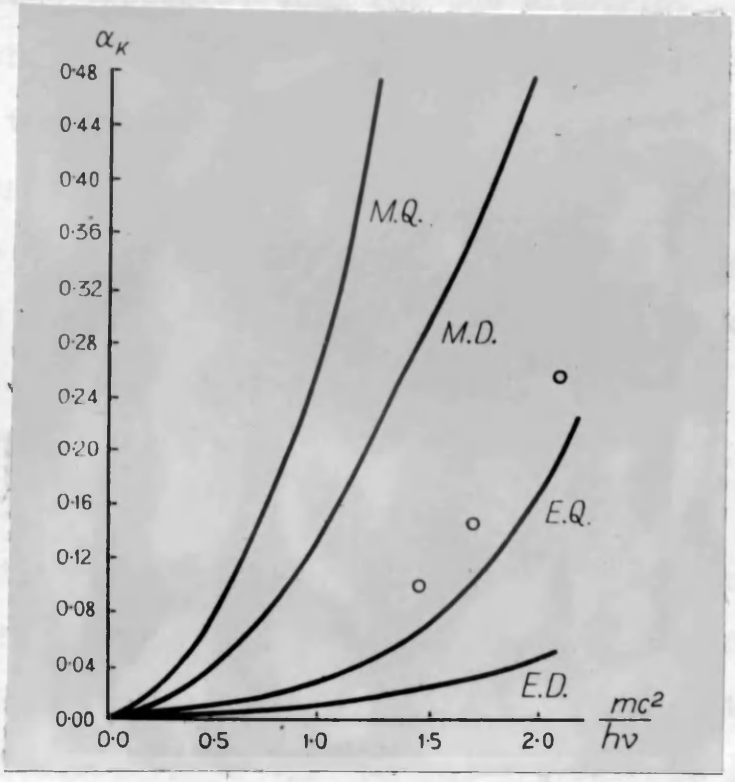

Figure 25. Theoretical Values of α_K.

Figure 25, which is taken from Gamow and Critchfield (1949) p.182, illustrates the theoretical values of α_K plotted against $mc^2/h\nu$, where $h\nu$, as before, is the energy of the transition, and/

and mc^2 is the rest energy of an electron. It will be observed that four curves are given, corresponding to the cases of electric and magnetic dipole and quadrupole radiation, converted in the K-shell of an atom of number Z = 83. The calculations illustrated in the diagram were carried out by Hulme (1932), Taylor and Mott (1932) and Fisk and Taylor (1934). It will be observed that the coefficients increase with diminishing transition energy, and with the multipole order of the transition, being higher for the magnetic transitions (which are less probable) than for the electric. A further feature of the coefficients, which is not illustrates in the diagram, is that they diminish rapidly with diminishing Z. This fact is brought out in the explicit expressions for the coefficients in the lighter elements ($Z<30$) obtained by Dancoff and Morrison (1939), where the coefficients are shown to be proportional to Z^3.

The various methods of determining the I.C.C. experimen-:tally are discussed in the comprehensive paper by Helmholz (1941). Ellis and Aston (1930) originally determined the coefficient for a number of gamma-rays from RaB and RaC by comparing, in a magnetic spectrometer, the intensity of internal conversion electrons with that of photo-electrons ejected by the corresponding quanta. This method suffers from the disadvantage that it involves the knowledge of the photo-electric cross section of the converting material, and also the scattering occurring in the convertor, and cannot be expected

to/

to yield accurate results. Another method (used by Helmholz) is to measure the ratio of α_K to α_L, by observing the ratio of the intensities of the internal conversion electrons. This method overcomes the difficulty of using a convertor, but suffers from the limitation that the L-conversion coefficient is likely to be small, and so the background intensity is troublesome. The best method, used by Flammersfeld (1939) is to measure the I.C.C. directly, by measuring the ratio of the number of conversion electrons to the number of disintegration electrons in a spectrometer equipped with a G.M. counter. The difficulty here is that this method is only applicable to beta-ray or positron emitters, and can only be applied successfully where the decay is simple, or well known. It is clear from the above discussion, that considerable attention has been directed towards the determination of the multipole order of transitions by the study of the I.C.C., and the multipole order of a number of transitions in elements in the upper half of the periodic table has been found in this way. Unfortunately the method cannot be applied to transitions in the light elements, since the Z^3 variation of the coefficients makes them all vanishingly small in this case, especially since, in the light nuclei, the transitions observed are usually very energetic. It is in this instance that the study of the internal pair creation effect becomes very interesting.

(c) Internal Pair Creation./

(c) Internal Pair Creation.

The first exact calculation of the theoretical magnitude of this effect and its variation with energy and atomic number, was carried out as long ago as 1935, by Jaeger and Hulme. These authors published curves[5] showing the values of the Internal Pair Creation Coefficient (I.P.C.C.) for Z=0 and Z=84, and for electric dipole and quadrupole transitions, in the energy range 1 to 3 M.E.V. The curves are shown in Figure 26, and it will be observed that unlike those for the I.C.C., they

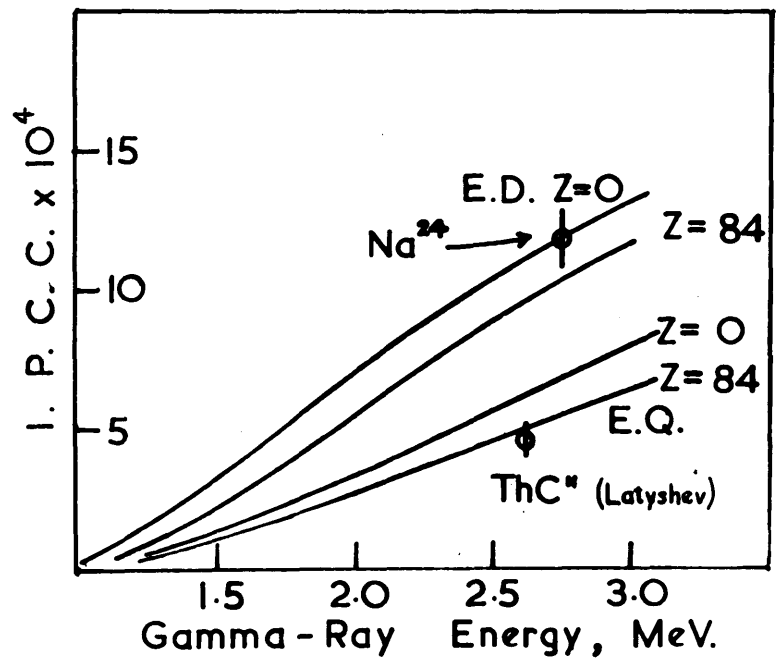

Figure 26. Theoretical Values of the I.P.C.C.

show a rise with increasing gamma-ray energy, and also exhibit very little dependence on the atomic number. At the time when these theoretical predictions were made, Alichanov, Alichanian and/

and Kosodaev were interested in this effect, and in 1936 they published the results of their study of the internal pair creation in ThB and Radon in equilibrium with their decay products. They carried out this study by observing the positrons emitted by each of the two sources mentioned, in a semi-circular focussing spectrometer of 10 cm radius, and they found the shape of the spectrum of the positrons to agree well with that predicted by Jaeger and Hulme. The main difficulty in the experiment was the detection of the small numbers of positrons against the strong background caused in the counter by the gamma-rays from the source. The authors overcame this difficulty by the use of two counters in coincidence, and were thus able to reduce the background to a workable level. Using sources having a strength of the order of 1 mC, the authors observed the positron spectrum of the source; they then reversed the polarity of the electro-magnet, cut down the solid angle of the spectrometer by a known factor, and observed the beta-ray spectrum. In this way they were able to determine the number of positrons emitted, and therefore the number of pairs created, per beta-ray emitted by the source. This quantity they found to have a value of approximately 2×10^{-4} for both the ThB and Radon sources. This work was repeated in 1946 by Bradt, Halter, Heine and Scherrer, and was carried to a very high degree of precision in later Russian work reviewed by Latyshev (1947). In his review paper, Latyshev exhibits curves showing the positron spectra of the two sources mentioned/

mentioned above, which show not only the main spectrum due to the strong energetic gamma-ray in each case, but also subsidiary steps in the spectral distributions, corresponding to the internal pair conversion of other minor gamma-rays. By measuring the areas under both the main and component curves, the authors were able to determine the relative values of the I.P.C.C. for those gamma-rays whose relative intensities were known from other experiments. (On the Compton electrons produced by those gamma-rays.) On the assumption that one particular gamma-ray line from each source was of electric dipole or quadrupole origin, as the case may be, the authors were able to show that the points corresponding to the other minor lines all lay close to one or other of the curves of Jaeger and Hulme. Latyshev also quoted an experiment in which the absolute magnitude of the I.P.C.C. was measured for the 2.62 M.E.V. line of ThC", and once again the value obtained agreed well with that given by Jaeger and Hulme for an electric quadrupole transition.

It is clear then, that the above work, mainly carried out by the Russians, established that the curves of Jaeger and Hulme gave the correct values for the I.P.C.C. for electric dipole and quadrupole transitions in a heavy element. More recent work has been confined to the investigation of the 100% pair producing transition in O^{16} (Hornyak and Lauritsen, 1948)* and the internal pair/

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* This is a very special case where the emission of gamma-radiation is completely forbidden, and need not concern us here.

pair creation due to the 3.1 M.E.V. gamma-rays from the reaction $C^{12}(d,p)C^{13}$. (Dougherty, Hornyak, Lauritsen and Rasmussen, 1948). These latter authors measured the I.P.C.C. very roughly for the transition investigated, and found it to be of the order of 10^{-3} pairs per quantum, thus showing that the prediction of Jaeger and Hulme, that the I.P.C.C. is nearly independent of Z, is certainly true qualitatively. It is this somewhat surprising result (surprising because the external pair-creation effect is proportional to Z^2) which makes the I.P.C.C. so important in the determination of the multipole order of transitions in the light nuclei. The importance of the process is enhanced still further by the fact that it increases with the energy of the transition, so that it provides a method which is complementary to that of observing internal conversion, since the new effect is strong in the very cases where the other is weak.

In view of the above argument, it seems surprising that the possibility of the use of the internal pair-creation effect to determine multipole order was completely overlooked until 1949 when it was pointed out independently by Devons (1949, p.100), and the present author (Rae, 1949) who used the effect to determine the multipole order of the 2.76 M.E.V. gamma-ray from the radioactive decay of Sodium-24. In 1949 also, the theory of the effect was subjected to further investigation by Rose, who published a comprehensive set of curves, giving the I.P.C.C. for both electric and magnetic transitions up to 2^5-pole, for a light element.

The/

The remaining sections of this chapter will describe the author's experiments on Sodium-24, and possible extensions of the technique employed, to determine the multipole order of transitions not following beta-decay, or where the lifetime of this decay is very short.

IV.2. Sodium-24.

(a) Experiment.

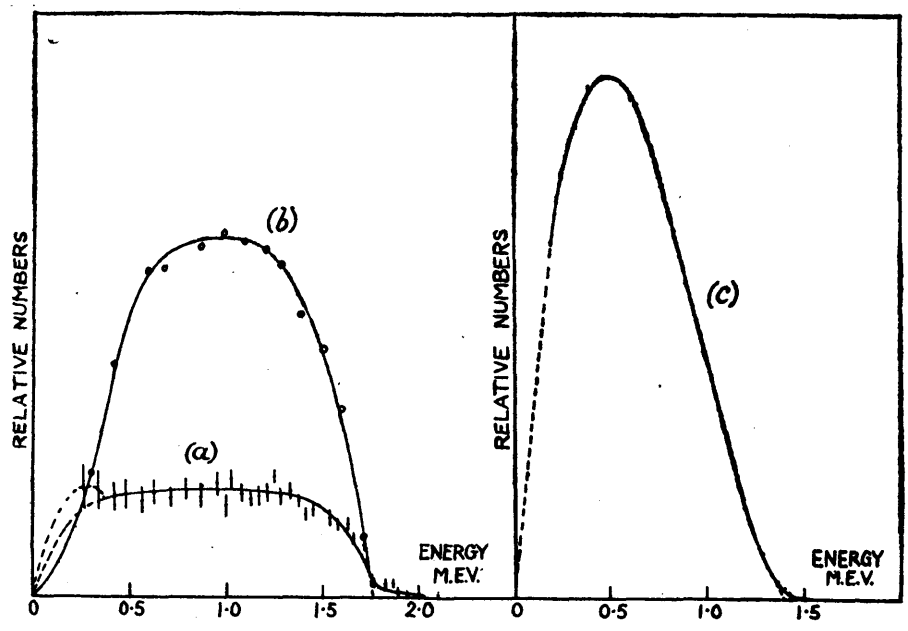
Sodium-24 was chosen as the subject of this experiment because it is the only light element whose radioactive decay combines the desirable qualities of a reasonably long half-life (15 hours) with the emission of an energetic gamma-ray (2.76 M.E.V.). It was particularly suitable for the experiment, in that, in addition to the above two properties, it was also known to suffer a simple beta-decay followed by the emission of two gamma-rays in cascade, of energies 1.38 and 2.76 M.E.V. (Wiedenbeck, 1947, and see also references quoted.) This meant that a measurement of the total number of positrons created by the gamma-ray concerned, in a given time, combined with a similar measurement of the number of decay electrons emitted, would provide a direct determination of the I.P.C.C. of the line. The main source of error in such a determination would be likely to arise because of the possible change in the overall efficiency of the spectrometer used, with energy. Here again the choice of Na^{24} was a particularly happy one, in that the maximum energy of the positrons produced is 1.8 M.E.V. which

is quite close to the maximum energy of the disintegration electrons (1.4 M.E.V.). Thus the error arising in this way is certainly trivial, since only a negligible part of each spect-:rum lies in the low energy region where losses in efficiency become appreciable.

The Na^{24}, which was obtained from A.E.R.E., was in the form of sodium carbonate, and 100 mg of the active material was dissolved in a few drops of water and then evaporated to dryness on a small tray of thin aluminium foil (0.002" thick) measuring 3.5 cm by 8 mm. The source thus formed was of suitable dimensions for use in the semi-circular spectrometer, and had an initial activity of the order of 10 mC. The spectrometer was used with a resolving power of 50, and with double counters to keep the background low. The technique used was to record the positron spectrum while the source was as active as possible, and then to compare the area under this curve with the area under the curve obtained by recording the beta-ray spectrum, the latter being determined after the source had been allowed to age for a few days, in order to bring the beta-ray intensity down to a workable level. The curves obtained are shown in Figure 27, and the value of the I.P.C.C. determined from this data is $(1.16 \pm 0.10) \times 10^{-3}$. The theoretical values of the coefficient, as calculated by Jaeger and Hulme, are shown in Figure 26, and it will be noticed that the above value very nearly coincides with the Z=0 curve for electric dipole transitions.

A/

A further check on this measurement is available if the number of positrons from the Na^{24} source is compared with the number from a source of ThC", provided the ratio of the gamma-ray intensities is known. In order to ascertain this ratio, the shutter on the spectrometer was used to place a thick lead foil immediately in front of the source. The positron spectra



Spectra of Na^{24}.

(*a*) Positrons from bare source. (*b*) Positrons from thick lead foil.
(*c*) Electrons.

Figure 27. Spectra of Sodium-24.

of Na^{24} with and without the lead foil in place are shown in Figure 27, and a similar pair of curves was obtained for a source of ThC". By comparing the areas under the four curves and making a small correction for the difference in energy between the two gamma-rays, a value of 2.38 ± 0.30 was obtained for/

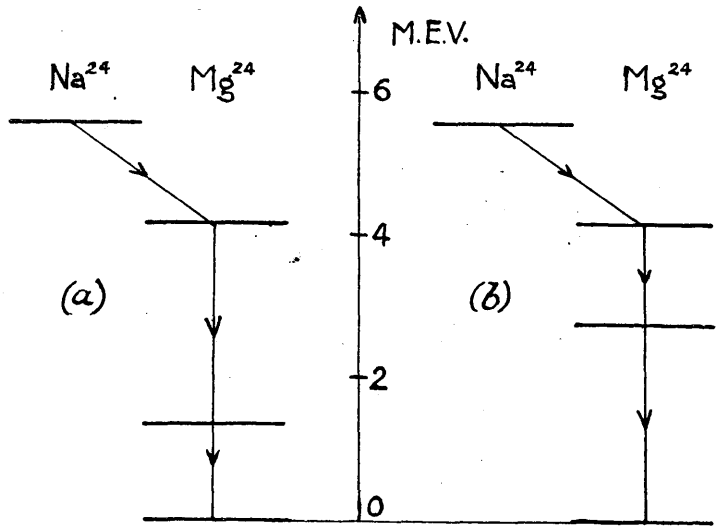
for the ratio I.P.C.C.(Na)/I.P.C.C.(ThC"). Assuming that the ThC" line is of electric quadrupole origin (Latyshev, 1947), we can obtain from Figure 26 theoretical values of this ratio for the cases of the Na line being either of electric dipole or quadrupole origin. These values are 2.32 and 1.35 respectively. Hence this extrapolation from the known case of the ThC" line also places the coefficient for the Na line on the electric dipole curve. Alternatively this measurement may be regarded as confirmation of the result quoted by Latyshev, that the I.P.C.C. of the ThC" line lies on the electric quadrupole curve, this method of measurement being simpler than that used by the Russians who had to make assumptions about the very complex decay of Th(B+C+C") in order to arrive at an absolute value for the coefficient.

(b) Discussion.

The experiment certainly shows that the theory predicts the correct order of magnitude for the I.P.C.C. of the gamma-ray investigated. Since, however, the theory is known to be in accurate agreement with experiment in the case of the heavy radioactive elements, it seems reasonable to go further and assume that it predicts the correct results for the simpler case of the light elements. If this is so, then the gamma-ray investigated is of electric dipole origin. This information enables us to establish a simple energy level scheme for the Mg^{24} nucleus, for it has been shown by Wiedenbeck (1947) that the level scheme is given by either

(a)/

(a) or (b) in Figure 28. Now Pollard and Alburger (1948), from experiments on the large angle scattering of the gamma-rays from Na^{24} by targets of Mg and Al, state that the hypothetical transitions to the ground state of the Mg^{24} nucleus from the levels at 1.38 and 2.76 M.E.V., (only one of which in fact exists) ~~if they exist~~) are certainly of quadru-:pole or higher order. If then we accept that the 2.76 M.E.V. line is of electric dipole origin, we must reject scheme (b) and assume that scheme (a) is correct.



Energy Level Diagram of Mg^{24} Nucleus.

Figure 28. Energy Level Diagram of Mg^{24} Nucleus.

We can also go further and assign tentative sets of spin and parity values to the levels in the decay scheme. If we make the simplest assumption, namely that the 1.38 M.E.V. line is of electric quadrupole or magnetic dipole origin, then since the/

the ground state has zero spin and even parity, it follows from the table quoted in IV.1.(b) that the 1.38 M.E.V. level is of even parity and has spin 1 or 2. The electric dipole nature of the 2.76 M.E.V. radiation makes the parity of the 4.14 M.E.V. level odd, and its spin 0,1, 2 or 3. To choose between the various possible sets of values, it is necessary to consider the nature of the beta-decay, which is first forbidden. (Siegbahn, 1946,b). This leads to the selection rules $|J| - |J'| = 0,1,2$ with a change in parity. The spin change zero is not permissible in this case, however, since this would always permit an allowed beta decay to the level at 1.38 M.E.V. which is not observed. (Spin change 0,1 with no change in parity). Also it is known from the observed shape of the spectrum, which is similar to that of an allowed transition, that the change in spin cannot have the value 2. (Konopinski and Uhlenbeck, 1941). Hence the spin change must have the value 1, and so it is possible to make a diagram of all the possible sets of spin values, as shown in Figure 29, and these are seen still to be eleven in number. Let us consider these sets in turn. (0,1,0,1) is untenable because it permits an allowed beta-ray transition to the state at 1.38 M.E.V., and in the same way we can rule out the sets (0,1,1,0), (0,1,1,2), (0,1,2,1), (0,2,1,2), (0,2,2,1), (0,2,2,3) and (0,2,3,2). This leaves the three sets (0,1,2,3), (0,2,1,0) and (0,2,3,4) of which the middle set is also untenable because it would permit a dipole/

dipole transition from the level at 4.14 M.E.V. to the ground state, which is not observed. Hence from the apparent maze of possible sets of spin values for the three unknown levels in the decay scheme, a knowledge of the multipole order of one of the gamma-rays and the assumption of the order of the other,

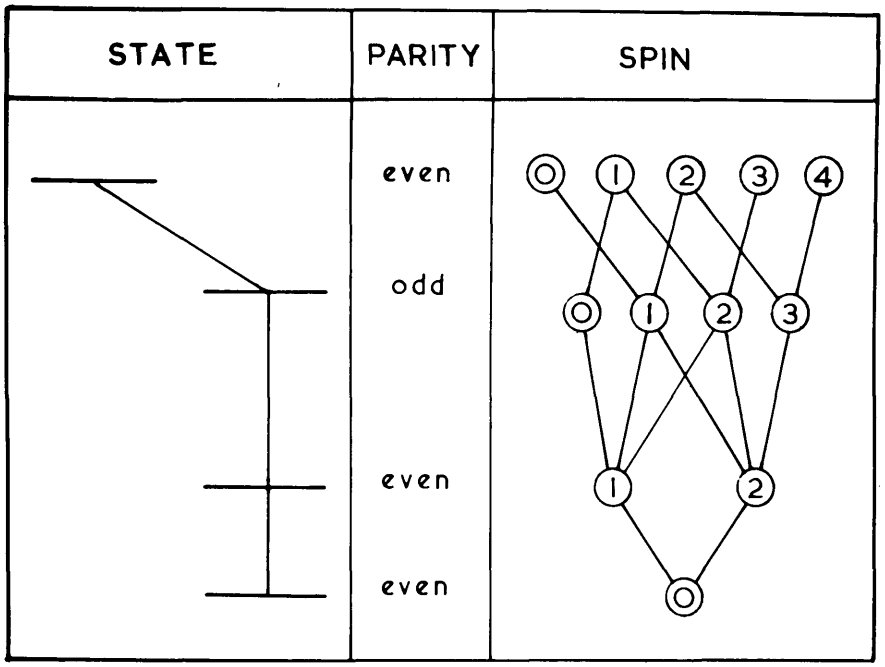


Figure 29. Possible Sets of Spin Values.

enables us to reduce the number of permissible sets to two. If the latter assumption is not made, and the 1.38 M.E.V. line is allowed to be of electric octupole or magnetic quadrupole order, then all the possible cases are considered, since higher multipoles are ruled out by considerations of the life-:time of the state. This additional possibility, however, only/

only introduces one new set of spin values, since an analysis of the above type shows that in this case the parities are (even, odd, even, odd), and the allowed sets of spin values

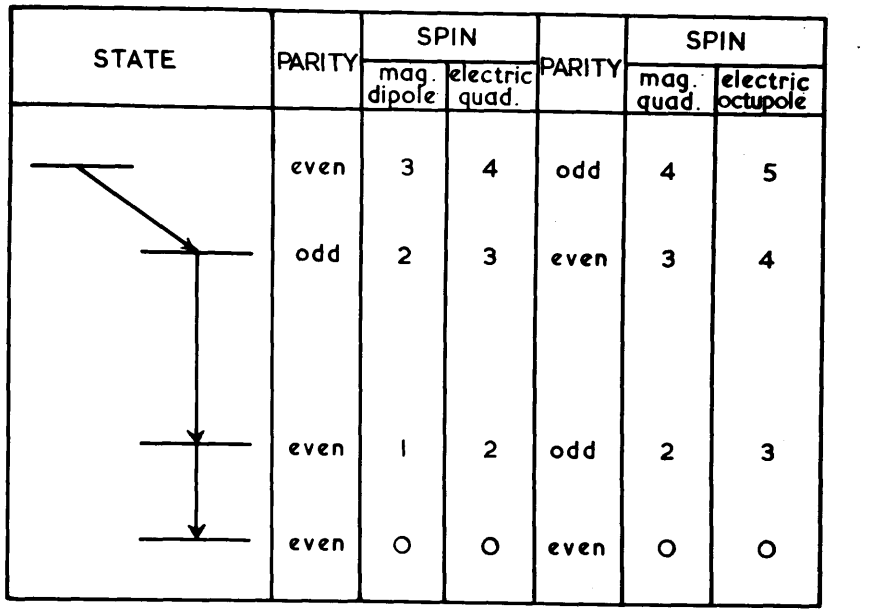


Figure 30. Allowed Sets of Spin and Parity Values.

are (0,2,3,4) and (0,3,4,5). The four possible complete specifications of the decay scheme are shown in Figure 30.

IV.3. Future Work and possible Extensions of the Technique.

It will be clear from the above discussion, that the simple measurement of the I.P.C.C. for one gamma-ray line, when combined with the results of other experiments on the same nucleus/

nucleus, can lead to the deduction of a surprisingly large amount of information concerning the stationary states of that nucleus. It is unfortunate, therefore, that the case of Na^{24} is unique in that it is beta radioactive with a reasonably long half-life, has a simple spectrum, and emits a hard gamma-ray. There are several more beta-emitters among the light elements which also emit hard gamma-rays, such as F^{20} and Al^{28}, but all have very short half-lives, and could not be investigated away from their place of origin. The method of investigation would then have to be to produce these isotopes by means of a nuclear reaction using the particle accelerator, and then to interrupt the beam periodically, and collect data on the positrons and disintegration electrons during these breaks in the bombardment.

Apart from these beta-emitters, there are also the reactions in which a heavy particle is emitted, such as $F^{19}(p,\alpha)O^{16}$, where the alpha-particles could be utilised to provide a measure of the number of transitions taking place, and this figure could then be compared with the number of positrons produced, to determine the I.P.C.C. Here the difficulty lies in the very short lifetimes of the compound nuclei, which make it necessary to count the alpha-particles against an intense background of scattered protons, but such experiments are possible and could be best performed with a spectrometer capable of focussing the alpha-particles as well as the positrons. It is clear, however, that there are many

cases/

cases of the emission of energetic gamma-rays from light nuclei, where there is no particle emission at all, such as the various proton and neutron capture radiations. For these cases the only means of counting the number of transitions occurring is to count the gamma-rays emitted by the target, using a G.M. counter, and to compare this figure with the number of positrons observed in the spectrometer. This method is by no means as unreliable as might be imagined, because the variation in the efficiency of G.M. counters of known construction with energy, has been studied at great length (Fowler, Lauritsen and Lauritsen, 1948), and could be applied with considerable confidence. The main source of difficulty would be the calculation of the overall efficiency of the spectrometer. This, however, need not be attempted, since it can be compared accurately with that of the counter by means of a calibration experiment, using a known beta-emitter such as Na^{24}. The relative efficiencies of the spectrometer and the counter could be measured at lower energies, using some other radioactive source, such as Co^{60}, and only in the extrapolation to much higher energies would the possibility of error arise. This, however, is the region where the theoretical behaviour of the counter is best known, and where also the efficiency of the spectrometer could be expected to remain constant, since the two main sources of inefficiency, window and source thickness, would be negligible; hence the extrapolation could be made with some confidence.

It/

It is proposed to investigate all these methods of determining the I.P.C.C. of high energy transitions in the light elements, and indeed the spectrometer has been prepared for these experiments and would have been used for this purpose some time ago had it not been for the recent concentration of effort on energy determinations carried out with the pair spectrometer. There is however one fundamental difficulty which will certainly limit the scope of such experiments as carried out with the present semi-circular resolver, and that is the weakness of the sources of radiation available. The source strength used in the sodium experiment was 10 mC, while even with the $F^{19}(p,\alpha)O^{16}$ reaction, which is extremely vigorous, the yield of gamma-rays that could be expected from the available proton beam would be of the order of 1 mC at the 660 K.E.V. resonance, and $\frac{1}{3}$ mC at the 340 K.E.V. resonance; for most reactions the yield would be much less. This is a serious difficulty when it is realised that even with the strong sodium source, the counting rate in the positron spectrum was only of the order of 50 counts per minute, compared with the ultimate counter background of 1.5 counts per minute. (The actual counter background was 19 counts per minute, on account of the leakage of gamma-rays through the lead shielding.)

It is clear then, that while the strong fluorine radiations can probably be analysed successfully with the present spectrometer, any attempt to study the radiations from much weaker reactions would involve the use of a spectrometer of much greater intensity factor. Since the instrument would also/

also be required to focus high energy particles, it would seem that the best type of resolver to use would be some modification of the double-focussing instrument, designed to give a large solid angle with comparatively low resolution. (It will be remembered here that the double-focussing instruments con-:structed so far, have all been designed with high resolution as their first requirement.) This problem has been discussed

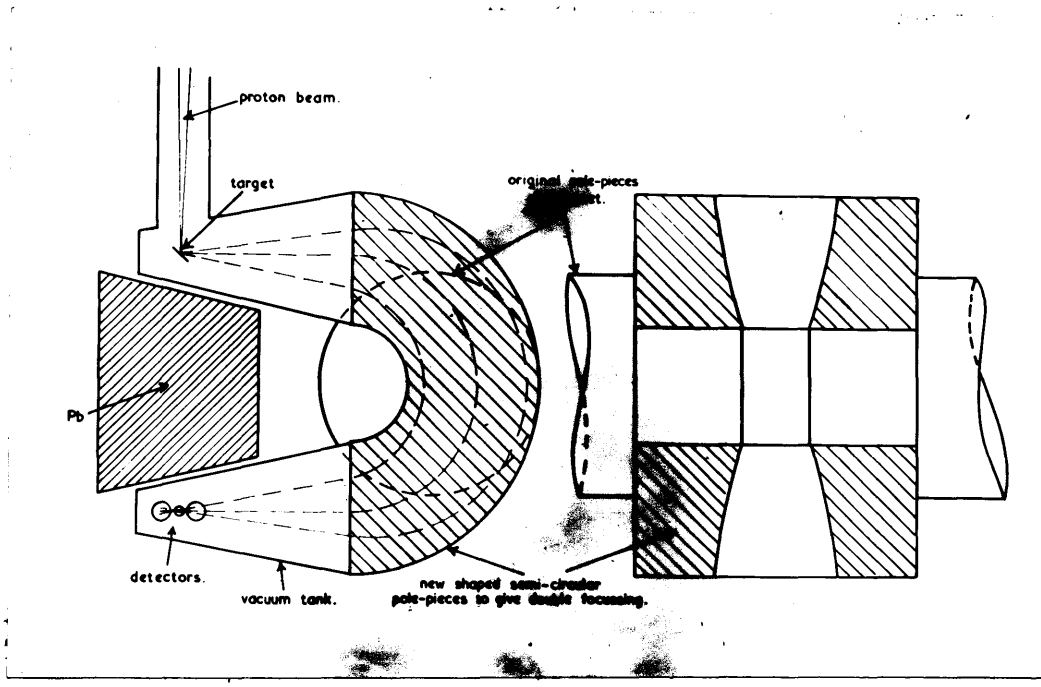


Figure 31. Semi-Circular Double-Focussing Wedge Spectrometer.

at length by the author and Mr. J.G. Rutherglen, who is also interested in the construction of such an instrument as an alpha-particle spectrometer, and the design most suited to the problem and to the electro-magnet available seems to be a semi-circular double-focussing "wedge". Such an instrument which is shown schematically in Figure 31, would have a solid angle only/

only slightly smaller than a full double focussing resolver, and would have the advantage that with the greater radius of curvature available, particles of higher momentum could be focussed. Other points in favour of the "wedge" design are that more space is available for lead shielding, and also that the source and detector are outside the magnetic field which makes the bombardment of the target much easier, and which would also permit the use of an electron multiplier as detector. It is proposed to proceed with the design and construction of such an instrument or instruments which will be used in the study of problems such as those discussed above.

To sum up this last chapter, we might say that the experiment on Na^{24} illustrates the simplicity and power of the method of determining the spins of nuclear levels through measurements made on the internal pair effect. With this method available, and possibly reinforced in the future by the construction of a spectrometer of much higher intensity factor, and with the pair spectrometer available for rapid survey measurements of whole gamma-ray spectra, it seems possible to close the chapter and indeed this thesis in full confidence that if the work described in these pages is carried forward diligently, then some real progress will have been made in the study of the stationary states of the light nuclei, and one more step will have been taken towards our final understanding of the structure of the atomic nucleus.

- - - - -

APPENDIX I.

A MAGNETIC SPECTROMETER OF LARGE SOLID ANGLE.

by

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(A paper accepted for publication by the 'Philosophical Magazine')

SUMMARY.

An account is given of a magnetic spectrometer of large solid angle and good resolution which should find applications in the study of complex beta-ray spectra by the method of beta-gamma coincidences.

The original apparatus, consisting of a segmented annular G.M. counter set round a radioactive source in a magnetic field is described, the method of use being to select from the output of the counter, large pulses which correspond to the simultaneous triggering of several sections by the passage of an electron tangentially to the annular counter. The performance of the instrument is discussed and modifications are described which rectify the defects in the earlier design and give a solid angle of 2.5% of 4π with a resolution of 5%.

The geometry of this type of spectrometer is considered and the performance which might be obtained with good design is discussed/

discussed. It is concluded that collecting angles up to the order of 50% of 4π are possible with good resolution.

1. INTRODUCTION.

An account has recently been published by Siegbahn and Slatis (1949) of an instrument for the determination of the energies of beta and gamma radiations. The device consists of an arrangement for placing the source of the radiations at the centre of an annular G.M. counter whose plane is at right angles to the direction of the magnetic field. Considerable work has been done here on an apparatus which is superficially very similar to that of the above authors, but which in fact has several ad-:vantages over it. For this reason it has been decided to place on record this short account of our method which confirms some of the results of Siegbahn and Slatis and which also leads to the design of a magnetic spectrometer of very large solid angle which should prove a valuable tool in the examination of complex beta-ray spectra by the method of beta-gamma coincidences.

2. DESCRIPTION OF ORIGINAL APPARATUS.

The device as originally designed by Dr. S.C. Curran consisted of an annular counter with the wire supported on a large number (about 40) of small insulating pillars which had the effect of splitting the main counter into a large number of small counters acting in parallel (Sever, 1942; Curran and Rae, 1947)./

1947). A sketch of the apparatus is given in Figure 1 and it will be seen that the counter had no window, the whole apparatus being filled with the counting mixture. The intention was to use the device to measure the energy of hard gamma-rays by detecting the positron-electron pairs ejected from a thin lead foil placed round the source, for in the case of equipartition of energy, and

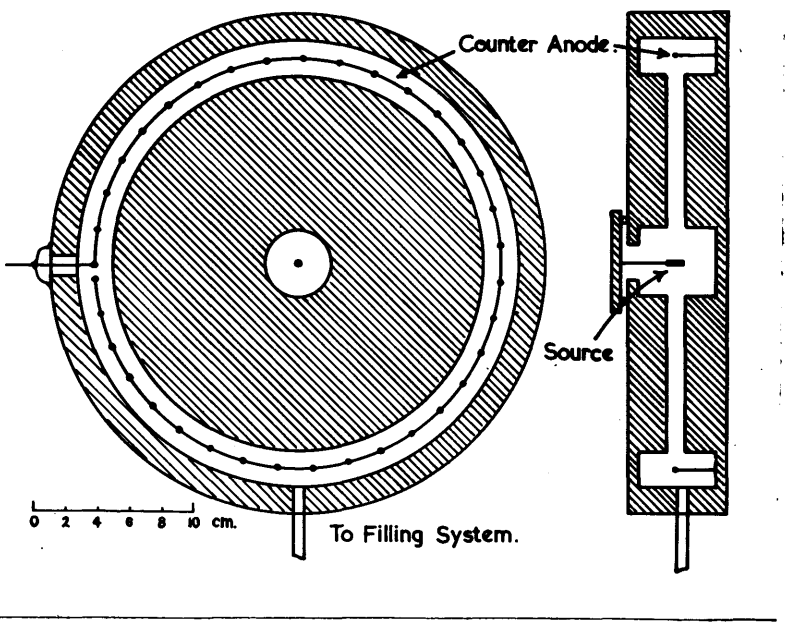

Figure 1. Schematic Diagram of Original Apparatus.

and for the correct value of the magnetic field, both positron and electron could trigger four or five sections of the counter, thus giving a pulse eight to ten times as large as the background single section pulses.

Unfortunately/

Unfortunately this simple and elegant arrangement did not yield the expected results, for two main reasons: firstly because the background was found in fact to contain a large number of double and multiple pulses owing to bad geometry which made it highly probable that a particle entering one section of the counter would be scattered into at least one more. This meant that there was a considerable number of four and five-fold pulses when a strong gamma-ray source was being used, and so the number of accidental coincidences between these, giving eight to ten-fold pulses was not negligible. The second difficulty was that because the counter sections were so short relative to their length they had very serious end effects which caused them to have only a very short plateau. This meant that even on the plateau the pulse size was a steep function of the high tension voltage, and so it was difficult to get stable working and reproducible results, since the method depended on selecting pulses of particular size with a discriminator. These same two difficulties also prevented the device from being used satisfactorily in a similar manner to determine ordinary beta-ray and secondary electron spectra. It was at this point that the method of removing the discriminator and counting all the pulses of all sizes was tried, since though it does not give the spectrum of the source directly, it does overcome the difficulties mentioned above. This is of course the same method as that used by Siegbahn and Slatis, and though it was not studied here in detail/

detail, the results obtained were very similar to those published by them. For comparison the curves obtained from the secondary electrons ejected from a thick lead foil by the gamma-rays of Co^{60} and the annihilation radiation of Cu^{64} are shown in Figure 2. From these results and a number of others, an empirical calibration curve was constructed for the device as used in this way.

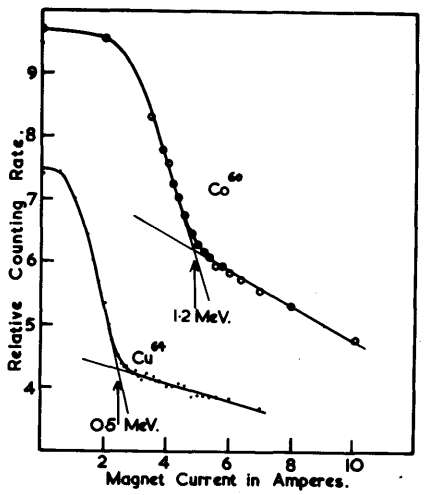

Figure 2. Integral Momentum Spectra of Secondary Electrons from the Gamma-Rays of Co^{60} and the Annihilation Radiation from Cu^{64}.

This method is however subject to several serious dis-:advantages. Firstly, even when one has obtained the experimental integral spectrum there is no explicit way of obtaining the true spectrum/

spectrum of the source because of the fact that for any setting of the magnetic field the solid angle of the device is a function of the energy of the particles detected. Thus when used in this way, the device is only suitable for determining end-points, unless one is prepared to carry out long and tedious successive approximations. Secondly, because of the high background in the counter, photo-electron lines and any other kind of fine structure are quite invisible, and thick convertors must be used for the determination of gamma-ray energies which makes the resolution of the device poor. For instance it will be noted that in the curves for Co^{60} given by Siegbahn and Slätis and by the present author, in neither case was it possible to resolve the lower energy line at 1.1 M.E.V. from that at 1.3 M.E.V. Thirdly, as stressed by Siegbahn and Slätis, the effect of scattering in the gas is such as to produce counts at values of the magnetic field much higher than that corresponding to the true end-point of the spectrum being examined, and this causes difficulties in the interpretation of the curves. In addition to these criticisms it should be mentioned that since one of the obvious uses for a large solid angle spectrometer of this sort would be the separation of complex beta-ray spectra by the method of beta-gamma coincidences, it would be a great advantage if the device could be made to give the true spectrum instead of an integral one, since the former would reduce the background of accidental coincidences by a very large factor near the end-point/

end-point, that is in the region of the greatest interest. For these reasons it was decided that it was worth while to attempt to overcome the difficulties in the original design in a different way.

3. THE IMPROVED APPARATUS.

A sketch of the improved apparatus is shown in Figure 3 and it will be seen that the number of sections into which the counter was divided has been reduced, thus giving longer

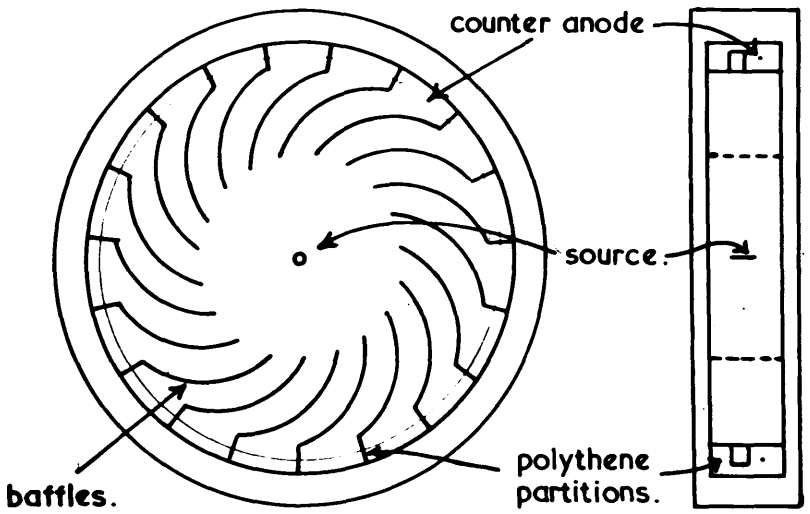

Figure 3. Sketch of Improved Apparatus.

sections and very much improved electrical performance. It will also be noted that the sections are separated by polythene partitions instead of the pillars of the original design, and that/

that these partitions have openings in them just large enough to permit the passage of electrons within the desired momentum range. This has the effect of cutting down to a very large extent the number of particles which are accidentally scattered into more than one section. Finally the device has been fitted with a set of baffles which permit only particles of the correct sign of charge and the correct momentum range to enter the counting system, and which together with the partitions ensures that only those particles are detected which have not been seriously scattered in the gas.

With these improvements it was found possible to take spectra with the discriminator set to count single, double, or triple section pulses with good reproducibility. The single section spectra contained a large number of spurious counts at low energies because of scattering, but the spectra obtained from the double and triple section pulses were very similar. The spectrum of RaE as obtained from an old thin walled Radon seed with triple section pulses is shown in Figure 4 and it will be observed that the shape is good apart from a displacement of the number maximum towards higher energies because of the scattering of the softer beta-rays in the gas filling. The filling for this run was 3 cm. Argon + 1 cm. Alcohol, the working voltage about 1100 V. and the estimated resolution (for triples) of the order of 5%.

These modifications to Curran's original apparatus thus produced/

produced a 360° spectrometer with a resolution of about 5% and a solid angle of 2.5% of 4π as compared with 1% of 4π for a corresponding semi-circular focussing spectrometer. It can however easily be shown that by altering the type of counting system and so obtaining a much wider slit, an instrument can be built which will give a solid angle of 20% of 4π with a 5% geometrical resolution, and further, that if the apertures in

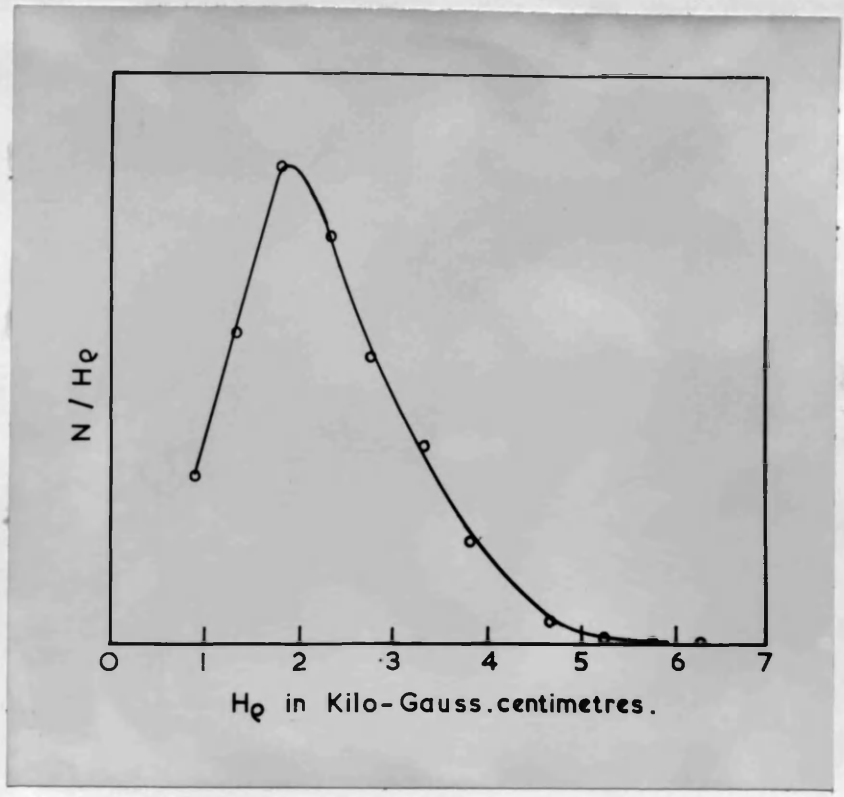

Figure 4. The Beta-Ray Spectrum of an old Radon Seed.

the partitions between the counters and the corresponding baffle systems are specially shaped, then solid angles up to the order of 50% of 4π might be obtained with 5% resolution. The design considerations for such an instrument both in the restricted/

restricted and general form are discussed in the next section.

4. DESIGN CONSIDERATIONS FOR VERY LARGE SOLID ANGLE SPECTROMETER

If we consider the diagram in Figure 5(a) which shows a section of the spectrometer by the median plane, then the circle

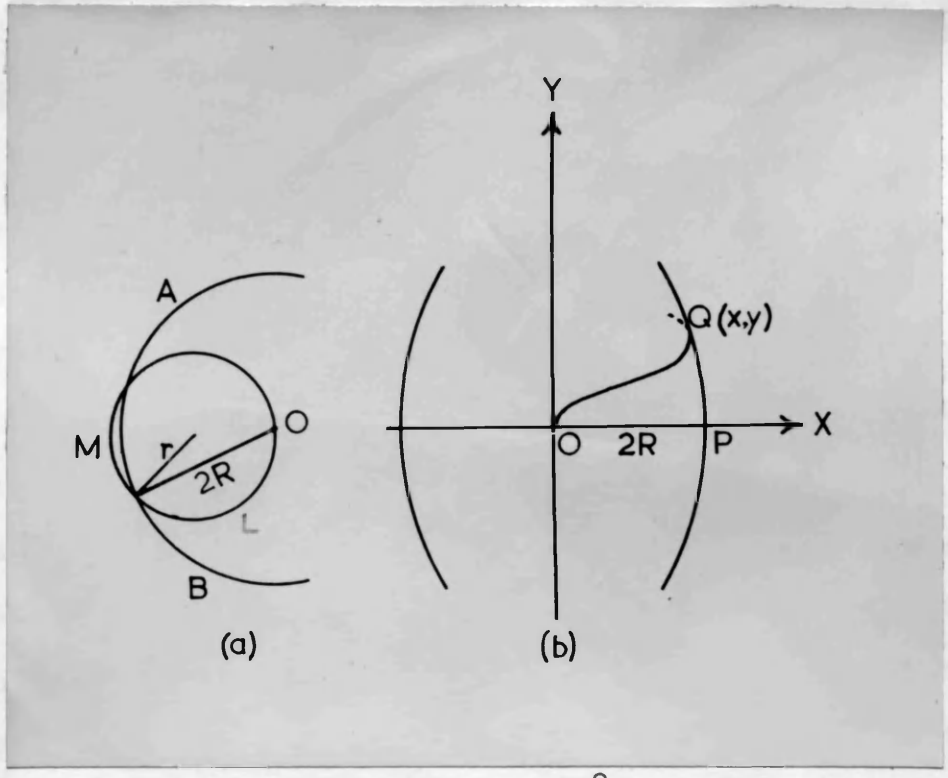

Figure 5. Geometry of 360° Spectrometer.
(a) Section by Median Plane.
(b) Section by Plane Containing the Axis of Symmetry.

AB represents the inner edge of the counting area which has radius 2R. OLM represents the path of a particle, radius r, wher r is just great enough to ensure that it intersects n counter sections./

sections. Now it can easily be shown that if α is the angle subtended at O by a single section, then:-

$$r/R = \sec(\overline{n-1}\alpha/2)$$

Hence we can draw up a table of values of r/R as a function of n and α, which table will tell us how wide we must make the counting area and what order of pulse size we must record to obtain a given resolution with a given value of α. With $\alpha = 15^{\circ}$, which is a suitable value for ease in construction, we find that the values of r/R for n=1,2,3,4,5 are 1.000, 1.009, 1.034, 1.082 and 1.154. This means that if we set the limit of our counting area at $2R_1 = 1.07 \cdot 2R$ and count triples, then we have a resolution of the order of 5%.

If we now consider Figure 5(b) which represents a section of the spectrometer by a plane containing the axis of symmetry, then the magnetic field lies along OY and O represents, as in Figure 5(a), the position of the source which in this case is assumed to be emitting mono-energetic particles. Then OP represents the projection in the plane of the paper of the semi-:circular trajectory of a particle emitted normally to the plane of the paper. The sine curve OQ represents the projection on the plane of the paper of the helical trajectory of a particle emitted in a plane through O perpendicular to OP but whose direction of emission makes an angle θ with the normal to the plane of the paper. Then if Q has coordinates (x,y) with respect to O as origin, it is clear that if OP = 2R, the locus of/

of Q is the ellipse given by the freedom equations $x = 2R\cos\theta$, $y = \pi R.\sin\theta$, i.e. the ellipse:-

$$x^2/(2R)^2 + y^2/(\pi R)^2 = 1$$

This means that the locus of the points of maximum distance from the axis of symmetry, of the particles emitted from O, is the ellipsoid of revolution:-

$$(x^2 + z^2)/(2R)^2 + y^2/(\pi R)^2 = 1$$

Now it can easily be shown that if we consider only those particles which are emitted with angles θ lying between $\theta = \pm\phi$ then the solid angle into which they are projected is $4\pi\sin\phi$. Hence for a geometry to collect 10% of all the particles from the source, $\sin\phi = 1/10$ and for a limiting particle $x/2R = \cos\phi = 1-1/200$. That is, the substitution of a right circular cylinder of radius 2R for the ellipsoid would introduce an error of only $\frac{1}{2}\%$ in the momentum of the particles registered. For 20% collection the error would be about 2% and for larger solid angles would increase rapidly. Thus where an overall resolution of the order of 5% is desired, a spectrometer of solid angle 20% of 4π could be built on the same principle as that described in the last section with simple cylindrical construction and rectangular apertures in the partitions. For larger solid angles, the partitions would have to be shaped, the shape being given by the envelope of the family of sine curves corresponding to the plot of the actual distance of the particle from the axis of symmetry against y. The general shape of this curve is shown in figure 6. and it has freedom equations/

equations given by:-

$$x^2 = -4R^2\sin^3X/\cos X(X - \tan X)$$

$$y^2 = 4R^2X^3/(X - \tan X)$$

where X is a parameter whose values are confined to those that make tanX/X negative.

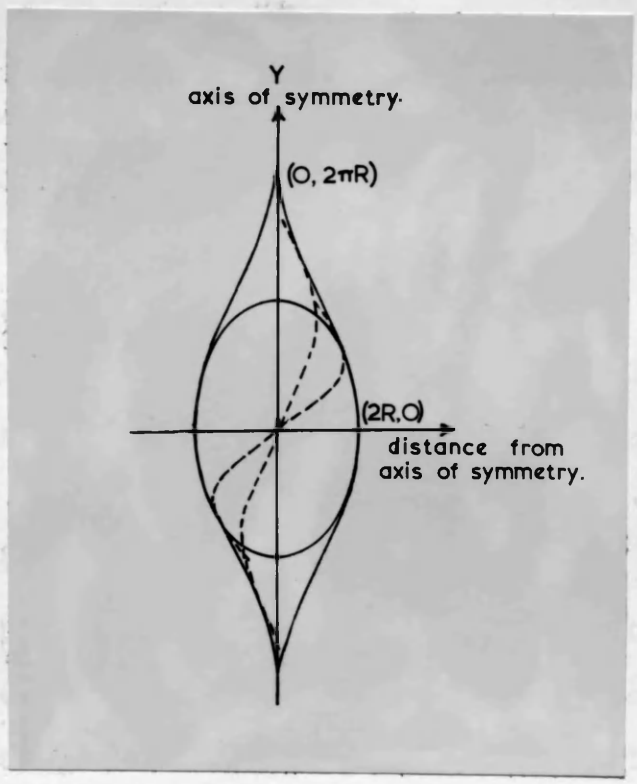

Figure 6. Section by Plane Through Axis of Symmetry of Envelope of Trajectories.

It is clear, however, that for these large solid angles the original scheme for having a common anode for all the counters/

counters running round the median plane would have to be aban-:doned since the depth of the counting space has become so great. The difficulty can be overcome by using counters of roughly square section when viewed along the axis of symmetry, and fitting separate anodes parallel to the magnetic field. Even with this method of construction, however, a reference to Figure 6 will show that solid angles in excess of about 50% of 4π would produce counters of such a shape that their efficiency might be rather poor for particles intersecting them near their ends. For this reason and because of the difficulty of con-:structing a baffle system or thin window of the correct shape, it seems probable that 50% collection would be about the practical maximum. It should of course be realised that these figures represent the ideal collecting fractions which might be obtained with perfect design; in practice any baffle system would obstruct part of the solid angle and any windows would cause the loss of particles by scattering as would also the gas filling. Nevertheless, the figures given above represent such an improvement on the collecting fractions available by any of the conventional methods of beta-ray spectroscopy that it is felt that the development of this method would provide a power-:ful tool in the study of complex beta-ray spectra by the method of beta-gamma coincidences.

I must acknowledge the help given me in this work by Dr. S.C. Curran who designed the original apparatus and with whom I had many discussions which were of the greatest value in suggesting/

suggesting ways of overcoming the faults in the early design. I must also thank Mr. D.L. Pursey for deriving the freedom equations to the envelope of the electron trajectories.

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A P P E N D I X I I.

CIRCUITS OF THE GLASGOW PAIR SPECTROMETER.

Figure 7 is a block schematic diagram of the circuits associated with the pair spectrometer, and it will be seen that despite the large size of the equipment, which contains no fewer than 150 valves, the basic circuits are simple.

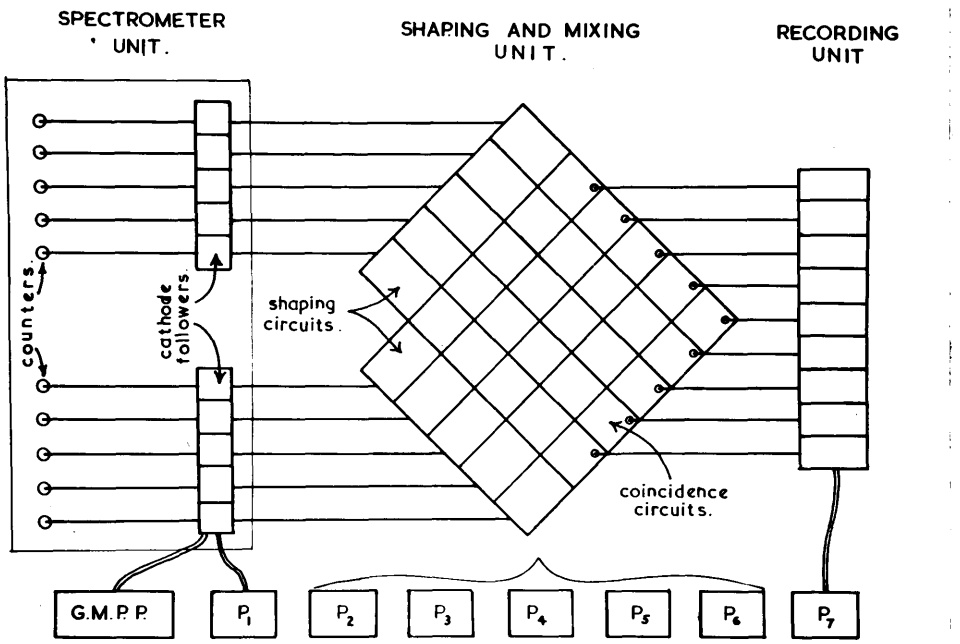

Figure 7. Block Schematic Diagram of Circuits.

Considerable effort, however, was expended in their design, in order to obtain the best possible performance from the avail-:able components. Taking the circuits in the order in which they occur, Figure 8 shows the cathode follower and shaping circuits,/

circuits, of which there are ten of each. The cathode followers are really part of the spectrometer proper, and perform the function of carrying the load of the long cables from the Spectrometer Unit to the Shaping and Mixing Unit. While no comment need be made on the cathode follower circuit, the shaping circuit is of some interest.

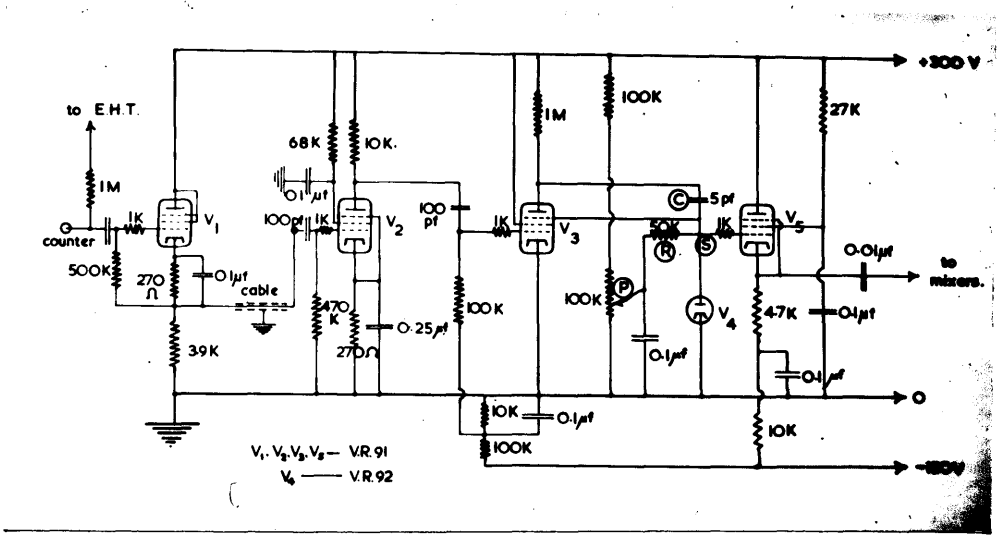

Figure 8. Cathode Follower and Shaping Circuits.

The function of this circuit is to produce from the counter pulse relayed by the cathode followers, which may be 20 to 50 μS long, a pulse of controllable length whose front edge will be coincident with the sharp front edge of the counter pulse, and whose length will be adjustable to a very short value. (less than/

than 1 μS). Several schemes were considered for producing this result including the use of a triggered multivibrator circuit, and a circuit embodying a delay-line to produce the necessary sharp pulses. Of these two circuits, the former, while ideal for producing relatively long square pulses, was found to be very difficult to trigger reliably when the pulse produced was really short. (Much shorter than the triggering pulse). The delay-line circuit produced results very similar to those obtained with that actually used, but was abandoned in favour of the extreme simplicity of the latter which used only resistors and condensers and did not require the winding of special inductances.

Returning to the circuit shown in Figure 8, V_1 is the cathode follower valve, and V_2 is a straightforward amplifier which accepts the negative pulses from the cathode follower, and produces on its anode a large positive pulse. This pulse must be large enough to ensure that V_3 is run into grid current, and the time of rise of the anode voltage must be an order shorter than the output pulse length of the shaping circuit, (less than 1 μS). The value of anode load chosen achieves both these results with a counter pulse of $\frac{1}{4}$ V. or greater.

The function of V_3 is to produce a very large and very steeply falling negative pulse which is differentiated by the small condenser C and the resistor R, the length of the differentiated pulse produced being controlled by the voltage applied to the earthy end of R by the potentiometer P. The requirement/

requirement for a large and steeply falling pulse is met by having V_3 normally cut off, and having it turned fully on when the pulse from the anode of V_2 drives it into grid current. The amplitude of the negative pulse produced at the point S depends on the rate of fall of the potential of the anode of V_3, (differentiation), with the proviso that the capacity C must be large enough to ensure that a sufficiently large part of the anode current of V_3 flows into C to replace the current through the diode V_4, since until this happens, the potential of S will not change, but will remain approximately at earth. Provided this requirement is met, the action of the potentio-:meter P in controlling the length of the negative pulse appearing at S is as shown in Figure 9. Diagram (a) illustrates the variation of the potential of S (E_s) with time if P is set to earth potential. When the circuit is triggered by a counter pulse, E_s drops sharply and then returns exponentially to earth with a time constant which is given by RC' where C' is the total capacity between S and earth. When, however, P is set to some positive potential, E, then after its initial fall, E_s approaches the line $E = E_s$ exponentially with a time constant RC', as shown in diagram (b). This means that it rises nearly linearly to the value zero in a very short time, and is held there because the diode then starts to conduct. With the valves available, the values of R and C actually used, namely 50kΩ and 5 pF, were found to give the best performance. With these/

these components, the effective length of the pulses appearing at S was found to vary from about 3 μS, when P was set to earth potential, to about 0.3 μS, when set to its maximum value of 100 V. The remaining valve in Figure 8, V_5, is simply a cathode follower which acts as a buffer between the point S which must have a low capacity to earth, and the input

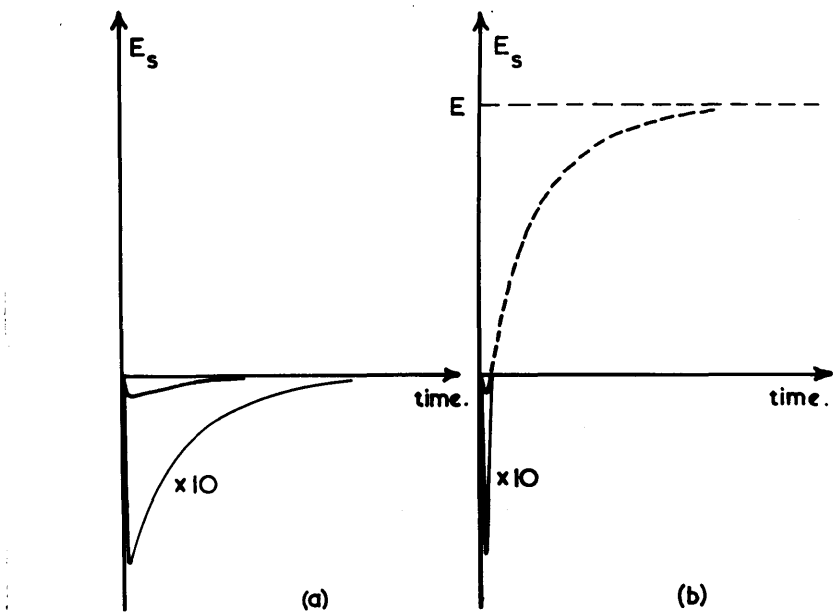

Figure 9. Variation of E_s with time.

impedences of the five coincidence circuits which are connected to each shaping circuit.

One of the coincidence circuits is shown in Figure 10, and it will be seen that the arrangement used is a very crude one. It was originally intended to use a Rossi circuit, but it soon became/

became clear that this type of circuit is unsuited to very short resolving times, since it involves the use of a large common anode resistor, which makes the rise in anode potential when a coincidence occurs, slow. Hence, if the pulses are short, the anodes have only risen in potential by a very small amount before the coincidence is over, and the anode potential

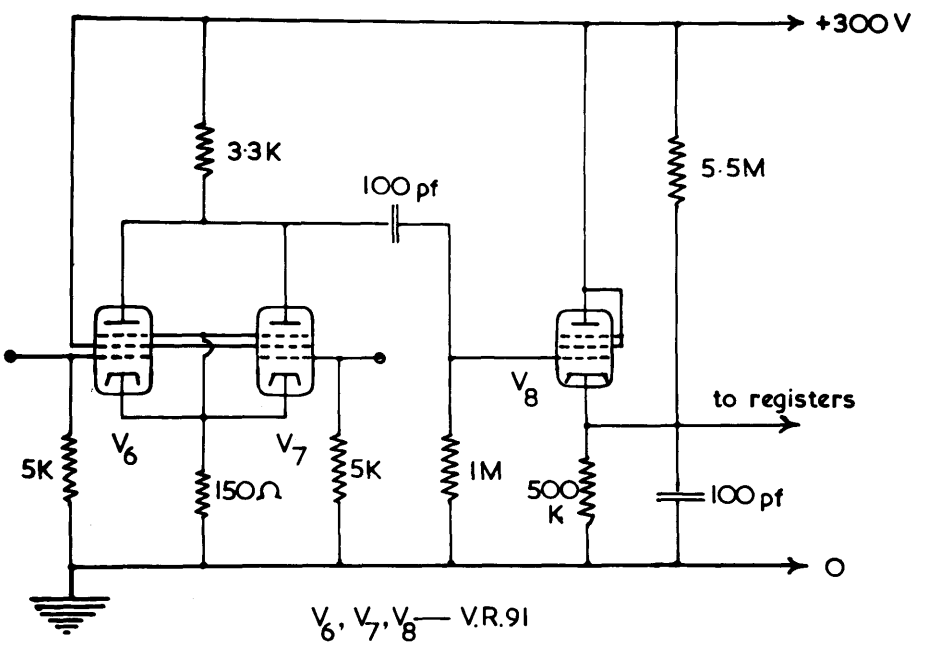

Figure 10. Coincidence Circuit.

falls sharply back to its normal value. In order to achieve an output pulse size which was sensibly independent of resolving time and of time of overlap, the common anode load of V_6 and V_7 had to be reduced to the small value used, which means that the pulse appearing on the common anodes when only one of the coincidence/

coincidence valves is pulsed, is quite large, being about $\frac{1}{4}$ of that obtained with a coincidence. The smaller pulses are eliminated by the third valve, V_8, which is a cathode follower which is normally cut off by its cathode being held at about 25 V above its grid. The small pulses due to non-coincidences are not large enough to cause this valve to conduct, but a coincidence applies a potential of about 40 V to its grid, thus causing an output pulse in the cathode of V_8 of about 15 to 20 V. The output pulse from V_8 (Figure 10) is made as long as possible by means of the 100 pF condenser connected from cathode to earth, but there is a limit to this lengthening, because this condenser must be small enough to enable it to be fully charged by the cathode current of V_8 during the very short duration of the coincidence pulse. The other element controlling the output time constant is the value of the cathode resistor, but this cannot be made too large either, without loss of stability which is essential since the stage is acting as a discriminator. The values of these two components used, which were the largest values practicable, give a time constant of 50 μS. This of course is totally inadequate to operate a mechanical register, and besides, the pulse is of the wrong sign since it was found that a G.P.O. telephone register operates more satisfactorily on a small current if it is normally energised and is switched off by the controlling impulse, than if the opposite is true.

In/

In Figure 11, which shows the circuit of an element of a Recording Unit, the valve V_9 performs the dual function of inverting the pulse from V_8, and increasing its amplitude and length to such values that it can easily control the register. V_9 is normally cut off since its cathode potential is kept at about 10 volts above earth. When however the valve is caused

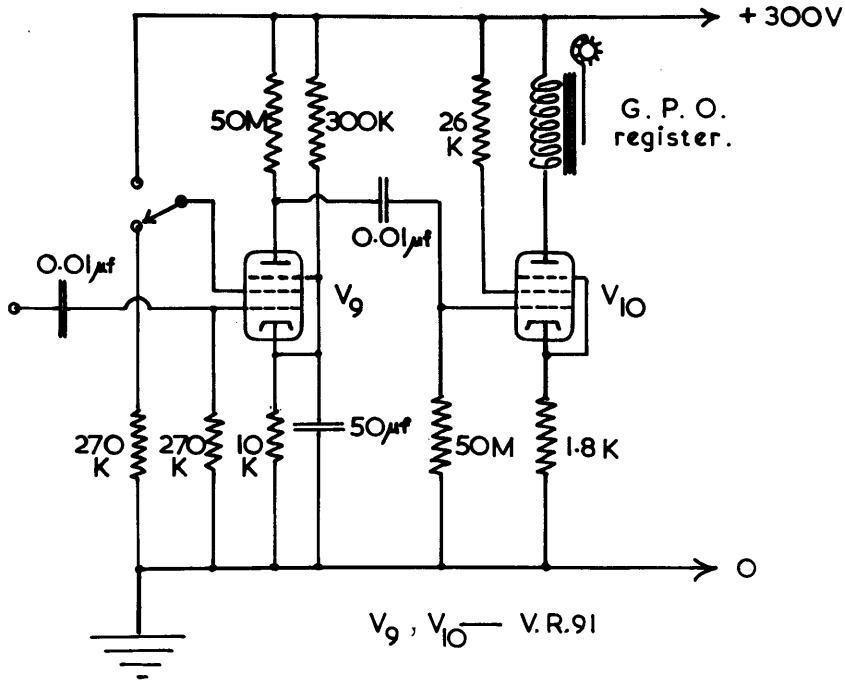

Figure 11. Circuit of an Element of the Recording Unit.

to conduct by a positive pulse applied to its grid, its anode rapidly falls to earth potential due to the very large current passed, (the screen is connected to H.T.), and can only return to its normal high potential after a time determined essentially by the time taken for the condenser K to recharge through the anode/

anode load. This is very long, being of the order of 1/20 of a second, which is the time required for the operation of the mechanical register. Since the coupling condenser is very large, as is also the grid leak, a pulse of this duration is applied to the grid of V_{10}, which is cut off, thus causing the mechanical counter in its anode to register the pulse.

The only units appearing in Figure 7 still remaining to be described are the Power Supply Units. Of these, the unit providing the E.H.T. supply for the ten G.M. counters is a standard commercial production designed by T.R.E. This unit is equipped with ten separate potential dividers which enable the potential applied to each counter to be separately controlled. The remaining units are all of standard design providing about 120 mA at 300 V, apart from that which supplies the power for the negative line used in the shaping circuits. This unit provides a supply of current (120 mA) at a negative potential which is neon stabilised at about 150 V. It may be wondered why the main Shaping and Mixing Unit is supplied by no fewer than five separate power packs of which four are identical. The reasons for this are two-fold. Firstly, had a single power pack been built, it would have weighed as much as the five taken together, and while the smaller units are conveniently portable, each weighing say 25 lbs., the single large unit would have been very unwieldy and would certainly have required two men to move it. Also, the total heater current to be supplied/

supplied is of the order of 35 Amperes, which is a difficult amount of current to handle without the use of very heavy and inflexible cables. The second, and possibly the more important argument in favour of the smaller units, is that a quantity of transformers of just the correct type for this size of unit had been acquired by the Department from Government Disposals, and as the use of the large unit would have involved the purchase of a large transformer, the interests of economy clearly demanded the use of the smaller units.

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