THESIS

PRESENTED FOR THE DEGREE

OF

DOCTOR OF PHILOSOPHY

UNIVERSITY OF GLASGOW

1956.

TITLE.

LOW ENERGY GAMMA-RADIATION FROM NUCLEAR REACTIONS

PREFACE

The writer has described in this thesis work carried out on the detection and measurement of low energy gamma-radiation emitted in certain nuclear reactions, and attempted to show how the results give information about the energy levels of light nuclei.

In the first chapter, the importance of a knowledge of nuclear states is briefly discussed and methods of studying these are compared, particular reference being made to de-excitation by gamma-emission.

The second chapter contains a discussion on the experimental methods of studying low-energy gamma-radiation. Most of the material of these first two chapters is taken from the literature.

Chapter three gives a description of the experimental equipment used in the experimental investigations. Much of the electronic apparatus, the counters used in preliminary work and the rotating target chamber had been constructed by Dr.R.D.Smith prior to the start of this work, but the gas-filled proportional counter used to obtain most of the experimental data, was designed by the writer. This applies also to the modifications to the single channel pulse analyser.

The experimental techniques used and the results obtained are given in the fourth and fifth chapters. The method of "differential absorption" was developed and used for the initial studies on the radiation from deuteron bombardment of Aluminium in conjunction with Dr. R.D. Smith, who was mainly responsible for the results obtained using scintillation counters. Later work on this reaction, the development of the photographic technique, and the studies of other reactions were carried out entirely by the author.

The last chapter contains a discussion and interpretation of the results, which is the sole responsibility of the writer.

The author would like to acknowledge his indebtedness to Professor P.I. Dee and Dr.S.C. Curran for their encouragement and advice given during this work and to Dr.R.D. Smith and Dr. J.G. Rutherglen for their co-operation and assistance.

PUBLICATION

The work on the gamma-radiation from the reaction $Al^{27}(d,p)\ Al^{28}$ has been described in the following paper:-

"31 Kev Excited State of Aluminium-28", by R.D. Smith and R.A. Anderson, Nature, London, 168, 429, 1951.

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CHAPTER 1

INTRODUCTION.

1. 1. THE IMPORTANCE OF NUCLEAR ENERGY LEVELS.

In classical atomic physics, the atom was thought of as a heavy nucleus, carrying a charge +Ze, where Z was the atomic number and e the electronic charge, and surrounded by Z electrons bearing negative charge. This picture, derived from experiments such asRutherford's work on alpha-scattering and the penetrability of beta-rays through matter, had, however, left two main experimental facts unexplained.

The first of these was the discrete nature of the electromagnetic radiations from excited atoms, this being inconsistent, on classical electromagnetic theory, with the stability of the atom. This was explained by Bohr, using ideas which later developed into quantum theory and which predicted atomic energy levels for the hydrogen atom, assuming that the forces involved were electrostatic.

The other difficulty was the realisation that nuclear forces were not purely electrostatic in nature. Experiments on the anomalous scattering of alpha-particles were explained by assuming a short range attractive force acting within the nucleus and such a force also explained the long lifetimes found for alpha-decay and the general stability of nuclei.

Meanwhile the study of particles and gamma-rays from radioactive sources had shown that there were well-defined groups of alpha-particles coming from any one nucleus (e.g. the work of Rosenblum (1930) on the fine-structure of alpha particle groups) and that there was a line structure in beta-ray spectra, such as RaB (Ellis & Skinner, 1924). As in atomic physics where the relationships between the frequencies of X-ray and optical spectra can be explained in terms of transitions between energy levels, these groups and line spectra from nuclei could be due to a similar structure of energy levels.

The study of atomic spectra had given much information about the interactions between electrons in the atom. Bohr's simple quantum idea of energy levels defined by the quantum number n (Bohr, 1913) had been followed by Sommerfeld's introduction of the orbital quantum number, l (Sommerfeld, 1916), and Moseley's work on characteristic X-rays of the different elements (Moseley, 1914) had explained the periodic table and suggested the shell structure of the electrons in the atom. Increased resolving power of optical instruments used in the study of more complicated spectra resulted in the observation of doublet and triplet lines and these led to the idea of "spin" (Goudsmit & Uhlenbeck, 1926).

Bohr's simple picture of electrons describing orbits round the nucleus has been replaced by the mathematical developments of quantum mechanics. These lead to a particle system having stationary states of definite energies, or energy levels, with properties arising from the force interactions between the particles

In the atomic case these are primarily electrostatic, but interactions of angular moments are also involved. Such a treatment also explains why certain transitions between energy levels either do not exist or else have very low intensity, leading to the concept of forbidden transitions or selection rules.

Thus the study of atomic spectra has lead to quantum mechanics, which can predict the spectra, assuming the force field; to the idea of angular momenta and the interactions between them; to a picture of closed shells, involving forces which can only link a limited number of particles ("saturation forces"); and to the principle of selection rules.

Now natural radioactivity showed the same phenomena of energy levels and the study of artificial radio-activity and nuclear reactions produced by high-energy particles and gamma-rays has revealed energy levels in practically every nucleus (Mitchell, 1950, Alburger & Hafner, 1950, Ajzenberg & Lauritsen, 1952). These levels must be due to the force interactions within the nucleus giving rise to stationary states and energy levels. Unlike the atomic levels, however, the precise nature of these forces is not known, but a detailed knowledge of the levels should give information about the magnitude and nature of these interactions, and any theroretical treatment of the forces must be consistent with the experimental data on these levels.

Since one of the major problems in physics is the determination of these nuclear short range forces as much information as possible about nuclear energy levels is desirable. In particular, knowledge of closely spaced levels, especially in light nuclei whose level spacing is usually large, would be extremely valuable, as these might lead to doublet structure analogous to that found in atomic spectra. The ability of any theory of the nucleus to predict such doublets in agreement with experiment would be a most valuable test of such a theory.

1. 2 METHODS OF STUDY OF NUCLEAR STATES.

In atomic physics, our knowledge of energy levels is derived chiefly from X-ray and optical spectra, though information also comes from ionisation potentials and work on Auger electrons. The level spacing is greatest for the lower states, decreasing for higher states, which tend asymptotically to the level equivalent to ionisation, i.e. at which the electron has enough energy to leave the atom. Above this there is a continuum of states, allowing the electron to leave with any energy and reducing the value of studies of particle emission.

The situation in the nucleus is very different. There is a discrete level spacing above as well as below the energy required to eject a particle. Below this we have bound states from which gamma-radiation only is possible, but above it, from the virtual states both gamma-radiation and groups of particles may be emitted, of which the latter are more likely. Thus the study of particle emission can give information about these levels.

Due to the continuum of excited states and low energies involved in the atomic case, it is usually easy to excite all the bound states in the atom. This is not the case with nuclear levels, high energies being involved and resonance effects often restricting the excitation.

Generally, particle emission from a virtual state will be more probable than gamma-emission, implying a shorter lifetime for particle emission ($t \sim 10^{-20}$sec) than for gamma-emission ($t \sim 10^{-12}$sec). Thus the emission of gamma-rays from highly excited levels will be improbable unless the probability of particle emission is reduced by a Coulomb barrier or is forbidden by other considerations. It will usually arise from residual nuclei in an excited case after the emission of a particle from the original nucleus.

Methods of study of nuclear levels depend on the atomic number, Z. For light nuclei and low excitation energies the level spacing is large, greater than the level widths and the resolving power of the experimental techniques, and it is feasible to study individual levels. In this region (below $Z = 20$) the Coulomb barrier is small enough to allow appreciable penetration by charged particles, for both bombarding and emitted particles, and thus the spectrum of energy levels in this region can be studied fairly fully.

For larger Z, and high excitation energies, the level spacing is small and it is difficult to resolve the levels and usually the statistical properties of the nuclear levels are studied in this region. Here also, Coulomb effects are significant and the levels studied are generally those not involving charged particles - low lying levels at about 1 Mev., from beta and gamma-spectra of radioactive isotopes and levels above the binding energy of a neutron from cross-section resonance in neutron capture.

If a reaction can be considered as due to the intermediate formation of a compound nucleus, then it can be represented by the equation:

$$A + P \longrightarrow B \longrightarrow C^{*} + R$$
$$C^{*} \longrightarrow C + h\nu$$

and the study of this reaction will give information about two nuclei, B and C. However, the whole of the level structure will not normally be covered in any one reaction, the region covered depending on the Q of the reaction. This is the amount of energy evolved in the reaction due to the mass differences of the reacting particles, not including any kinetic energy of the initial particles.

Energy levels can be studied by various methods, of which the following are relevant to the work described in this thesis:-

(a) Heavy particle emission

(b) Gamma-emission

(c) Lifetimes or transition probabilities of excited states.

(d) Studies of properties of ground states.

Heavy particle emission.

In the compound nucleus B formed from A + P, the emission of a heavy particle will normally occur if energetically possible, the re-emission of the initial particle being a possibility competitive to any other reaction. In calculating the relative probabilities of charged particle and gamma emission from two excited states of a nucleus, the Coulomb effect must be considered, for this may reduce considerably the probability of emission of charged particles, as in alpha-decay of heavy radioactive nuclei.

Generally, if two or more groups appear in the same reaction, for the same energy of bombarding particle, they may be assigned to energy levels in the residual nucleus.

The measurement of the energies of charged particles can be carried out by various techniques, as follows:-

By bending the charged beam in electrostatic or magnetic fields. The resolution of this method has been greatly improved in recent years, largely using 180^{o} focussing (Strait, Van Patter, Buechner, & Sperduto, 1951).

By measurements of the range of the particles in air or in thin absorber foils. This is the simplest and most straight-forward, but if several groups are present the straggling reduces the resolution, and it is also difficult to detect short-range groups of low intensity against a background of long range particles.

By counters of the proportional type, which, in effect, measure the ionisation caused by the particle or by subsidiary effects associated with the ionisation. These include ionisation chambers, gas-filled proportional counters and scintillation counters, and nuclear emulsion plates may also be thought of in this category.

The major difficulty, particularly for low energy groups, is scattering of the bombarding beam or competing reactions which may mask the groups being studied. This has been overcome by combinations of two of these methods. Thus magnetic analysis with its high resolving power has been used with various detecting systems of comparatively low resolution - proportional or scintillation counters (Burcham and Freeman, 1949) or nuclear emulsions (Strait, Van Patter, Buechner, & Sperduto, 1951). Range measurements have been improved by using a proportional counter biassed to count particles at the end of their range only (Benson, 1948).

The resolution of these charged particle energy determinations is high, but it is only recently that it has been reduced to better than 10 Kev., resulting in the separation of multiplet levels with separations of the order of 50 Kev.

Measurements of the energies of neutrons is more difficult because of their lack of charge and negligible interaction with atomic electrons. For fast neutrons, methods involving either knock-on protons or nuclear reactions are employed, but the resolution obtained is much poorer than that obtained with charged particles. Such measurements are certainly incapable of resolving closely spaced energy levels. Slow neutrons are studied by velocity selectors or crystal diffraction methods, but as such particles are not generally produced in any great intensity in nuclear reactions, the high resolution possible is of greatest value in the study of neutron resonances, in the restricted region just above threshold for the neutron induced reaction.

Gamma-emission.

The theory of gamma-emission will be treated more fully later.

Gamma rays are absorbed by matter, but, unlike charged particles have no definite range. The intensity of a homogeneous beam after passing through a thickness of matter x is given by $I = I_0 \exp.(-\mu x)$, where I_0 is the original intensity and μ the absorption coefficient. The absorption is due to three distinct effects - the photo-electric effect, in which an electron is ejected from the atom with energy given by $E = h\nu - K$, where K is the ionisation potential of the electron shell concerned; the Compton or scattering effect, in which the gamma-ray is scattered from one of the atomic electrons with a change in energy (and hence wave-length), the electron taking up the energy lost; and pair-production, which occurs if the energy of the gamma-radiation is greater than 1 Mev., and in which an electron-positron pair is produced with energy ($E = h\nu - 2\,mc^2$).

The absorption co-efficient and the relative importance of the different processes can be expressed in the following formula for the absorption co-efficient per atom:-

$$\mu = AZ^4 \lambda^3 + BZ\lambda + CZ^2 f\,(1/\lambda)$$

where the three terms are due to photo-electric, Compton and pair-production effects. A, B, C are constants, Z the atomic number of the absorber and λ the wave-length of the radiation.

Generally, it is true to say that the photo-electric effect is most important for soft gamma-radiation, (energies up to about 100 Kev.), the Compton effect for energies from 100 Kev. to 2 Mev., and pair-production for higher energies, though the value of Z will influence to a large degree these figures.

There will also be nuclear effects, such as reactions like Cu^{63} (γ, n), Cu^{62}, in which the activity of the product will only be found for radiation above the threshold energy - in this case 11 Mev., and usually rather high. There is also the photo-disintegration of deuterium, $H^2 + h\nu = p + n$, with a threshold energy of 2.18 Mev., where a determination of the energy of either product particle gives the energy of the incident radiation. The resolving power of these methods is poor, and they will not be discussed further.

For high energy gamma-radiation, the best determination of energy comes from pair-production, which had been studied in cloud-chambers, in order to find the energy of both particles. However, the development of the pair spectrometer by Walker & McDaniel (1948), has improved the efficiency and resolution of measurements of gamma-ray energies. The resolving power of this technique is about 6% which is similar to that obtained in the photo-disintegration of deuterium in nuclear emulsions (Gibson, Green & Livesey, 1947), but with much superior efficiency of detection and statistics.

The measurement of the absorption co-efficient of gamma-radiation is useful for low energies, but for high energies this becomes dependent on the geometry used. Absorption co-efficient measurements are probably of greatest value in the region 100 Kev. to 1 Mev., where the electrons produced are largely due to Compton effect. The energy in this region may be determined from measurements of the "edge", or maximum energy of the distribution of the Compton electrons. Recently work has been carried out on coincidences between Compton electrons and the scattered gamma-rays at a fixed angle, using two scintillation counters (Bair, Mainschein, & Baker, 1951 and

and Bannerman, Lewis & Curran, 1951).

Generally all these methods are useful for gamma-rays of a single energy but they have insufficient resolution to separate gamma-rays emitted from closely spaced levels, and are also of little value in the presence of large intensities of background and high energy radiation.

Thus it appears that gamma-radiation from transitions from closely spaced levels will not be resolved by the methods available, and it will be necessary to look for radiation between such levels. This will have energies up to about 100 Kev., and we will discuss in a later section the possibility of such radiation and methods of detecting it, based on the photo-electric effect.

Lifetimes or transition probabilities of excited states.

The determination of probabilities for transitions by gamma-emission is of great importance in deciding the polarity and parity change of the transition. For isomeric states with lifetimes greater than seconds, normal methods of measuring the intensity at intervals over a period of several lifetimes may be used.

For extremely short lifetimes it may be possible to use the method of Delbruck & Gamow (1931), in which a competitive heavy particle transition from the same excited level occurs. This is the case particularly in naturally radioactive sources. By comparing the intensity and the number of heavy particles emitted, the relative probability of the two processes is found. Hence, if the transition probability of the particle emission is known that of the gamma transition is determined. This method has been used for partial lifetimes for gamma-emission as low as 10^{-12} sec., but it is usually only in the heavy elements that the Coulomb barrier reduces the probability of particle emission sufficiently for it to be measurable.

A more common method for gamma-rays arising from residual nuclei is the technique of delayed coincidences between the gamma-rays and the particles emitted in the formation of the residual nucleus (usually beta-particles) (De Benedetti & McGowan 1946). If the number of coincidences is plotted against the delay time, a decay curve is obtained, with decay constant that of the gamma transition. This method has been used with lifetimes from 10^{-6} to 10^{-8} sec.

Transition probabilities and hence half-lives can also be obtained from level widths in excitation functions.

Ground state properties.

Most of the techniques outlined so far do not give any direct information about the properties of energy levels, merely about transitions to other levels or to the ground state itself - the energy difference, change of angular momentum and parity, lifetimes, etc. To obtain the properties of these states it is therefore necessary to know those of the ground state.

With unstable nuclei, it may be necessary to study the results obtained in beta-decay experiments, but usually the angular momentum, spin and magnetic moment will be found by experiments such as the study of optical fine structure, the magnetic deflection experiments of Rabi (1937, 1939) and radio-frequency experiments (Alvarez and Bloch, 1940).

1.3. THEORETICAL EXPLANATIONS OF NUCLEAR STATES.

Many attempts have been made to derive models of the nucleus which would explain the experimental data regarding nuclear levels, of which three main types have had a degree of success in explaining certain features of the data.

In the statistical or many particle models, no attempt is made to consider individual levels or individual nucleons, but a statistical analysis is made of the level density, thinking in terms of the nucleons as a gas or liquid in the nucleus. Results obtained from such models are suitable for comparison with results on levels of high excitation in heavy nuclei, where individual levels are not resolved. We shall not consider this type of model in any detqil.

At the other extreme is the independent particle model, in which the energy levels are considered as arising from single particles moving in a fixed field, in the same way as an atomic electron in a Coulomb field. If the rotational or vibrational levels of such a model are considered, nuclei with medium Z would be expected to have equi-spaced levels.

Thus Wilson (1950,1952) considers a uniform shell with rotational and vibrational levels which give a spacing of 0.387 Mev. for the vibrational levels of all nuclei and compares this to the results of Wiedenbeck (1947) in which levels of Ag, Au, and In were found with spacing about 0.4 Mev. Rotational levels reduce the spacing to about 0.1 Mev. for all elements and excitations and the interaction of the two types of motion give sets of levels corresponding to each vibrational level, with a spacing varying with the values of A and Z. By taking different values of the constants involved agreement is obtained with experimental results for certain elements of medium Z and in particular certain triplets in Si^{28} are explained as due to overlapping of different sets of such levels. However, rather high values of the rotational and vibrational quantum numbers are required and many possible values for energy levels are not experimentally found. It has been suggested that further study of level schemes with sufficient resolving power will find these levels and give the triplet states into which all the levels should group in Si^{28}, on this theory.

Attempts have been made to explain discrepancies between experimental results and the predictions of this type of theory by suggesting that rotational and vibrational levels do explain the observed regularly spaced levels butthat, due to the selection rules for angular momentum and parity, not all the levels will be detected in any particular reaction. Particularly for light elements these theories are not very satisfactory.

Examination of the stability properties of nuclei and binding energies of neutrons and protons indicate that certain numbers of neutrons and protons correspond to exceptional stability and these numbers have been termed the "magic" numbers (the same for neutrons and protons). Since in the atomic case such high stability in the inert gases is due to the closing of the electronic shells, it has been suggested that there might be closed shells of neutrons and protons in nuclei. Several attempts have been made to construct shell theories giving closed shells for the correct numbers and that of M.G. Mayer (1950) has been very successful in explaining these and other features of nuclei and will now be discussed.

This model is based on a single particle theory in which the particle moves in a potential which is a mixture of the three dimensional oscillator, which gives energy levels $E = (n + \frac{1}{2})h$, for n = 1,2,3.....with parity $(-1)^n$, and the square well type, which removes the degeneracy and splits the oscillator levels into states with different values of l, each of which is doubly degenerate due to the spin of the particle giving $j = l \mp \frac{1}{2}$ and further degenerate as 2j + 1. Such a theory had been advanced before (e.g. Feenberg, 1950) but gave different values for the magic numbers from those found experimentally.

To obtain the desired shells further assumptions are made,

1. that there is strong spin-orbit coupling (j-j coupling)
2. that in the lowest energy state the momenta of the even nuclei combine to give l = 0, j = 0, and hence for an odd

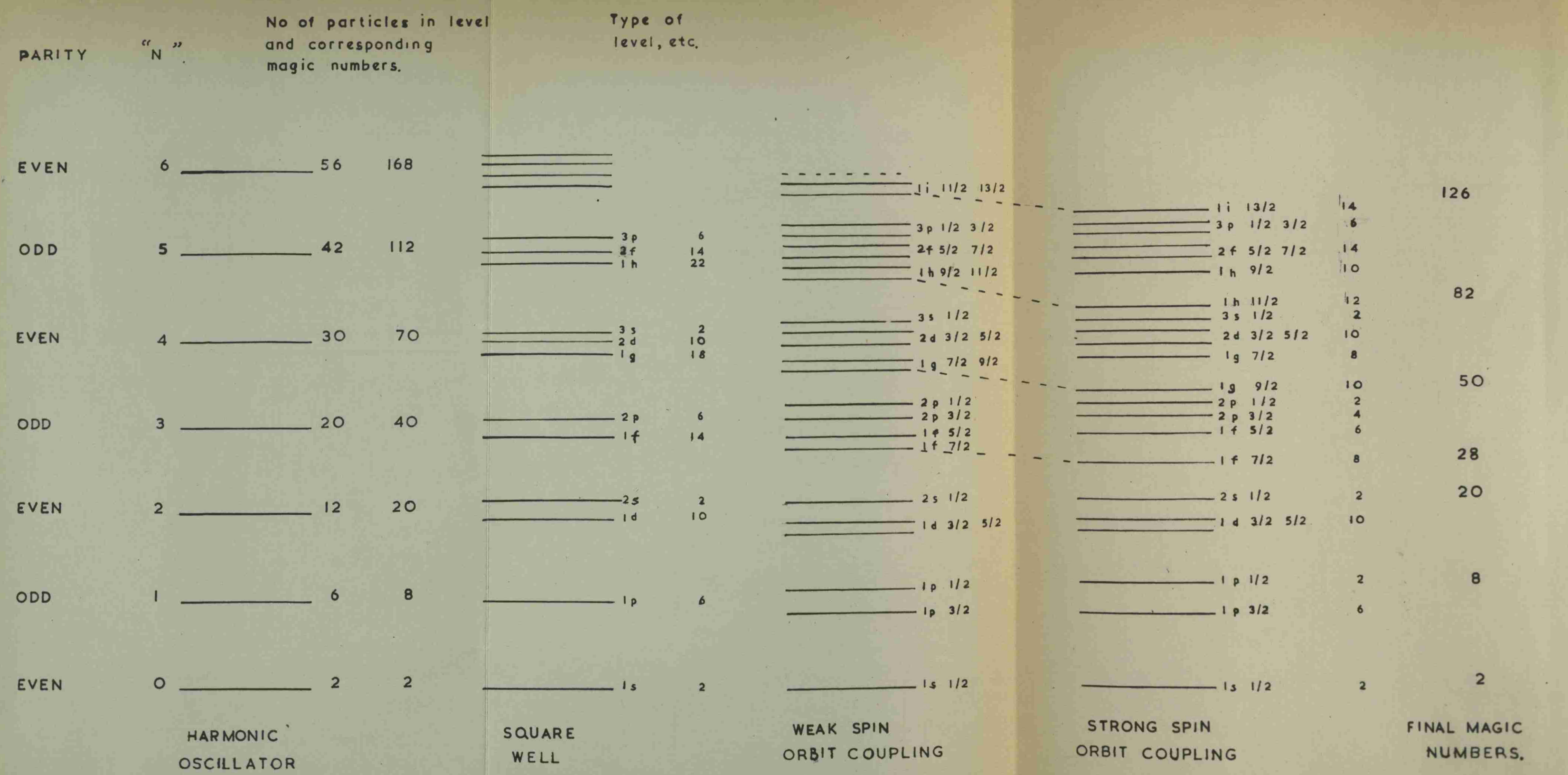


FIG. I LEVEL STRUCTURE PREDICTED BY SHELL THEORY number of neutrons or protons, the angular momentum is that of the odd nucleon.

3. there is a negative pairing energy of the nucleons which increases with the value of j for each member of the pair.

4. the value of the spin orbit coupling which separates the terms $j = l \pm \frac{1}{2}$ increases with l and reduces the energy of the $l + \frac{1}{2}$ level.

The result of these assumptions is to produce a level structure as shown in Fig.1 which gives a grouping in agreement with the magic numbers.

Other features of nuclear properties which this theory predicts in agreement with experiment are the spins and magnetic moments of nuclei with odd A and the position of regions of isomerism in the periodic table.

Any shell will then consist of levels arising from the same oscillator level n and hence with the same parity, and for higher shells a level from the next oscillator level n = 1, with opposite parity and with the highest value of j available from that level. This will be $j \geqslant j' + 2$, where j' is the highest j in the shell apart from this. Since any low lying levels are presumably from the same shell as the ground state a transition between low-lying and ground states of a nucleus should either have no parity change and a small change in j possible or a parity change and a change in j of at least 2. Electric diple gamma-radiation corresponds to parity change and carries away angular momentum of 1, and hence on this picture electric dipole radiation between low-lying and ground states is not possible. The existence or absence of such radiation would be a valuable test of this theory.

The importance of this model is the prediction of level properties and particularly of the ground state which it makes, and although the calculations for excited levels are rather complex the predictions for light elements are not inconsistent with the theory (Inglis, 1953).

1. 4 DE-EXCITATION BY GAMMA-EMISSION.

Gamma-radiation arises from a transition from one excited state to another in the same nucleus, the frequency being given by $h\nu = E_1 - E_2$, the difference between the energies of the two states. The intensity of the radiation will be determined by the transition probability, which can be expressed as

$$\lambda = f(h\nu)\int\psi_1^* q\psi_2\, dv \int\psi_2^* q\psi_1\, dv.$$

where f is a function of the energy, $\psi_{1,2}$ the wave-functions of the states and q an operator which depends on the type of radiation.

In a nuclear reaction, there will only be radiation arising direct from the compound nucleus formed if the competitive heavy particle decay is improbable, and will almost certainly be of very low intensity in light nuclei.

For compound nuclei from which particle emission is energetically impossible, and from residual nuclei left after particle emission, the radiation will be much more intense and will also have a well-defined energy, since the longer lifetime compared to a state from which particle emission is possible implies a smaller level width

On a semi-classical basis, it may be shown that if the radiation is thought of as arising from a dipole with dimensions about that of the nucleus, the lifetime for radiative transitions should be about 10^{-14}sec. However, Delbruck & Gamow (1931) tried to determine the lifetimes of gamma-rays emitted in competition to long-range alpha-particle emission by finding the branching ratio of alphas and gammas, which will be the relative numbers of long and short range alpha-particles. Since both groups arise from transitions to the same residual nucleus, Gamow's alpha theory will give the transition probability for the long range particles in terms of the experimentally determined lifetime for emission of the short range alphas. Hence the transition probability for gamma-emission and thus the effective lifetime may be found. For the intense 0.62 Mev. gamma-radiation from RaC', the lifetime was found to be about 10^{-11} sec., about 10^{3} times greater than was expected.

Weiszacker (1936) suggested that this might be due to the multipolarity of the radiation, but it was the study of isomerism or metastable states which raised the necessity for a more comprehensive theory. It is found that in certain artificial radioactive materials excited states may have extremely long lifetimes, of the order of seconds or longer, even years, and that nuclei excited to these states may have properties very different from those in the ground state. Such nuclei are termed isomers, and it is necessary to explain these long lifetimes. This is done by assuming that the states have angular momentum very different from that of the ground state (or other lower levels) and hence the transitions can only occur by the emission of multipole radiation. Such transitions are much less probable than dipole radiative transitions and are termed forbidden transitions.

This idea, which will now be more fully developed, shows that not only the transition probabilities, but also the internal conversion co-efficients are influenced by the polarity of the radiation, and Helmholtz (1941) has studied these related properties for various isomeric states and found that they were consistent with a common value for the polarity.

Multipolarity of gamma-radiation.

In determining the transition probabilities for gamma-emission, the matter may be considered classically as due to the emission of electromagnetic radiation from a system of currents and charges in a nuclear system. Then Bohr's correspondence principle may be used to transpose the results to a form suitable for the application of quantum methods.

Classically the power emitted by a radiator of angular frequency w, and current distribution such that the component perpendicular to the line of observation is given by j, may be shown to be

$$\frac{\omega^2}{2\pi c^3}\left|\int j\, e^{-i\underline{k}.\underline{r}'}\, d\tau'\right|^2$$

per unit solid angle, where k = w/c is the wave-number, and the integration is carried out over all the current distribution at distance r' from the reference point of the radiating system.

This expression can be transferred to quantum mechanics by replacing the continuous charge distribution by discrete particles of charge e, mass M, and momentum P, and thinking of each photon as carrying away energy $h\nu$ where $2\pi\nu = w$. If this is done the number of photons emitted per solid angle becomes

$$\frac{w}{2\pi\hbar c^3}\left|\int \Psi_f^* e^{-i\underline{k}.\underline{r}'}\frac{e}{M}P_{op}\Psi_i\,d\tau'\right|^2$$

For atomic and nuclear radiators, the dimensions are less than the wave-length and thus $\underline{k}.\underline{r}'$ will be small. If the exponential is expanded we get

$$e^{-i\underline{k}.\underline{r}'} = 1 - i\underline{k}.\underline{r}' - \tfrac{1}{2}(\underline{k}.\underline{r}')^2$$

and the first term in this expansion will be predominant. This is said to represent electric dipole radiation, and will normally be greater than the other terms. If r' is taken as about equal to R, the radius of the nucleus, successive terms in the expansion would be reduced by about $(kR)^2$ due to this effect. For example, if R is taken as 6.5×10^{-13}cm., the reduction for an energy of 1 Mev. will be about 10^{-3}.

If, however $\int \Psi_f^* P_{op}\Psi_i\,d\tau'$

disappears, then

$$\int \Psi_f^*(\underline{k}.\underline{r}')P_{op}\Psi_i\,d\tau'$$

may not, and the radiation intensity will be largely due to this term and reduced by about $(kR)^2$. Such radiation is termed electric quadrupole radiation. If this term also disappears, the next one gives us electric octopole. The value of the integral is termed the matrix element of the transition, and if this can be calculated the transition probability and life-time for the transition may be found. The precise value depends on the value of R taken, but Bethe (1937) has given as an approximate formula for the life-time of an excited state for de-excitation by gamma-radiation

$$\tau \doteq 5 \times 10^{-21} \, (\, l!)^2 \, (20/E)^{2l+1}$$

where E is in Mev., and the transition is E 2^l.

A fuller analysis considers radiation due to magnetic interactions as well as electric, and these may be thought of as due to currents, rather than varying charges. These will depend on the velocities of the charges within the nucleus and will be reduced from the corresponding electric radiation by a factor of about v/c, which is also about 10^{-3}. Note that while E 2^l and M 2^{l-1} radiation are often considered as arising from the later terms in the exponential expansion, and having the same transition probability, this will only be true for gamma energies of about 1 Mev.

<u>Selection Rules.</u>

The transition probabilities are governed by the terms in the expansion of $(\underline{k}.\underline{r}')^l$ which give non-zero values in the integral i.e. which matrix elements are non-zero. Properties of the initial and final states which effect these elements will therefore determine which type of transition is possible and thus give us selection rules. If the states are such that

$$\int \psi_f^* P \psi_i \, d\tau' = 0$$

electric dipole radiation is forbidden, if

$$\int \psi_f^* (\underline{k} . \underline{r}') P \psi_i \, d\tau' = 0$$

electric quadrupole is forbidden and so on.

<u>Angular Momentum</u>.

Heitler (1936) showed that a photon from a 2^l radiation carries away angular momentum $l\hbar$ and thus if the initial and final states of the nucleus have angular momentum I and I', then $|I - I'| \leqslant l \leqslant |I + I'|$ determines possible values of the polarity of the radiation. This may also be expressed by saying that $\int \psi_f (\underline{k} . \underline{r}')^{l-1} P \psi_i \, d\tau'$ vanishes except for values of l as given above.

<u>Parity</u>.

Since the parity of a self-contained system cannot change, the parity of a gamma-radiation must be determined by that of the two nuclear states involved. It can be shown that, since the operator $\underline{p} = \hbar/i . \nabla$ contains the first power of $\underline{r}$ only, it must have odd parity. Thus radiations corresponding to the term $(\underline{k}.\underline{r}')^{l-1}$ have parity $(\text{odd})^l$, as follows:

Electric dipole	parity change	yes
E.Q. and M.D.	no change	no.
E.O. and M.Q.	change	yes

Electric Radiation	Dipole	Quad	Oct	2^4 pole	
$\lvert I + I' \rvert \geq$ $\lvert I - I' \rvert \leq$	1	2	3	4	
Parity Change	Yes	No	Yes	No	
Magnetic Radiation		Dipole	Quad	Oct	
$\lvert I + I' \rvert \geq$ $\lvert I - I' \rvert \leq$		1	2	3	
Parity Change		No	Yes	No	
Approximate lifetime	10^{-11}		10^{-8}	10^{-5}	sec

TABLE 1. ALLOWED MULTIPOLE RADIATIONS

Generally, the transition with lowest polarity not forbidden by the above considerations of momentum and parity will be predominant in the radiation, being of the order of 10^3 times greater than any other. It should be mentioned however, that experimentally it has been found that electric dipole radiation is rather less probable (about 10^{-3}) than would be expected on this simple theory. This can be explained as due to the symmetry of the nucleus, which reduces the charge asymmetry necessary for dipole radiation.

Table 1 summarises these ideas. For example a transition between states with I = 4, and I = 2, and different parities would give magnetic quadrupole and electric octopole, but not electric quadrupole. It also illustrates the predominant type of radiation associated with different changes in angular momentum. It should be noted that transitions between two states with I = 0 are completely forbidden, for a radiative transition involves angular momentum being carried away.

Probability of emission of low-energy gamma-radiation.

Since the transition probability for electric dipole radiation is proportional to W^3 and thus to E^3, and for higher polarities to a further factor of $(kR)^2$, which is proportional to E^2, the emission of low energy gamma radiation of about 100 Kev. is reduced considerably. Hence the emission probability for such radiation is less than that for a 1 Mev. radiation by about 10^{-3} for electric dipole, about 10^{-5} for quadrupole, and 10^{-7} for electric octopole, and a 100 Kev. dipole transition has a

Type of radiation	T (secs.)	α_K	$T/(\alpha_K + 1)$
Electric dipole	2×10^{-11}	0.55	1.3×10^{-11}
Magnetic dipole	10^{-9}	0.034	10^{-9}
Electric quadrupole	2×10^{-3}	22	8.7×10^{-5}
Magnetic quadrupole	10^{-1}	1.1	5×10^{-2}
Electric 2^3 -pole	3×10^5 ($\sim$ 100 hrs.)	7.5×10^2	4×10^2
Magnetic 2^3 -pole	1.5×10^7 ($\sim$ 200 days)	33	4.5×10^5 ($\sim$ 6 days)
Electric 2^4 -pole	6×10^{13} ($\sim 10^6$ yrs.)	2.5×10^4	2.4×10^9 ($\sim 10^2$ yrs.)
Magnetic 2^4 -pole	3×10^{15} ($\sim 10^8$ yrs.)	10^3	3×10^{12} ($\sim 10^5$ yrs.)

TABLE 2. Theoretical life-times and internal conversion coefficients for the de-excitation of the 32 Kev. excited state of Al^{28}.

similar theoretical emission probability to 1 Mev., quadrupole radiation. Hence low energy gamma-radiation in competition with high energy radiation will have comparatively low intensities unless the high energy transitions are forbidden, and any such radiation detected is more likely to arise from a transition from a low-lying state to ground than from one between two excited states. For such low energy radiation, too, the degree of competition from internal conversion will be high. This will not effect the transition probability, but for short lived excited states where equilibrium in a reaction is soon reached, the intensity of the low energy gamma radiation will be reduced.

See, for example, table 2, where the approximate results to be expected for the soft gamma-rays which might come from the low-lying level in Al^{28} reported by Strait, Van Patter, Buechner & Sperduto (1951). The formulae used for these figures may be found in the following references:-

Blatt & Weisskopf, 1952, pp.618, 627
Dancoff & Morrison, 1939

The final column gives the lifetimes which would be observed experimentally, being shorter than for purely radiative transitions due to the competitive effect of internal conversion which we now discuss.

Competitive processes.

If the degree of multipolarity is large and the transition by electromagnetic radiation highly forbidden, the life-time for such a transition will be large, but the nucleus may de-excite by interacting with the atomic electrons, ejecting one of them from the K or L shell. This internal conversion effect is strictly a competitive process with a definite transition probability, causing a reduction in the life-time of the excited state compared to that expected from gamma-emission alone. It is not a case of gamma-emission followed by a photoelectric effect. The value of α , the ratio of the number of ejected electrons to the number of gamma-rays emitted, will depend on Z, on E the energy of the transition, and also on the polarity of the transition, for the interaction is between the wave-functions of the two nuclear states and that of the electron, and these wave-functions will depend on the momenta of the nuclear states.

Selection rules for internal conversion.

These are similar to those for gamma-emission, but electrons may be emitted when gamma-rays are completely forbidden e.g. in $0 \rightarrow 0$ transitions gamma-emission is not possible but the transition may occur by emission of a K-shell electron.

Dancoff & Morrison (1939) and Hebb & Morrison (1940) have derived expressions for α_K as a function of the energy and polarity of the transition and the atomic number of the atom, and more exact values have been worked out by Rose, Goertzel, Spinrad, Harr & Strong (1951). Internal conversion in the L-shell is also possible and the ratio α_K/α_L is of some importance, involving the polarity of the transition, and this has been calculated by Hebb & Nelson (1940).

It should be noted that the conditions for isomeric states are similar to those for high internal conversion co-efficients, i.e. low E and large changes in l, and so the two phenomena may be studied in the same nucleus, with a view to determining the polarity of the transition. This was done by Helmholtz (1941) when he obtained results for T,

A further de-excitation process is internal pair production for high energy transitions with I = I' = 0 and no parity change. This is relatively rare due to the possibility of gamma-transitions to intermediate allowed states and the most notable example is the production of electron pairs of energy 6 Mev in the reaction

$$F^{19}(p,\alpha)\ O^{16*}\quad ;\ O^{16*} \longrightarrow O^{16} + e^{+} + e^{-}.$$

Electromagnetic transitions by a single process with I = I' = 0 and parity change are completely forbidden, but the formation of two electrons or two quanta is a theoretically possible process of small transition probability (Sachs, 1940).

CHAPTER 2.

THE STUDY OF LOW ENERGY GAMMA-RADIATION

2. 1. METHODS OF DETECTING SOFT GAMMA-RAYS AND OF MEASURING THEIR ENERGY.

The detection of soft gamma-rays whose energies may be determined otherwise is usually carried out by the effect on photographic plates or by the ionisation caused by the secondary electrons produced in ionisation chambers, for measuring total intensity, or in photosensitive Geiger-Muller counters with thin windows, for counting the actual number of photons. Recently, the development of scintillation techniques, in which light excited by the passage of charged particles is detected by photo-electric multiplier tubes, has provided a sensitive method of detection of the secondary electrons following the capture of gamma-radiation in a crystal.

The energy of the radiation may be determined by measuring the actual wave-length of the beam by methods analogous to those used in the optical and X-ray regions. These involve constructive reflection of the beam at successive planes of atomic structure in crystals. Each plane will reflect the beam at an angle equal to the angle of incidence, but the radiation from successive layers will interfere with each other and the reflection will only occur if $n\lambda = 2d \sin \theta$, where n is integral, λ the wave-length of the incident radiation, d the distance between the reflecting planes and θ the angle of incidence and reflection with the plane. This effect is used in the Bragg spectrometer, in which a highly collimated beam of X-radiation falls on a crystal face. A photographic plate or ionisation chamber is positioned to measure the reflected beam and as the crystal is rotated, the X-ray intensity measured will give the spectrum of the beam. Such methods give extremely good resolution and have been used in studying soft gamma-radiation from natural sources up to 770 Kev., as in Rutherford, Chadwick & Ellis (1930). Such energies, however, are very difficult to measure, for glancing angles of only about 10' are required and this involves very good collimation, cutting down the intensity of the beam. Long exposures and high intensities are required even for energies about 20 Kev., for the reflection co-efficient of crystals at this energy has been given by Compton & Allison (1935) as only 10^{-5}. Thus it appears that for nuclear reactions induced by particle bombardment, considerations of intensity render this technique of little use.

If a gamma-ray beam of homogeneous energy passes through matter, a certain number of the quanta will be scattered or absorbed, reducing the intensity of the beam. It is found that the intensity after passing through a distance x of a material is given by $I = I_o e^{-\mu x}$, where I_o is the original intensity, and μ the absorption co-efficient, which is related to the mass and atomic absorption co-efficients. These vary widely and depend on the atomic number of the absorber and the

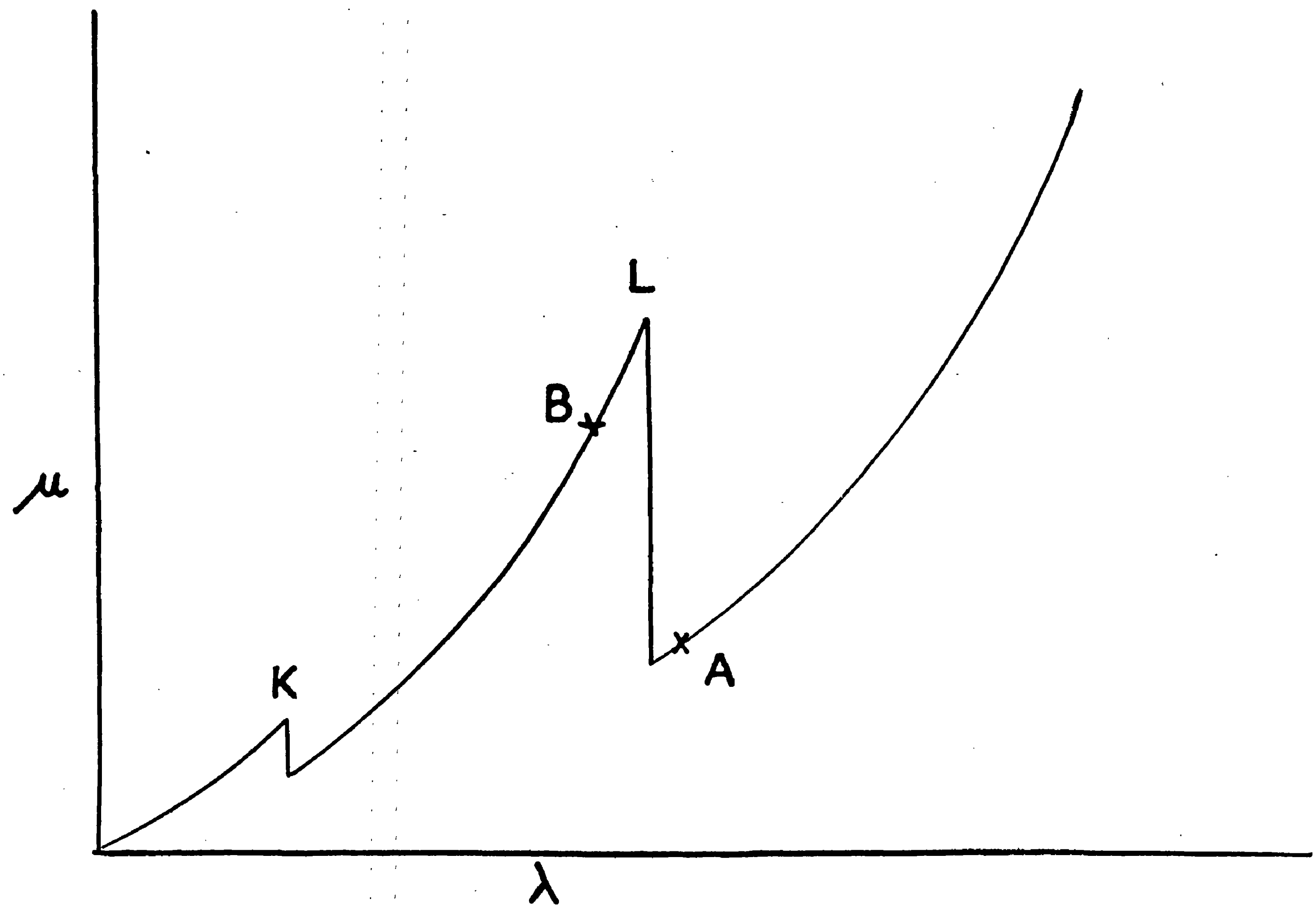


FIG. 2 VARIATION OF X-RAY ABSORPTION COEFFICIENT (μ) WITH WAVELENGTH (λ)

energy of the radiation, but have been studied extensively, both experimentally and theoretically. For the region of soft gamma-rays we will consider chiefly the absorption co-efficient due to the photo-electric effect, for which μ_A, the atomic absorption co-efficient, is proportional to $Z^4 \lambda^3$. This rule is strictly true for the absorption due to each electron shell, no absorption occurring in a shell until the energy is great enough to eject a photo-electron, after which absorption occurs. This results in discontinuities at values of the gamma-ray energy corresponding to these energies, as shown in fig.2. Thus, although the most efficient absorbers are generally those of high Z, the increase in μ at the K and L edges can effect this and the most suitable absorbers for different energies may be obtained from tables of absorption co-efficients.

However, a valuable way of determining the energy of a soft-radiation of homogeneous energy is often, instead of measuring its absorption co-efficient with an arbitrary absorber, by using the method of critical absorbers, as long as E is less than 90 Kev. For one element, of atomic number Z, the gamma-ray may just not have enough energy to eject a photo-electron and so the absorption will be small (equivalent to point A in fig.2). For the element with atomic number Z-1, however, energy required to eject the photo-electron will be slightly less and the absorption curve will be shifted slightly to the right. Thus the absorption edge will lie at a slightly lower energy than that of the gamma-ray, which will have a correspondingly higher absorption co-efficient. By inserting absorbers of different atomic numbers and finding where a plot of μ against Z shows a sharp change a value of λ can be found. This method is simple, can be carried out with low intensities, and gives a resolving power sufficient to establish the energy between limits in the ratio of about Z/Z+2. Absorption methods, however, are not so suitable for complex spectra or where there is a large background of other radiation.

When gamma-rays are captured, secondary electrons are emitted with energy $E = h\nu - W_k$, $E = h\nu - W_l$, etc., where W_k, W_l, etc., are the binding energies of the electrons in the atom. Thus gamma-radiation falling on an element may emit electrons of well-defined energies, whose measurement will give that of the incident radiation. This measurement may be carried out in several ways. The most direct is the emission of the photo-electrons from a thin foil of lead placed over the source and the study of these electrons in a magnetic field, as in a normal beta-spectrometer. Very thin foils are required as converters to reduce the spread of energy due to energy loss of the secondary electrons in the foil, and for this reason, internal conversion electrons are valuable. They may be compared to photo-electrons without the use of external converters.

If the gamma-rays are captured in a gas the range or ionisation of the secondary electrons may be determined in a cloud-chamber or gas-filled proportional counter, thus giving a measure of their energy. In the latter case, the X-ray emitted by the converting atom when it de-excites may also give rise to ionisation, and the result is that if this X-ray is also captured the ionisation produced will be a measure of the total energy of the incident radiation. A similar effect occurs in the scintillation counter, in which the energy of the gamma-radiation absorbed in a crystal is ré-emitted as light which can be detected by a photo-multiplier tube. The emission of the tube gives a measure of the energy of the incident gamma-radiation. In these types of measurement, the uncertainty in the energy due to spread in the output of the counter etc., is due to statistical variations in the processes involved and not to the energy loss of the electrons in the converter. For these reasons increased efficiency of detection does not involve a decrease in resolution, as is the case using foils as converters. The use of proportional and scintillation counters will be discussed more fully in later sections.

2. 2. THE USE OF GAS-FILLED PROPORTIONAL COUNTERS.

Most of the methods described in the above section are unsatisfactory in the presence of a background of high energy radiation, with an intensity comparable to that of the soft gamma-rays being investigated. This is the situation encountered in the study of low-energy transitions between states of light and medium nuclei excited by particle bombardment. However, the development of gas-filled proportional counters (Curran, Angus & Cockcroft, 1949) suggested the possibility of distinguishing low energy gamma-rays from background radiation. In designing a counter for this purpose, the criterion must be a high counting efficiency for low energy gamma-rays, coupled with a low efficiency for other types of radiation. Bearing this in mind, a counter with an exceptionally large window, which could be operated at pressures of 3 atmospheres of filling gas, was designed and built.

The essential feature of a gas-filled proportional counter is that the potential difference between the case and the central wire causes a multiplication of the ionisation causes by the incident radiation. In the ionisation chamber, the field is such that the mean free path of the electron in the gas is too short with the field strength applied to give the electrons enough energy to ionise the atoms it strikes. Thus the total charge collected on the central wire will not be greater than the original amount of ionisation. In the Geiger-Muller counter, on the other hand, the potential is so great that any original ionisation causes a discharge along the whole length of the counter, and the total charge collected is large, many times greater than the original ionisation and independent of it. The proportional counter lies between these two cases and in this the original electrons of the ionisation cause no further ionisation until they approach a critical distance from the central wire where the field is high, and then produce a limited number of further electrons. This results in each initial electron giving a number of electrons, termed gas multiplication. Ideally this number of electrons produced by each initial electron is constant, and deviations from this are responsible for the finite resolution of such counters, but we will neglect these here. The total current collected on the central wire is then proportional to the original ionisation. The value of the gas multiplication factor is a function of the operating voltage, the type of gas and the pressure used, the presence of impurities and the dimensions of the counter. While theoretically it might be possible to calculate the pulse size for a given ionisation from these variables and the capacity of the associated circuits, this is not practicable. To obtain quantitive results for the ionisation produced and hence the energy of the radiation incident on a proportional counter, it is necessary to calibrate the counter by using particles of known energy, E. If these produce a pulse height, h, the ration E/h gives a constant which may be used to determine energies of other particles. The assumption of proportionality may be verified by studying several radiations of known energy.

For measurements of soft gamma radiation, the calibration may best be carried out using X-rays, produced by one of the following techniques.

An ordinary X-ray machine will give white radiation, but by collimating the beam and directing it on metal foils, observation at right angles to the incident beam will give characteristic X-rays of homogeneous energy practically free from white background.

Certain radioactive sources decay by K-capture of an orbital electron, followed by emission of the characteristic X-rays of the daughter element as the vacant K-level is filled, for example:

$$Zn^{65} \xrightarrow{\text{K capture}} Cu^{65} \longrightarrow \text{Cu X-rays}$$

This gives the possibility of a range of convenient X-ray sources.

If materials are bombarded with charged particles, these will cause ionisation, which will be followed by emission of characteristic X-rays of the material. In conjunction with a source of high-energy protons, such a technique can be equivalent to fairly strong sources, and if the counter is being used to study excitation levels arising from proton or deuteron bombardment, it is of great value. Previous work by Henneberg (1933), Peters (1936), Livingstone, Genevese & Konopinski (1937) and Smith (1950) has shown that the intensity of the radiation is roughly proportional to $E^{4 \text{ or } 5}/Z^{12}$, where E is the energy of the incident beam and Z the atomic number of the radiator.

2.3. BACKGROUND AND EFFICIENCY CONSIDERATIONS.

The counter used was similar to an ordinary proportional counter, fitted with guard rings and field tubes as described by Cockcroft & Curran (1951), but to give a large efficiency it had a large window. This had a diameter of 1.8", and consisted of a foil of Al of thickness 0.01". There was an internal lining of Al, 0.002" thick. Such a window has a transmission factor better than 50% for gamma-rays of energy greater than 15 Kev.

The counting diameter of the tube was 10 cm., and the counting length 15 cm. Thus if the criterion for proportional counting is taken to be that the range of secondary electrons is less than the radius of the counter, it can be seen from the ranges of electrons given in Curran & Craggs (1949) and Rasetti (1936), that the counter may be used satisfactorily up to 80 Kev. if filled to a pressure of one atmosphere with argon, and up to 150 Kev. if filled to three atmospheres.

Because of the large window, the solid angle efficiency will be large, but the intrinsic efficiency of the counting gas will be low, about 1% for 100 Kev. radiation and 6% for 40 Kev. radiation at a pressure of three atmospheres.

Since the purpose of the proportional counter is largely to separate the soft gamma radiation from general background, some consideration of the relative magnitudes of these to be expected and the relative efficiencies of the counter will now be given.

First, consider the spectrum produced by soft-gamma radiation. This will produce in the gas both photo and Compton electrons, and these will be about equal at 75 kev., with the photo-effect of much greater importance at lower energies. However the elecrons arising from Compton scattering will have a large spread in their energy distribution with a maximum of intensity well below the energy of the photo-electrons e.g. at 10 Kev. for E = 50 Kev., and at 28 Kev. for E = 100 Kev

The spectrum due to photo-electrons will appear as a peak of half-width about 20% and at a much higher energy than that due to the Compton effect, and thus the latter will not effect the sharpness of the photo-electric peak.

Any soft gamma radiation incident on the walls of the counter will be absorbed, owing to their thickness, as will secondary electrons and X-rays resulting from interactions by higher energy radiation. The purpose of the Al lining is to ensure that any characteristic radiation reaching the gas will be low energy Al X-rays rather than Cu or Zn X-rays from the brass of the counter body.

Soft gamma-rays which are absorbed in the window of the counter will produce secondary Al X-rays which are so soft (energy about 1 Kev) that they give negligibly small pulses, and also photo-electrons from Al, many of which will be totally absorbed in the window and the others will have an energy spread due to energy loss before leaving the foil. Since the range of photo-electrons of given energy is known, the number of gamma-rays which will be absorbed in a layer near enough to the surface to produce electrons energetic enough to reach the counting gas can be determined. This can be shown to be only about 2% for 50 Kev. and 0.5% for 100 Kev. gamma-radiation, and not all the electrons produced in this way will travel forward and reach the gas. Thus, as with Compton electrons, the background from this effect will not be enough to mask the main peak of photo-electrons.

The background which will be of most concern will be that arising from high energy gamma-rays, neutrons, and beta-rays from nuclear reactions, which might be expected to have similar intensities to that of the soft radiation being studied. The latter may be eliminated by the use of hydrogenous absorbers and magnetic fields and in any case would only be expected to enter by the window, but gamma-rays and neutrons will be considered further.

If we take gamma-radiation of up to 10 Mev., it will produce electron pairs in the counter walls and surroundings with ranges much greater than the counter dimensions. They will tend to cause minimum ionisation in their passage through the counter gas. If this is taken as about 50 ion-pairs per cm. at atmospheric pressure the ionisation created in the 10 cm. average path will be about 500 ion-pairs or equivalent to a 15 Kev. X-ray. At 3 atmospheres this will be 45 Kev. Again there will be a broad spectrum of pulses but they will lie about the energy region of particular interest.

Particularly with deuteron induced reactions, the presence of neutrons will give heavily ionising knock-on particles from the gas and walls of the counter. For argon these will have an energy about 0.1 times that of the neutron and so may produce rather large pulses.

To obtain an estimate of the relative efficiencies for hard and soft gamma-radiation, consider the counter as having dimensions as follows:

Length 6", diameter 4", window diameter 1.8".

The X-rays will count only if they pass through the window but hard gamma rays must be considered as counting if they strike the counter anywhere within the counting dimensions.

$$\text{Therefore} \quad \frac{\text{Efficiency of detecting soft gamma rays}}{\text{" \quad " \quad " \quad hard \quad " \quad "}}$$

$$= \frac{\text{area of window x mass absorption coeff x mass of argon}}{\text{" \quad " \quad counter x " \quad " \quad " \quad " \quad " brass}}$$

= approximately 1/7.

Thus gammas will be expected to give an order of magnitude more counts than an equal number of soft.ones.

2.4. PREVIOUS EXPERIMENTAL WORK.

A search of the literature shows no sign of any detailed work to determine the existence of soft gamma-radiation from nuclear reactions with light elements, with $Z \leq 20$, although the existence of long lived isomers with large Z, involving transitions with large internal conversion factors, is known. At the time this work was started the results of previous work on energy levels of nuclei with $Z \leq 10$ had been summarised by Hornyak & Lauritsen (1948) and Hornyak, Lauritsen, Morrison & Fowler (1950), and gave no indication of low-lying levels, but showed that close doublets of levels separated by less than 100 Kev. were known in several cases. It was originally proposed to undertake a general survey of reactions in this region, using protons and deuterons of energy up to 800 Kev., but this was not carried out, as will be explained later.

For slightly heavier nuclei, Z between 10 and 20, the level spacing is rather less, and Alburger & Hafner (1950), reporting the known experimental results in this region, give indications of level spacings about 50 Kev. for large excitations, of the order of 8 Mev., in several of the nuclei mentioned. The observations of soft gamma-rays from these nuclei would verify previous work and give information regarding the changes of parity and angular momentum in such transitions.

These levels have been studied mostly by work on neutron absorption. Such techniques give the energy levels about the excitation energy available from the capture of a neutron of zero energy, i.e. the Q value of the reaction. The level spacing is precise, though the absolute value of the excitation may be uncertain to the extent of the uncertainty of the Q-value. These levels have also been studied by gamma-ray excitation curves from proton bombardment. If it is assumed that the reactions are (p,γ), these curves give levels of the resultant nucleus which are high and which may be closely spaced. There may well be a possibility of a soft radiation between two such levels in competition with the transition to the ground state. Work done by Brostrom, Huus & Tangen (1947), Burling (1941), Curran and Strothers (1939), Plain, Herb Hudson & Warren (1940), Swann, Mandeville & Whitehead (1950) and Tangen (1947) indicated that the following reactions would give rise to level spacing about 10-100 Kev. with the energies available from the Cockcroft-Walton particle accelerator in Glasgow.

$Na^{23}(p,\gamma)\ Mg^{24}$; $Mg^{25}(p,\gamma)\ Al^{26}$; $Mg^{26}(p,\gamma)\ Al^{27}$;
$Al^{27}(p,\gamma)\ Si^{28}$; $Si^{29}(p,\gamma)\ P^{30}$; $P^{31}(p,\gamma)S^{32}$

The (p,γ) reactions mentioned in this review may imply that the gamma-radiation may come directly from the capture nucleus, or arise from the daughter nucleus following particle emission. The latter case would still indicate level spacing in the intermediate compound nucleus, but the probability of gamma-emission, particularly of low energy, in competition with particle emission would be very small. Later work on the energy of the gamma-radiation for proton bombardment of P (Grove, Cooper, & Harris, 1950) and of Al (Rutherglen, Rae, & Smith, 1951) indicates that in these reactions at least, the gamma radiation comes from the direct (p,γ) reaction.

However, transitions between close but high levels are rather improbable due to competition from transitions direct to the ground state, unless the latter are forbidden. More promising from an experimental point of view and of greater significance theoretically would be transitions from a low-lying level to the ground state.

Such levels in light nuclei have only been observed by studying the emission of high energy particles in nuclear reactions, using magnetic-focussing spectrometers to give the high resolution of less than 100 Kev., of which other methods are not capable. Using this technique, Strait, Van Patter, Buechner & Sperduto (1951) have studied the reactions $Al^{27}(d,p)\ Al^{28}$ and $P^{31}(d,p)P^{32}$ and found that the proton groups previously known as due to transitions to the ground states were actually doublets, indicating levels in Al^{28} at 31.2 Kev. and in P^{32} at 77 Kev.

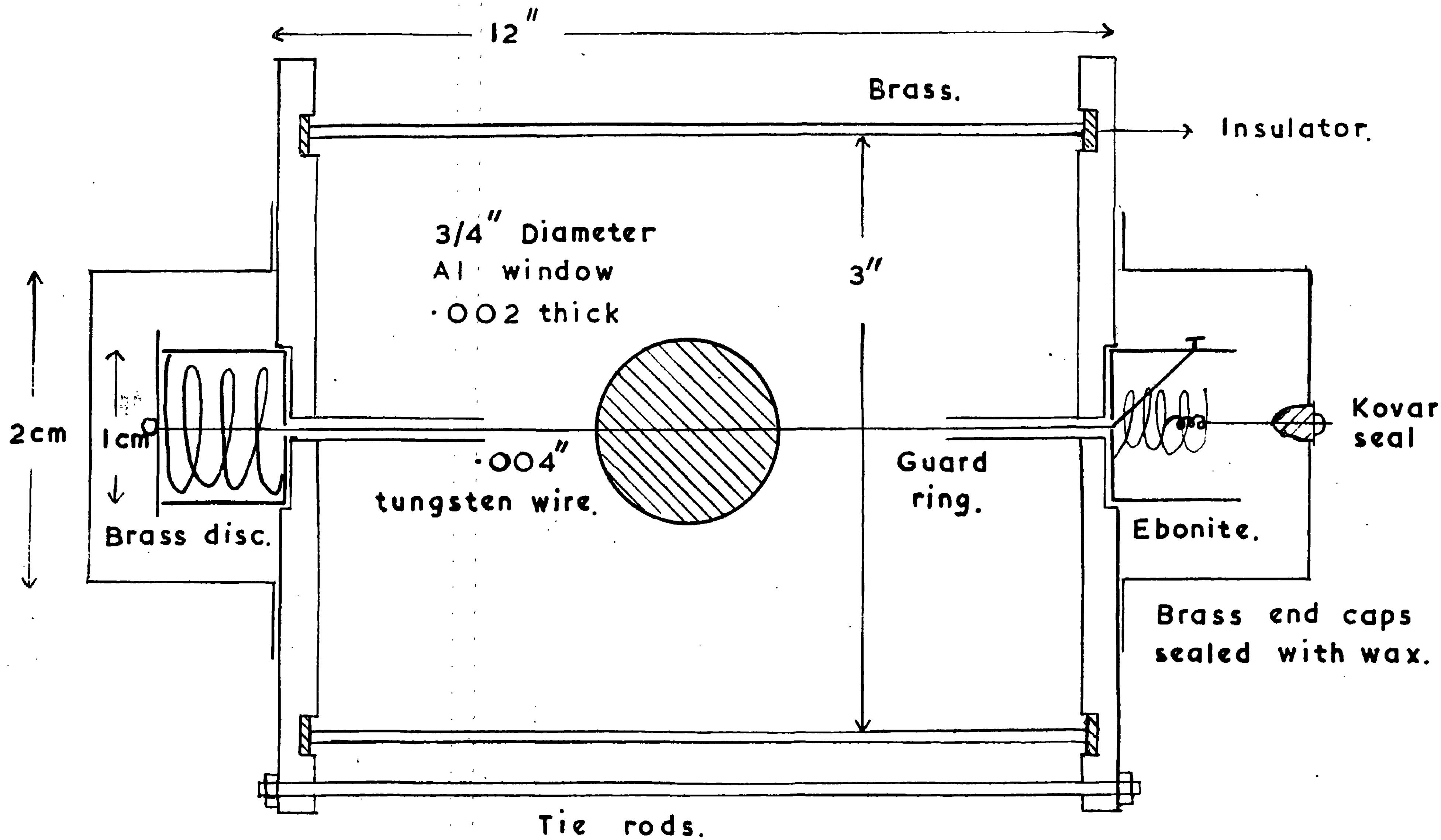


FIG. 3 , COUNTER "A" (NOT TO SCALE.)

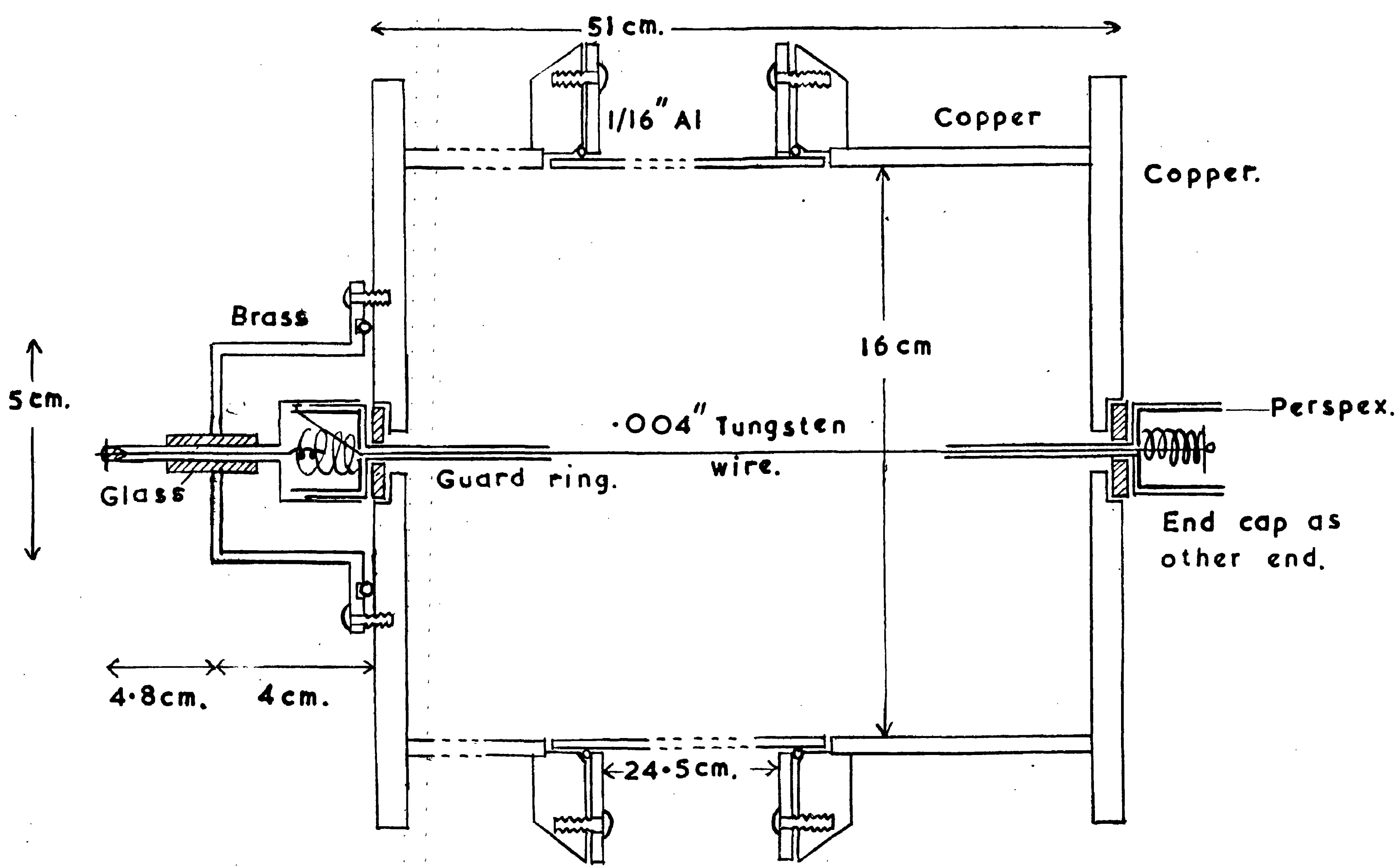


FIG. 4 COUNTER "B" (NOT TO SCALE)

CHAPTER 3.

EQUIPMENT.

In this chapter no description will be given of electronic equipment in general use in the beam and control room of the Glasgow high voltage generator, such as the generator itself, the current integrator, and timing unit, nor will standard T.R.E. equipment such as the 1008 amplifier, scalers and the 5-channel pulse analyser be discussed in detail.

3. 1. GAS-FILLED PROPORTIONAL COUNTERS.

Three of these were used in preliminary work, though only the third (counter "C") was used to obtain the results described later. The other two will be described briefly.

"Counter "A", as shown in Fig.3 was a small brass counter which had been used previously by Dr.R.D. Smith, and was known to be in good working order. This was used to check that the electronic equipment was in correct working order before using the other two counters.

Counter "B", as shown in Fig.4 had been designed to have a large solid angle and work at high pressures of filling gas. As illustrated the window consisted of the aluminium central portion, which had been obtained seamless from a large beaker, and joined to end-pieces with "O" ring connections. It was found that the pulses from the X-rays of a Ge^{71} source give very poor groups which rapidly deteriorated. It was suspected that

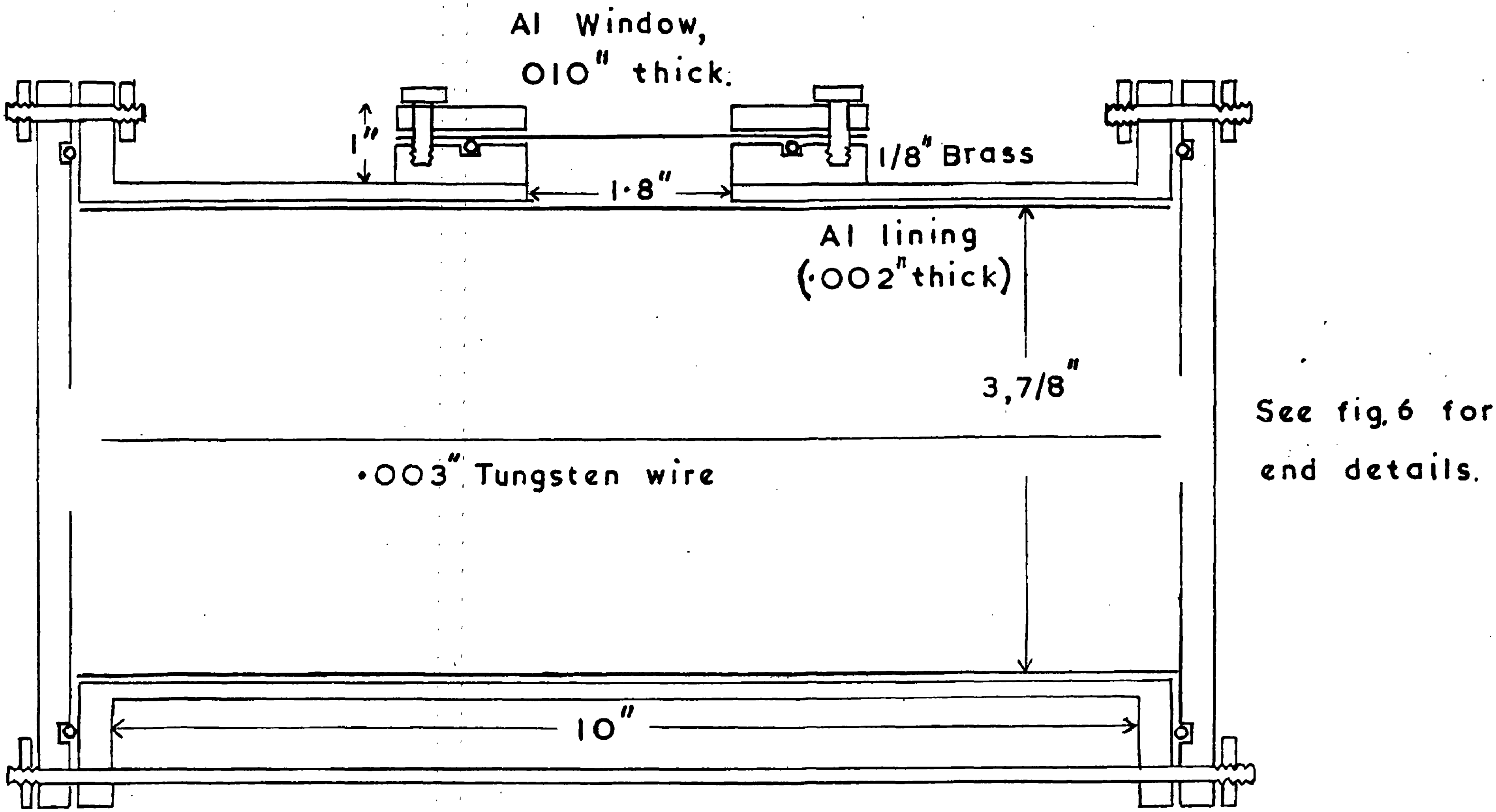


FIG 5 COUNTER "C"

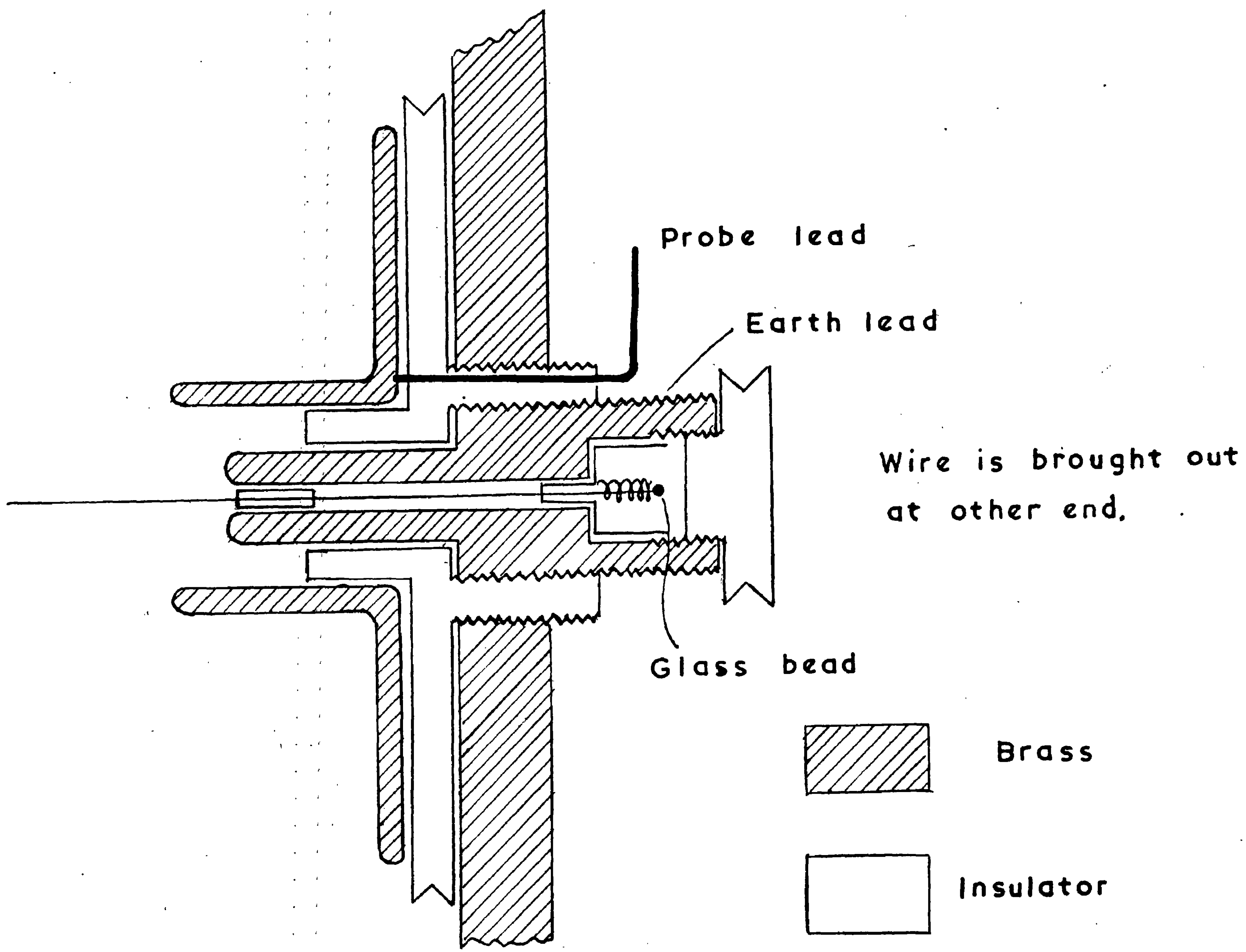


FIG. 6 COUNTER "C" END DETAILS.

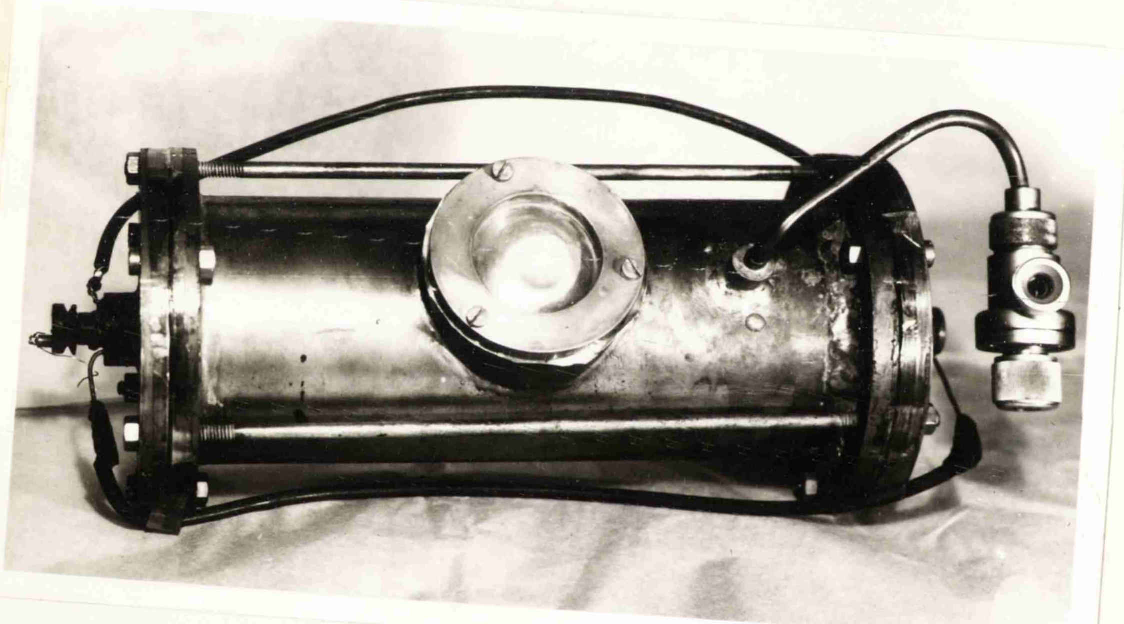


PLATE 1, Counter "C"

this was due either to small leaks in the counter or to poisoning of the gases by vapours coming from insulators, etc., and a hot calcium purifier, with a diaphragm pump to circulate the gas, was fitted to attempt to improve the counter's performance. No improvement was noticed, however. By filling counter "A" with gas from this counter after different lengths of time it was verified that the poor groups and deterioration were partly due to progressive poisoning of the filling gas and partly inherent in the counter itself. Work on this counter was finally abandoned and counter "C" designed and built.

Counter "C", as shown in Figs. 5 and 6 and Plate 1, was designed with a large window able to stand filling pressures of 3 atmospheres. At this pressure it was estimated that gamma-radiation of up to 150 Kev. energy would produce secondary electrons with a range of less than the radius of the counter and thus give proportional counting.

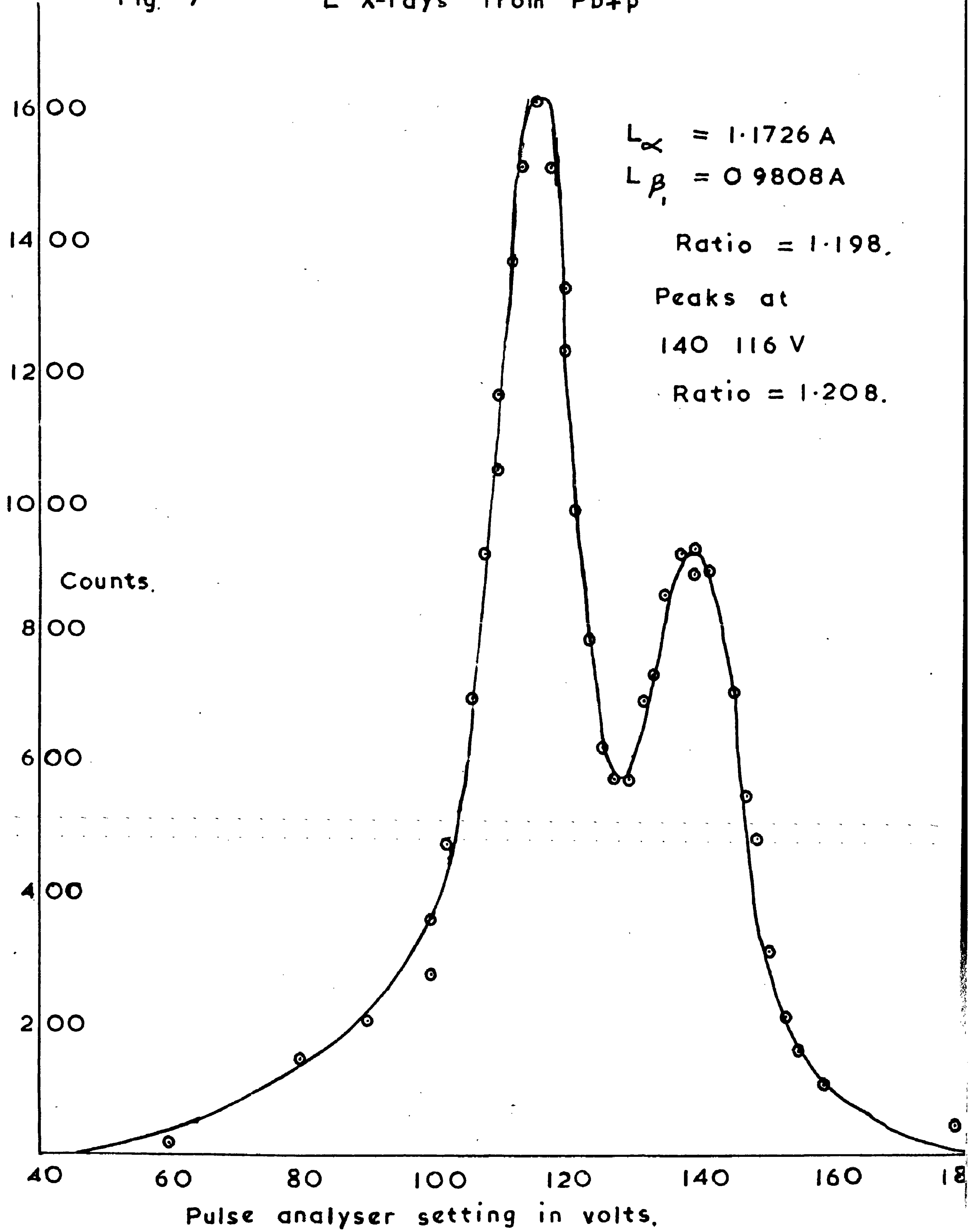
This counter was of the end-corrected type, as developed by Cockcroft & Curran (1951), with a field tube around the guard ring to obviate non-proportionality due to end effects. This tube is maintained at a potential corresponding to its diameter in the counter, which is given by $E_1/E_o = \log (r_2/r_1) / \log (r_3/ r_1)$, where E_1, E_o are the potentials of the field tube and case, and $r_{1,2,3}$ the radii of the wire, the field tube, and the case. In this counter using a wire of diameter 0.003", this ratio is thus 0.725.

As the large window might be expected to distort the field, some time was spent arranging that this would not occur.

E. (Kev.)	u_m A1	u_m A	% absorbed in A of Counter	% passed by A1 window	% passed by A1 and 2.7 cm.A	Apparent Efficiency	Real Efficiency
5	170	475	100	-	-	-	
10	26.3	62	96.5	11.6	4.75	11.3	4.6
15	8.0	19.6	63.7	51.8	39.2	33	24.8
20	3.2	9.2	39	77.0	67.5	30	26.3
25	1.9	5.5	26	85.3	78.0	22.2	21.2
30	1.16	2.8	13.7	91.2	87.5	12.5	11.9
40	0.6	1.2	6.2	95.3	93.0	5.9	5.75
50	0.38	0.80	4.2	97	97	4.1	
60	0.27	0.56	2.97	98	98	2.97	
70	.23	0.40	2.16	100	100	2.16	
80	.204	.35	1.89	100	100	1.89	
90	.188	.28	1.53	100	100	1.53	
100	.176	.24	1.29	100	100	1.29	

TABLE 3. Efficiency of counter "C" for various gamma-ray energies.

Fig. 7 L X-rays from Pb+p



Finally the Al lining was made of thickness 0.002" and covered the gap in the cylinder at the window. It was pierced many times, care being taken that no sharp edges were left, and this ensured that the foil was not disturbed while the counter was being evacuated or filled. The size and number of these holes was known and hence the effect of this foil in reducing the efficiency of the counter could be calculated.

Previous experience with counter "B" had shown that the system would be very liable to pick up the high-frequency supply used for heating the valves of the high tension generator and to overcome this the counter was placed in an insulated box covered with thin aluminium foil. All leads were led shielded into this box which was earthed and the output to the head amplifier was also shielded. As a result the R.F. pick-up was reduced to little more than the noise due to the amplifier. This arrangement also facilitated the use of metal absorbers between the counter and the source, as the voltage on the counter was not exposed.

A table of the efficiency of this counter is given in Table 3. Note that as the region between the window and the Al lining is not part of the countinggas, but acts as an absorber, this will reduce the actual efficiency. The table includes the apparent efficiency, which neglects this effect, and the actual efficiency.

Calibrations carried out with the X-rays from proton bombardment of iron, copper and lead verified that the counter was counting proportionally and Fig.7 showing the results for lead X-rays illustrates the performance of the counter.

The filling normally employed was 15 cm. partial pressure of CH_3 and three atmospheres of A. Gases of commercial purity were used and it was not found necessary to use cold traps or other purifying systems while filling. The size of the pulses due to radiation of a specific energy drifted slightly over a period of days and calibration runs with proton-induced X-rays were carried out for each experimental run. There was little deterioration in resolving power, however, and it was found adequate to refill the counter once a week. It should be mentioned that contamination of the filling system may spoil the performance of a counter filled therefrom. At one stage of the work described, the performance of the counter deteriorated to such an extent that groups were not obtainable, and this was only overcome by dismantling the counter and filling system and thoroughly cleaning them. As other workers had similar difficulties it was concluded that this was due to the presence in the filling system of Xylene, which was being used in liquid scintillation experiments. Great care was therefore taken that no traces of such organic liquids were allowed to enter filling systems used for proportional counters.

3. 2. SCINTILLATION COUNTERS.

These were not used as much as the proportional counters. The detecting system was similar to that used by Drs. R.D.Smith and J.G. Rutherglen, and consisted of a thallium-activated sodium iodide crystal, of dimensions 1 cm. square and thickness

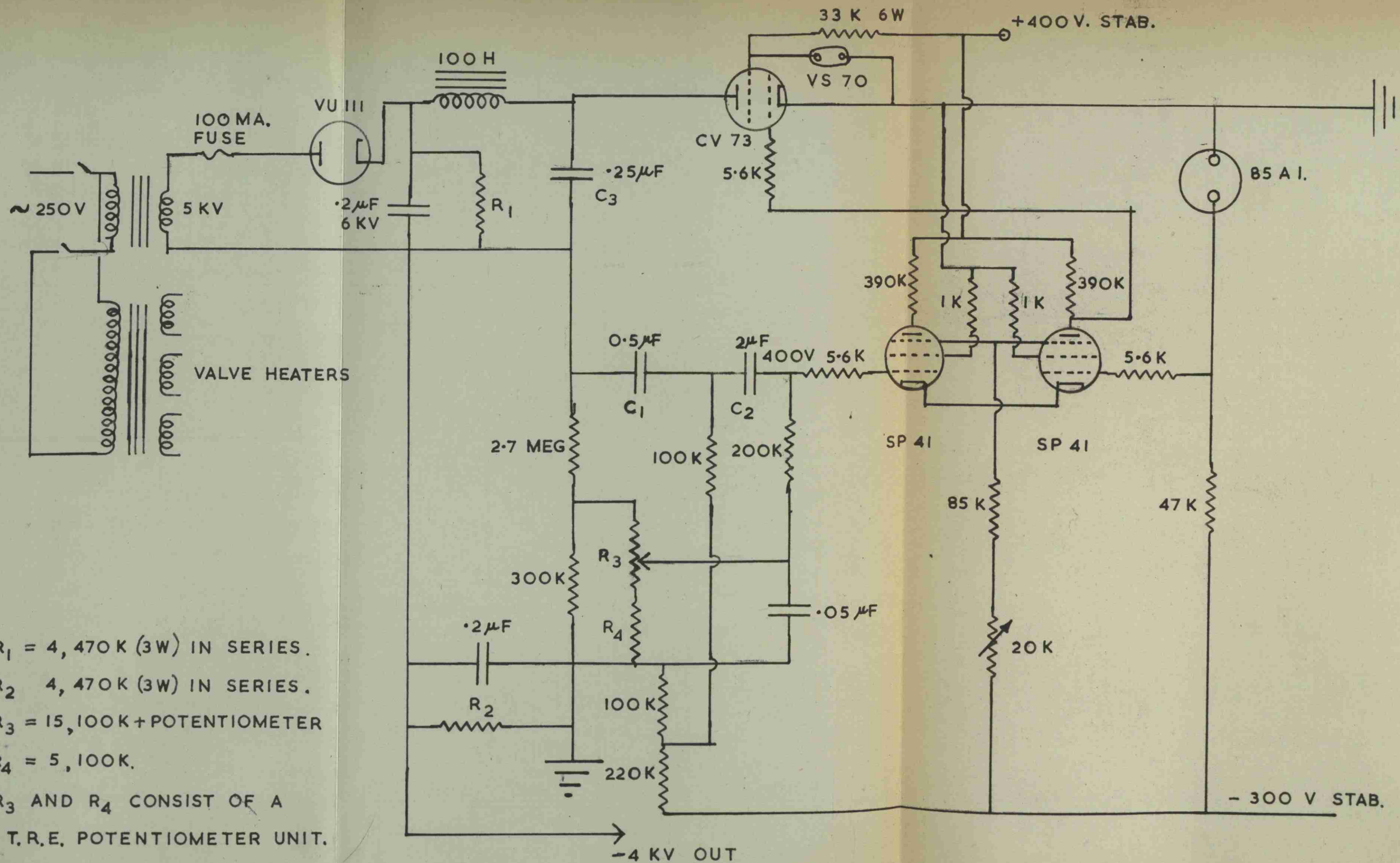


FIG. 8 STABILISED POWER SUPPLY

R_1 = 4, 470 K (3W) IN SERIES.

R_2 4, 470 K (3W) IN SERIES.

R_3 = 15, 100 K + POTENTIOMETER

R_4 = 5, 100K.

R_3 AND R_4 CONSIST OF A T.R.E. POTENTIOMETER UNIT.

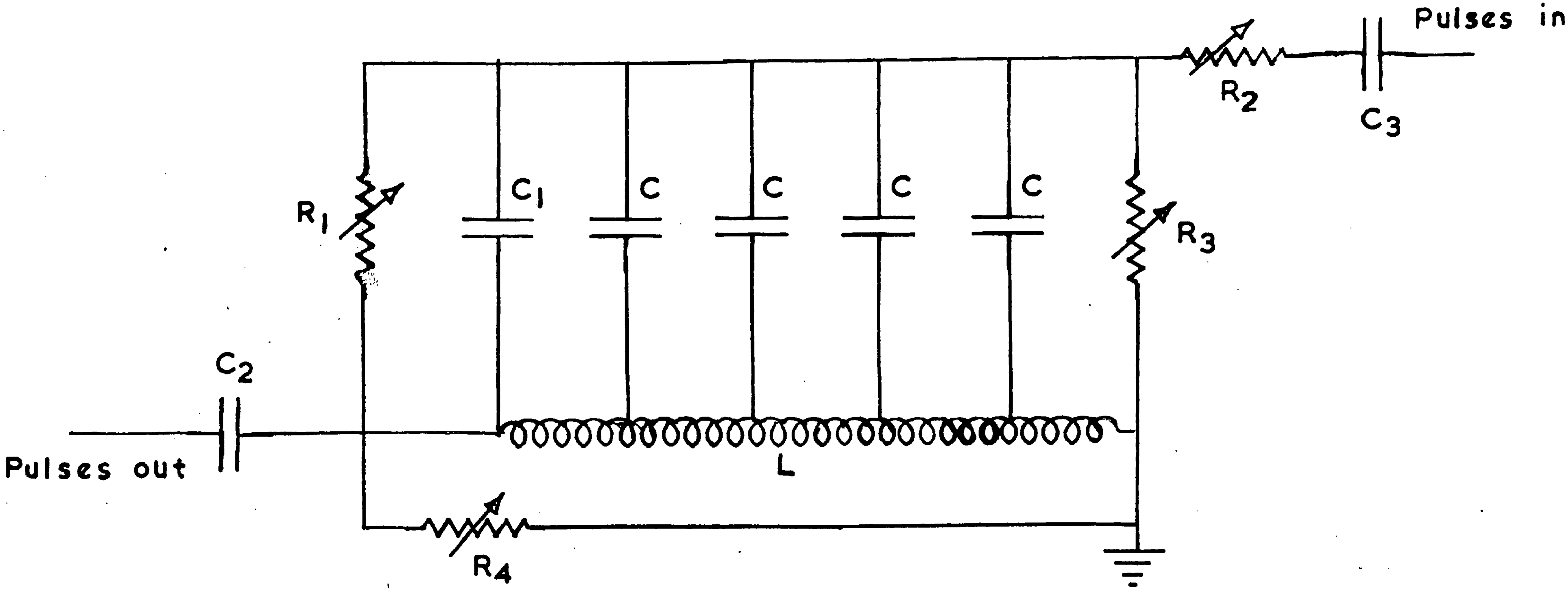
1 mm., immersed in liquid paraffin to prevent deliquescence and the top surface covered with a thin foil of aluminium, to increase the light intensity reaching the photo-multiplier tube. This was the E.M.I. type 5311.

3. 3. POWER SUPPLIES.

The high-tension supply used was obtained from a stabilised 4 Kev. power back due to Dr.R.D. Smith and shown in Fig.8. This is of the series parallel type, in which a smoothed output appearing across C_3 is taken to the H.T. output through the controlling valve, CV 73. The output is also fed through a resistance chain. Part of this voltage is thus fed to the amplifying valves (SP 41s), whose output is applied to the grid of the CV 73, thus resulting in stabilisation. C_1 and C_2 serve to feed ripple to the stabiliser, while stopping the D.C. from reaching it. The reference voltage is the neon stabiliser valve 85 A 1 fed from a -300 volt supply, the screen voltage of the CV 73 is maintained by the VS 70 from a +400 volt supply, and the output voltage is determined by the setting of the potentiometer $R_{3,4}$ which is a standard T.R.E. potentiometer.

3.4. AMPLIFIER.

The amplifier used was the T.R.E. type 1008 with high-frequency head amplifier, with the modification that the heater supply to the valves of the main amplifier was fed separately, in order that D.C. might be used to reduce hum from A.C. heating.



$C = 2700\ \mu F$; $C_1 = 1000\ \mu F$; $C_2 = \cdot 01\ \mu F$; $C_3 = 10\ \mu F$.

$R_1 = 500\ \Omega$; $R_2 = 1000\ \Omega$; $R_3 = 200\ \Omega$; $R_4 = 20{,}000\ \Omega$.

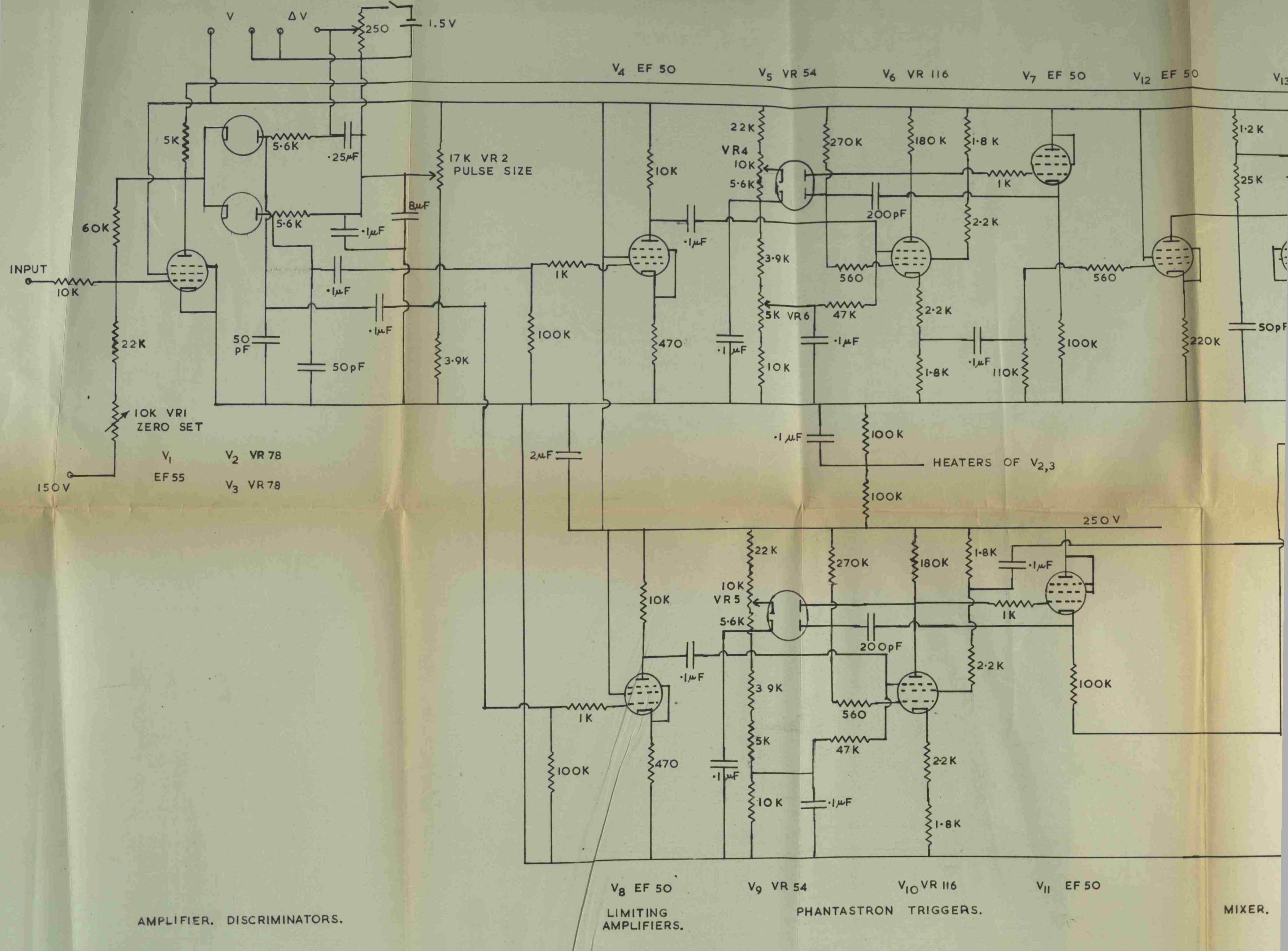
L consists of 5 sections, each of about 50 turns of 16 S.W.G. copper wire on a former, diameter 2"

FIG. 9 DELAY LINE.

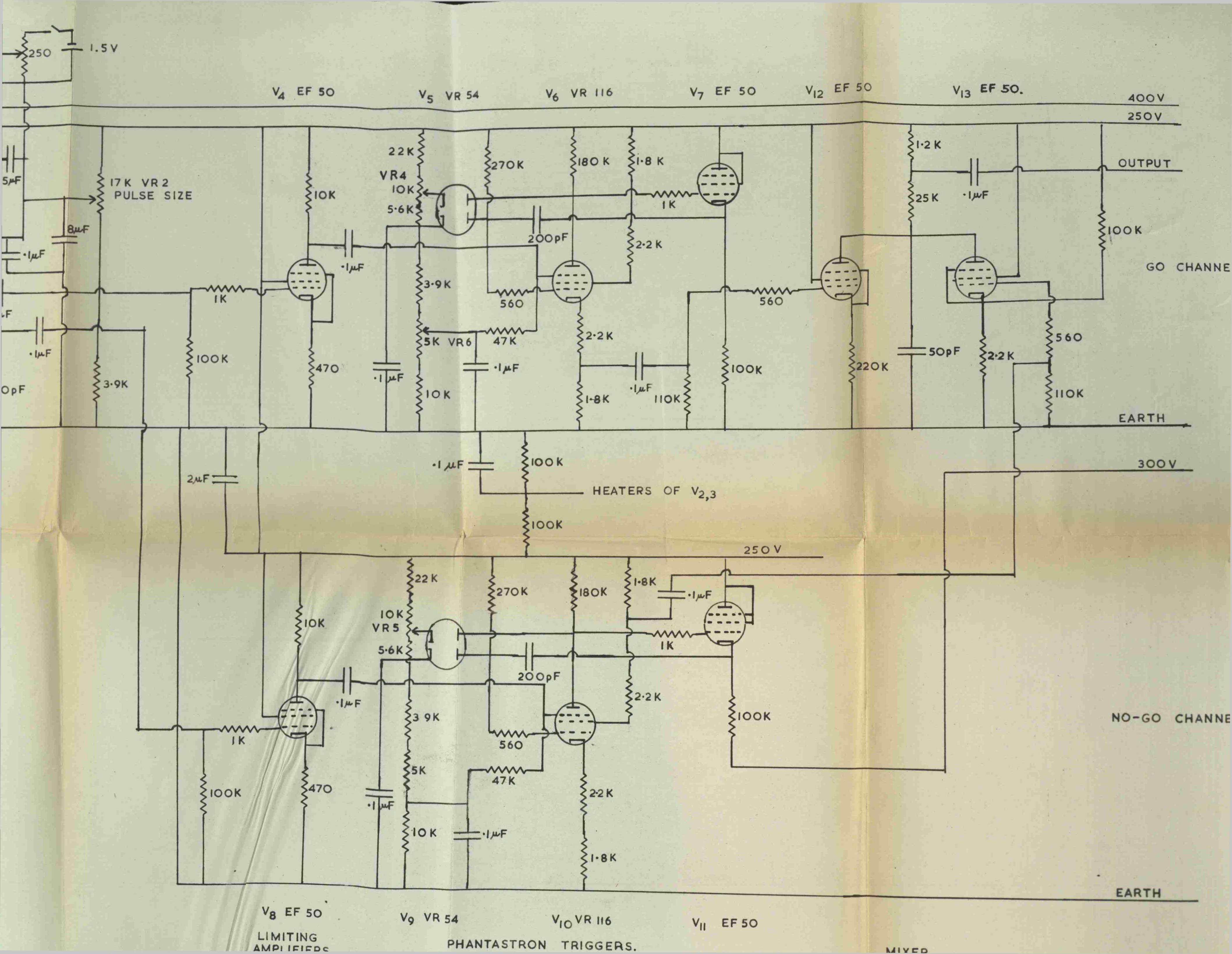
3. 5. PULSE-SHAPING.

As discussed by Wilkinson (1950(b)) the pulses from proportional counters are fairly long (of the order of 100 usec), due to the action of positive ion collection. For fast counting rates this may result in distortion of the spectrum due to pulses lying on top of one another. To overcome this difficulty of slow pulse formation, it is desirable to sharpen the pulses. This may be done by using small time-constants of differentiation and integration before the main amplifying stage, and the output pulses will then have a width about that of these time constants. If the rate of rise of the pulses is independent of the pulse size, as is usually the case with proportional counters, the spectrum will not be distorted, but there is a danger of overshoots at the back-edge of the pulse, which may be undesirable.

It is therefore more satisfactory to use a delay line, as discussed in Elmore & Sands (1949). By using a delay line, the original pulse has imposed on it another pulse similar in shape but of opposite sign which has been delayed by the time taken to travel down the line. This second pulse is usually attenuated by the line. For a square wave this results in a sharp pulse of width t, the time taken for the pulse to travel down the line. A similar effect occurs with a pulse with a sharp leading and slow back edge. In the work described, the delay line with lumped parameters shown in Fig.9 was used, having a characteristic time of about 2 usec.



INPUT
10K
60K
22K
10K VR1
ZERO SET
150V
V
ΔV
250
1.5V
5K
5·6K
·25μF
5·6K
·1μF
8μF
·1μF
·1μF
50 pF
50pF
17K VR2
PULSE SIZE
3·9K
1K
100K
2μF
V_1 EF55
V_2 VR78
V_3 VR78
V_4 EF 50
V_5 VR 54
V_6 VR 116
V_7 EF 50
V_{12} EF 50
10K
470
·1μF
22K
VR4
10K
5·6K
3·9K
5K VR6
10K
·1μF
270K
200pF
560
47K
·1μF
180K
2·2K
1·8K
1·8 K
2·2K
1K
·1μF
110K
100K
560
220K
1·2K
25K
50pF
·1μF
100K
HEATERS OF $V_{2,3}$
100K
250V
10K
1K
100K
470
·1μF
22K
10K
VR5
5·6K
3 9K
5K
10K
·1μF
·1μF
270K
200pF
560
47K
180K
2·2K
1·8K
1·8K
·1μF
1K
2·2K
100K
V_8 EF 50
LIMITING
AMPLIFIERS.
V_9 VR 54
V_{10} VR 116
V_{11} EF 50
PHANTASTRON TRIGGERS.
AMPLIFIER. DISCRIMINATORS.
MIXER.



250
1.5V
V_4 EF 50
V_5 VR 54
V_6 VR 116
V_7 EF 50
V_{12} EF 50
V_{13} EF 50.
400V
250V
OUTPUT
GO CHANNE
17K VR2
PULSE SIZE
8μF
·1μF
22K
VR4
10K
5·6K
270K
180K
1·8K
1K
1·2K
25K
100K
200pF
2·2K
3·9K
560
5K VR6
47K
470
10K
2·2K
1·8K
110K
220K
50pF
EARTH
300V
·1μF
2μF
HEATERS OF $V_{2,3}$
250V
VR5
3 9K
NO-GO CHANNE
V_8 EF 50
V_9 VR 54
V_{10} VR 116
V_{11} EF 50
LIMITING
AMPLIFIERS
PHANTASTRON TRIGGERS.
MIXER

Variable resistances were adjusted to ensure that the line was suitably matched at the input and output and that the reflected pulses were attenuated correctly to prevent over shooting.

3. 6. PULSE ANALYSERS.

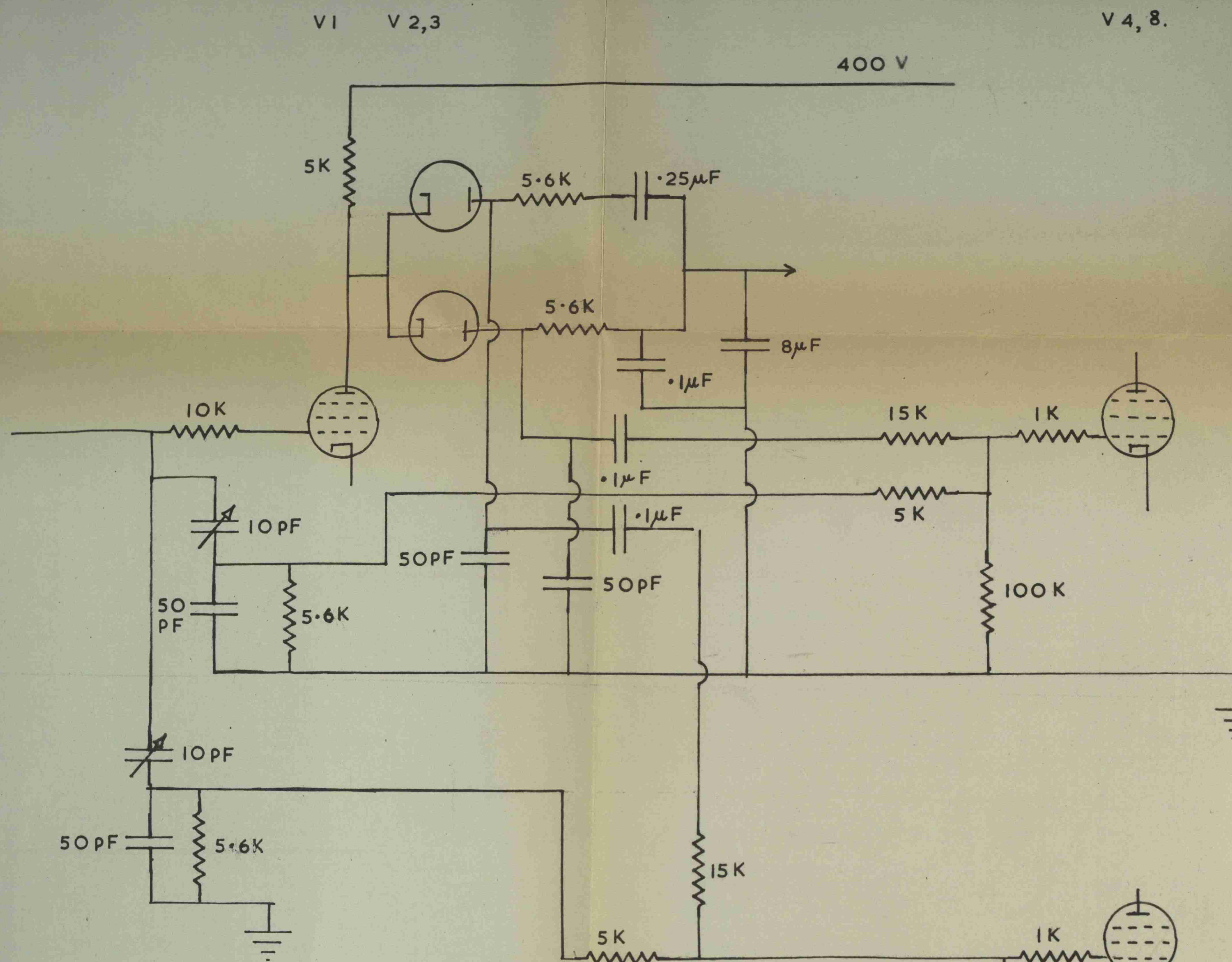
When this work was started it was decided, rather than build a multi-channel kick-sorter, to use one involving a single channel only. Such an instrument requires stabilised power supplies which were available in the control room of the proton accelerator and should be able to deal with a high counting rate to give reasonable statistics. To do this the circuit shown in Fig.10 was used, having been originally designed by Dr.R.D. Smith, but modified during the course of this work.

The output pulses from the 1008 amplifier are fed into V_1 and amplified by a factor of about four to up to 200 volts. This valve normally has its anode set by the zero set potentiometer VR 1, at the same voltage as the 250 volt supply, to which the positive terminal of the amplitude meter is connected. The other terminal is connected to the anode of the diode V_3, and hence the meter reads the voltage across the diode, which will be the smallest pulse size which can thus enter the "GO" channel. The sub-standard voltmeter used may be read to 0.2 volts which is therefore the degree of amplitude discrimination.

The anodes of the diodes are held at V and $V + \Delta V$ volts below their cathodes, where V is the reading of the meter and ΔV is the channel width supplied by a 1½ volt battery, monitored by a meter. Thus pulses greater than V can pass the discriminator and fire the "GO" channel, those greater than $V + \Delta V$ firing the "NO-GO" channel as well. By taking the outputs of the two channels in anti-coincidence, the result will be a count if and only if the original pulse had a voltage between V and $V + \Delta V$. Both channels are similar, a limiting amplifier firing a cathode coupled phantastron trigger circuit, which gives square pulses about 10 μsec. long. This run down time is determined by the time constant of the 200 pf condenser and 100 K resistance in the grid circuit and variable resistors VR 4,5. VR 6 adjusts the triggering potential of the "GO" channel and is set so that, if $\Delta V = 0$, both channels trigger simultaneously.

The outputs of the two channels are fed into the mixer circuit. In this V_8 is normally conducting and V_9 cut off. Thus, if a negative pulse from the "GO" channel appears on the grid of V_8 this will be cut off and a pulse appear at the output, unless at the same time a positive pulse from the "NO-GO" appears on the grid of V_9 making it draw current instead.

When this kick-sorter was put into operation it was found that certain modifications were required for satisfactory results. There was a zero error due to the finite voltage required to fire the phantastrons, and this was reduced by increasing the bias on the grids of $V_{6,10}$ as far as possible. This involved increasing the suppressior grid resistances from the original 2.2 K to 10 K. There was a tendency for self oscillation if this bias was made too great and to ensure maximum sensitivity consistent with this a variable resistance was also included in the "NO-GO" channel.


V1
V 2,3
V 4, 8.
400 V
5K
5·6K
·25μF
5·6K
8μF
·1μF
10K
15K
1K
·1μF
5K
·1μF
10pF
50PF
50pF
100K
50
PF
5·6K
10pF
50pF
5·6K
15K
5K
1K

When this had been done it was found that, in spite of the 50 pf condensers from earth to the anodes of the discriminating diodes, spurious pulses from the anode-cathode capacitance of these valves were large enough to trigger the channels, particularly for large amplitudes of input pulses. The size of these spurious pulses was therefore reduced by feeding the grid of $V_{4,8}$ with a portion of the input pulse out of phase with that coming through the diodes but passing through similar RC combinations, where the diodes were represented by variable capacities of about 10 pf. This reduced the spurious pulse size considerably. These modifications are shown in Fig.11.

The work described was started with this pulse analyser but only a few experiments were carried out with it before the T.R.E. five channel pulse analyser was made available to the Glasgow Department of Natural Philosophy and most of the later work was carried out using it. This instrument has been described by Cooke-Yarborough, Bradwell, Florida & Howells (1950). In principle it counts all pulses greater than a set size and divides them in four channels whose upper limits have to be set and one which takes all pulses greater than the top limit. As a result all pulses greater than the lower level fire a trigger circuit which brings the actual analysing and counting circuits into action. Following this there is a dead time during which no further pulses are counted. For this analyser this dead time is about 60 u sec, and this restricts the total number of counts including those in the top channel with no upper limit. Thus a background of pulses higher than those which are being

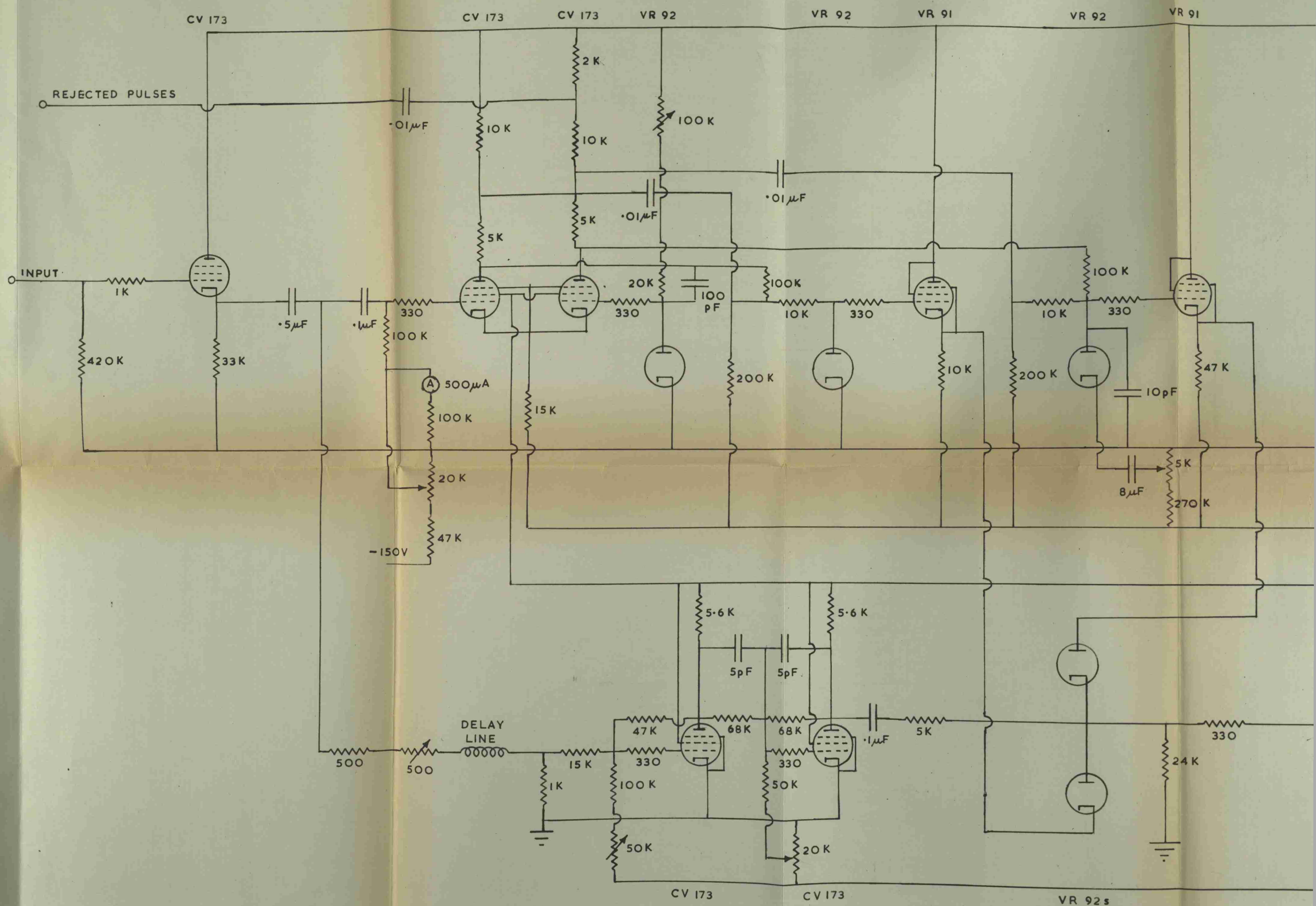
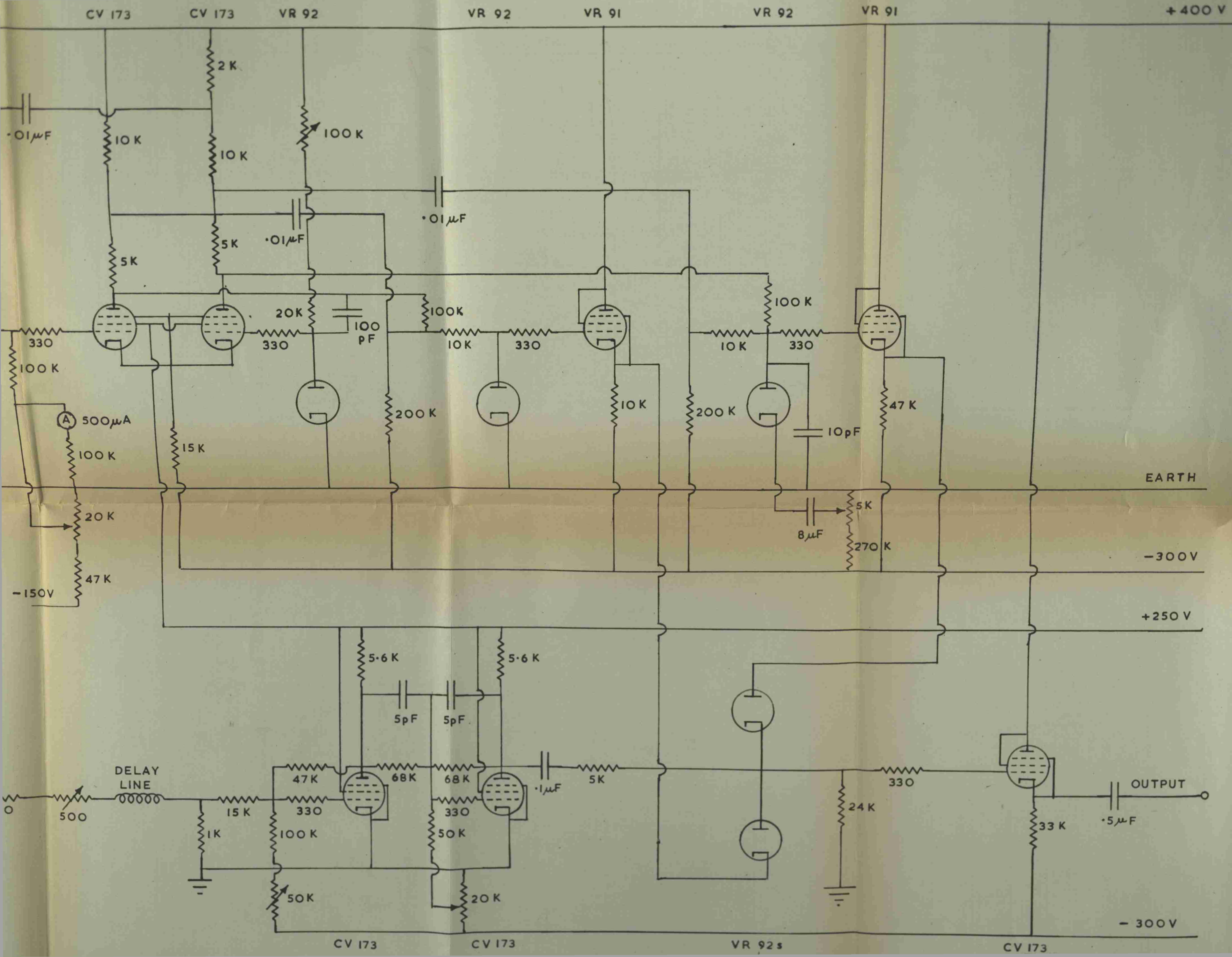


FIG. 12 LOW PASS DISCRIMINATOR UNIT.


CV 173
CV 173
VR 92
VR 92
VR 91
VR 92
VR 91
+400 V
·01μF
10 K
2 K
10 K
100 K
·01μF
·01μF
5 K
5 K
20 K
100 pF
100K
100 K
330
330
10 K
330
10 K
330
100 K
500μA
100 K
15 K
200 K
10 K
200 K
47 K
10pF
EARTH
20 K
5K
8μF
270 K
47 K
-150V
-300V
+250 V
5·6 K
5·6 K
5pF
5pF
DELAY
LINE
47 K
68K
68 K
·1μF
5K
330
OUTPUT
500
15 K
330
330
24 K
33 K
·5μF
1K
100 K
50K
50K
20 K
- 300V
CV 173
CV 173
VR 92s
CV 173

analysed will reduce the counting rate available. To overcome this it is desirable to prevent pulses with amplitudes greater than those being counted in the analysing channels reaching the trigger circuit and this led to the development of the low-pass discriminator, described later.

In using this pulse analyser it is necessary to set the channel widths and to determine their values. This was done, in the first place, by using a pulse generator and setting the channel heights in terms of the single channel kick-sorter. Later, when doubts arose about the zero level of the latter, this procedure was replaced by taking the output of a pulse generator through a resistance chain and hence obtaining accurate relative pulse sizes with which the analyser was adjusted. The relative channel widths were verified experimentally by taking readings from a radioactive source such as radium D, and using different D.C. levels in the analyser. This meant that the same part of the spectrum would fall in different channels on different readings and thus the relative numbers of counts gave the relative widths of the channels.

3. 7. LOW-PASS DISCRIMINATOR.

As mentioned before, the comparatively long dead-time of the T.R.E. 5 channel pulse analyser makes it desirable to prevent all pulses greater than those being counted reaching the input of the analyser. To do this, the circuit as shown in Fig.12 was used. In this, the output of the main amplifier is fed through a cathode follower to prevent over-

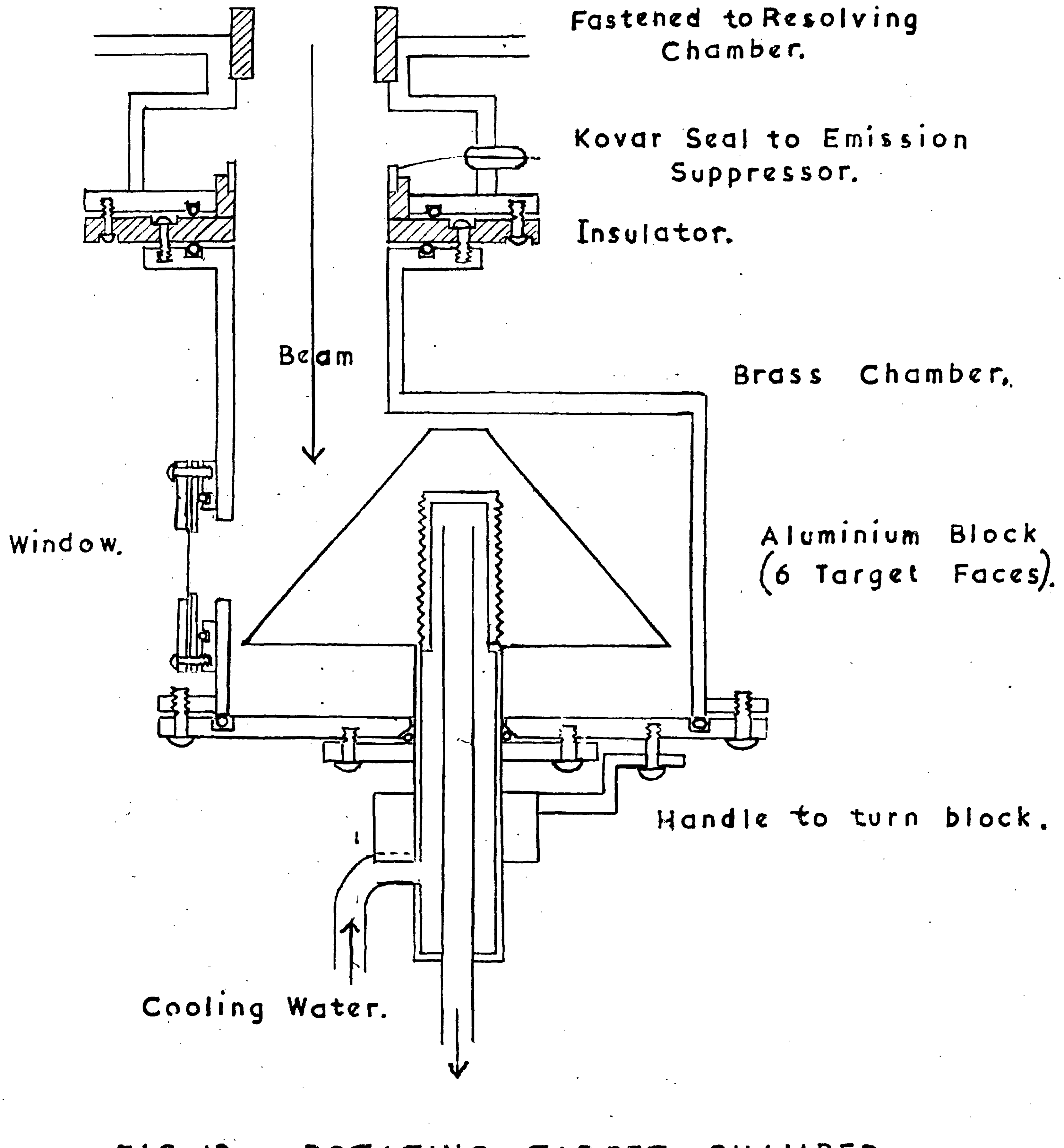
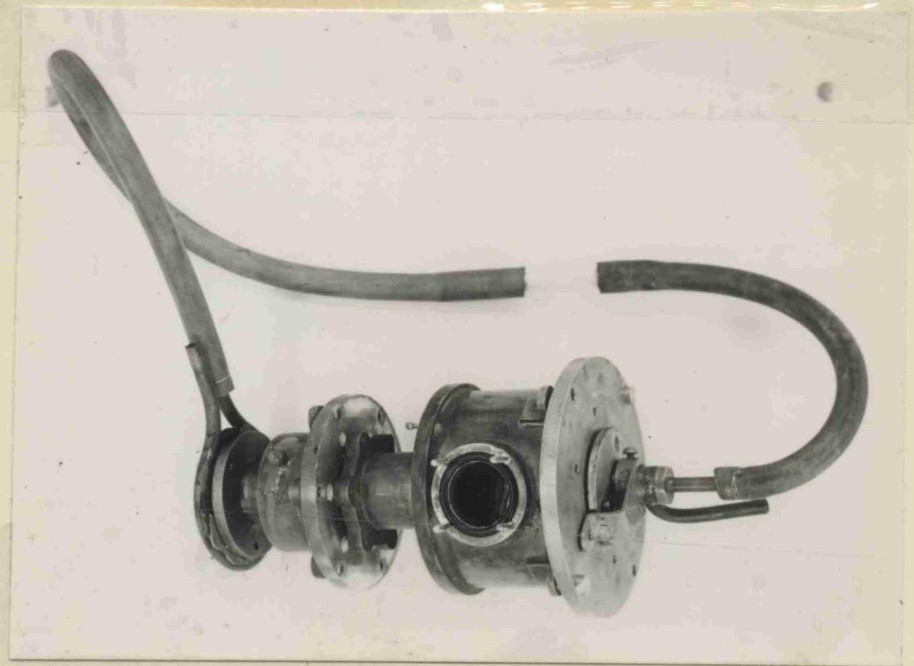
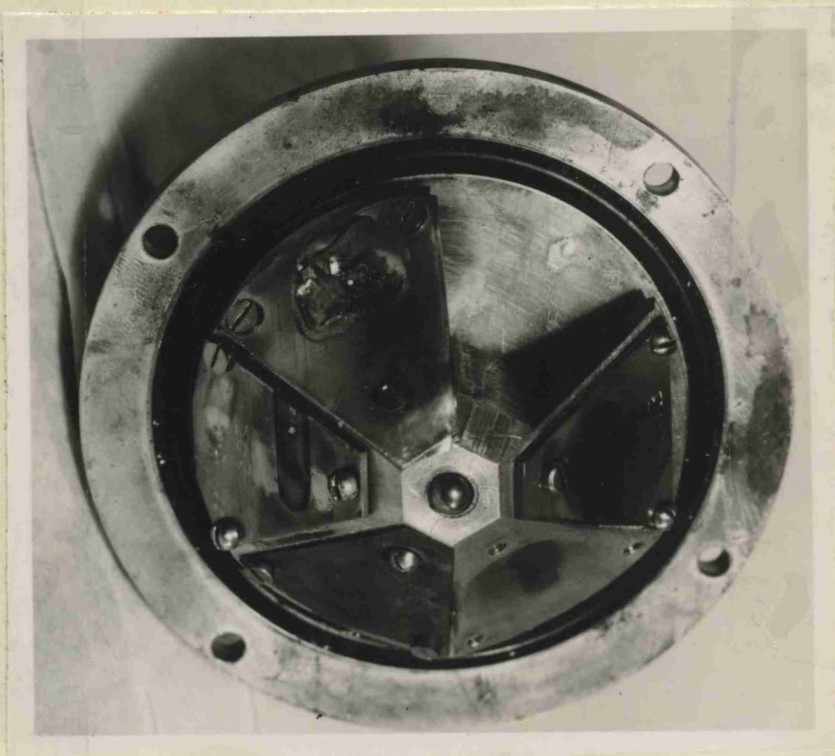


FIG. 13 ROTATING TARGET CHAMBER.





PLATES 2 and 3, Rotating Target Chamber

loading of the amplifier, and then fires a trigger circuit, whose triggering amplitude is adjusted so that the width of the top channel of the pulse analyser, as restricted by this circuit, is about that of the other channels. Any pulse greater than this size then produces a 5 u sec blanking pulse which is applied to a double diode clamp. This then prevents the original pulse from reaching the output of the system. To give the trigger time to fire, it is necessary that the pulses must be delayed before reaching the gate and this is done by passing them through a length of delay line, followed by a fed-back amplifier to off-set the attenuation. The circuit reduces the pulse amplitude by about 40% but is linear and does not have any zero error. The introduction of the delay line provides facilities for triggering C.R.O.s, etc., from the output of the cathode follower and this was made use of in later work.

3. 8. ROTATING TARGET CHAMBER.

The most convenient source for calibration purposes in this work was the bombardment of targets by energetic protons from the Cockcroft-Walton accelerator. This, however, involves changing targets between the calibration and the experimental run, and it is most undesirable to have to open the target chamber and admit air during this change. To avoid this difficulty, the rotating target chamber shown in Fig 13 and Plates 2 and 3, was used. This is essentially a six-sided aluminium block screwed on to a brass rod which, by using a rubber "O" ring as a gasket, could be rotated in the target chamber without admitting air. Suitable calibration and experimental targets could be fastened to the various faces, and the blank face was available for background runs. To reduce soft gamma radiation as little as possible in intensity, it is necessary to have a thin window on the target chamber. This must be able to withstand variations of pressure of up to one atmosphere and should be fairly large. At first a foil of cellophane 0.002" thick was used but this disintegrated under pressure. It was replaced by 0.015" of "Styrene" which, however, was found to leak. Finally a foil of 0.005" of cellophane was used and this proved satisfactory.

CHAPTER 4.

4. EXPERIMENTAL PROCEDURES

This chapter contains an outline of the various experimental techniques used in this work.

4. 1. WORK WITH GAS-FILLED PROPORTIONAL COUNTERS.

It was soon realised that a simple analysis of pulse size would not be capable of resolving any soft radiation from background, for the latter was large and also variable with time, showing large fluctuations as well as a steady increase. To determine the soft radiation a method using absorbing foils was used. The general principle of this technique was that successive readings were taken with and without suitable absorbing foils between the target and the counter. The difference between these successive counts was then taken as being due to the soft gamma radiation, and this procedure could be carried out at different settings of pulse analysers being used.

At first a foil of tin, thickness 0.017" was used, but it was realised that this would also reduce beta-radiation from either N^{13} of Al^{28}, in the case of the deuteron bombardment of Al. To overcome this, pairs of foils were used, of equal surface densities, but different materials, so that their absorption of the soft-gamma radiation was very different, but that of the beta radiation very similar. The first ones used were 0.017" of Sn, and 0.048" of Al, but these were soon

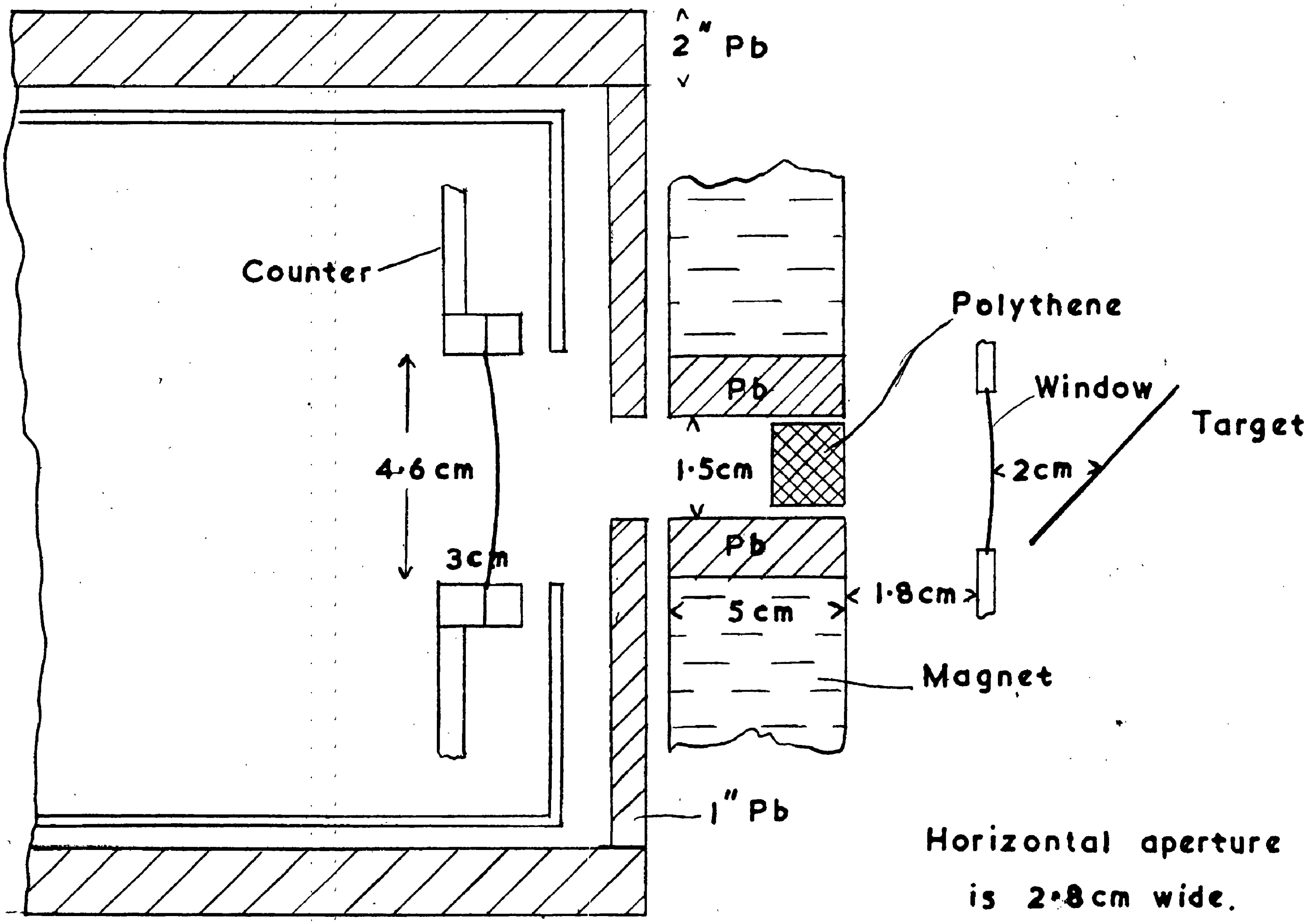


FIG. 14 SHIELDING OF COUNTER (NOT TO SCALE)

replaced with 0.0025" of Pb and 0.011" of Al. As there was a steady increase in the background, each setting of the pulse analyser involved two sets of two readings, one with the Al foil, and then the Pb foil, and the other with the Pb foil first. This gave two sets of difference counts and the mean of these was taken.

Since some of the background came from the beta-radiation mentioned above, it was desirable to shield it off, and this was done by the use of perspex or polythene absorbers and by using a deflecting permanent magnet to remove any electrons which might penetrate these absorbers. The effect of these methods was verified by studying the beta-spectrum after the beam had been cut off following a run, and the absorption of the gamma-radiation by the polythene examined by studying its effects on X-rays from the proton bombarment of tin,

Some time was spent analysing the large background. It was concluded that much of the background arose from the resolving chamber of the accelerator, where the particle beam struck the sides, and particularly from the "d on d" reaction when deuteron induced reactions were being studied. This would explain the slow increase in background counts during runs and why the background should vary from run to run, as did the time necessary for a run. As a result of this analysis, the counter was finally arranged as shown in Fig.14, the counter itself being surrounded with 2" - 3" of lead. Great care was taken during runs that the accelerator and target chamber were carefully aligned and that the beam did not strike the walls, and the target chamber and counter were placed as far as convenient from the resolving chamber. Such precautions reduced the background to such an extent that it was possible to carry out runs for which the spectrum due to the soft gamma-radiation was clearly visible over the background. It was not, however, always possible to reduce the background as much as this.

The standard procedure when using gas-filled proportional counters was to carry out a calibration, using a natural source such as Ge^{71} or RaD, or X-rays from the proton bombardment of suitable targets such as $BaCl_2$, Sn or Mo. The pulse analyser was set to count in the region to be covered, as indicated by the calibration, and successive counts taken with, for example, the Pb, Sn, Sn and Pb absorbers. The pulse analyser setting was then altered and a further group of counts taken. This procedure ensured that systematic variations of the background during the experiment were not involved when the counts with the Pb absorber were subtracted from those with the Al absorber to give figures which were taken as due to soft gamma radiation of an energy corresponding to the pulse analyser setting. A further calibration was usually taken at the end of the experiment to ensure that there had been no drifts of the analyser, amplifier or other equipment during the run. To keep the background reasonable constant, the beam current was maintained steady, as it was found that rapid drifts of the beam resulted in variations of background even if the integrated resolved beam current was the same during each run. For this reason a note of the time taken for each run was usually noted and any runs showing marked deviations in this were discarded.

4. 2. WORK WITH SCINTILLATION COUNTERS.

The techniques used here were similar to those with the gas-filled proportional counters. Shielding was rather easier in this case, but it was found when studying the reaction P^{31} (d,p) P^{32} that the high-energy background was exciting fluorescent X-rays in the lead shielding and therefore the absorbers used were of Sn and Al rather than of Pb. The crystal was also shielded from all lead by 0.032" of Sn foil to prevent this. Generally it was found that, owing to the lower resolution of the scintillation counter and its efficiency for detection of background the results obtained did not show the presence of soft gamma radiation as clearly as did the proportional counter results. A thin crystal, about 0.3 m.m. was prepared by rubbing down a thicker crystal with a damp cloth, to attempt to reduce background. This was partly successful but still did not give results comparable with the proportional counter.

4. 3. CRITICAL ABSORPTION METHODS.

These were used to verify the energy of the radiation found by other methods. Solutions were made up containing equal masses/cm^2 of the elements whose K-absorption edges lay near the estimated energy of the radiation. The strengths of the solutions were calculated to give an optimum increase of absorption in going through the absorption edge. Following a calibration the pulse analyser settings were then arranged so that the assumed energy corresponded to the centre of the counting channels, and counts taken of the spectrum with the different absorbers between the target and the counter. A decrease in the total counts in the four channels was taken as due to the absorption of the soft gamma radiation whose energy then was given to within 1 or 2 Kev.

4. 4. PULSE PHOTOGRAPHY.

The methods given above were used for the study of the 32 Kev. gamma-radiation from the reaction $Al^{27}(dp)\ Al^{28}$, in which results by other workers had given an indication of the energy at which the radiation was to be expected. Even with this information, the difficulties of background rendered experiments very slow and laborious, and it was felt that the methods would not be directly applicable to a general study of other reactions in which there was no indication of the possible existence and energy of soft-gamma radiation, It was desirable to develop some technique which would be capable of determining the existence of low energy gamma-radiation from a reaction, with an approximate indication of the energy.

To do this, the technique of pulse photography as outlined below was developed and its value determined by comparing the results obtained with it from the reaction Al^{27} (d,p) Al^{28} to those obtained by other methods.

The pulses were fed into a cathode ray oscilloscope (T.R.E. Monitor C.R.O. type 1000), from the output of the low-pass discriminator, the C.R.O. being triggered by the input. Since the signal proper has a delay of 3.5 u secs. this results in the signal appearing in the centre of the screen.

An oscilloscope camera was attached to the screen and a series of exposures taken at different screen intensities and numbers of counts, using R55 film. When developed the more suitable ones were examined for evidence of maxima of intensity denoting low-energy gamma radiation. The best screen intensity and number of counts required was obtained by experience, but it was usual to take ten or a dozen exposures as the work and time involved in taking extra exposures was small compared with that in setting up the equipment and developing the film.

To see whether or not the method was quantitative some of the exposures were enlarged on to quarter-plate size lantern plates and examined on a microphotometer. The results were not satisfactory due to the graininess of the plates and the uncertainty of the position of the base-line. However, no attempt was made to develop the technique to give numerical results as it was felt that the methods described above were more suitable and were capable of giving intensities. This method was used only to determine the existence and approximate energy of soft gamma radiation in nuclear reactions, which

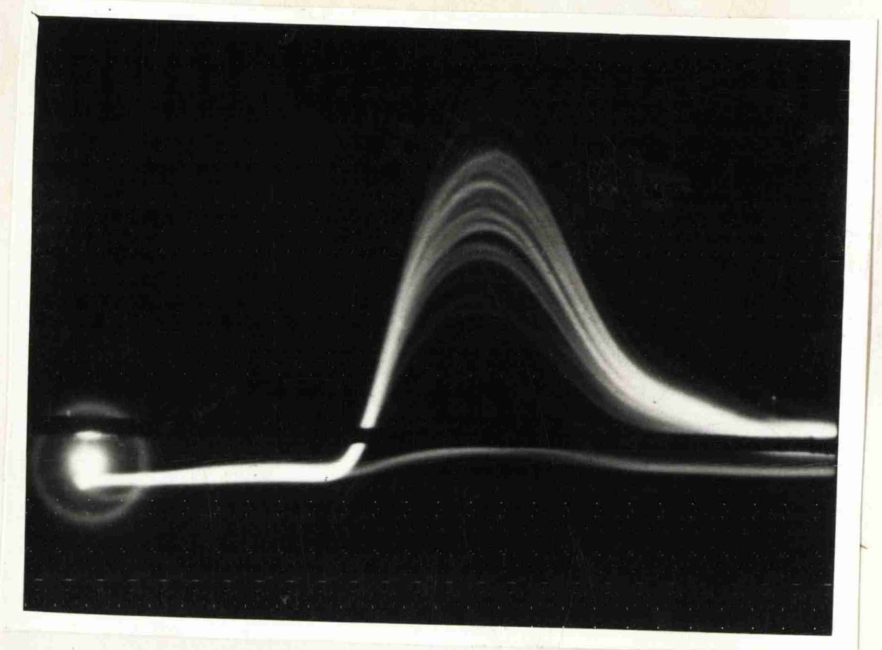


PLATE 4, Gamma-radiation from RaD.

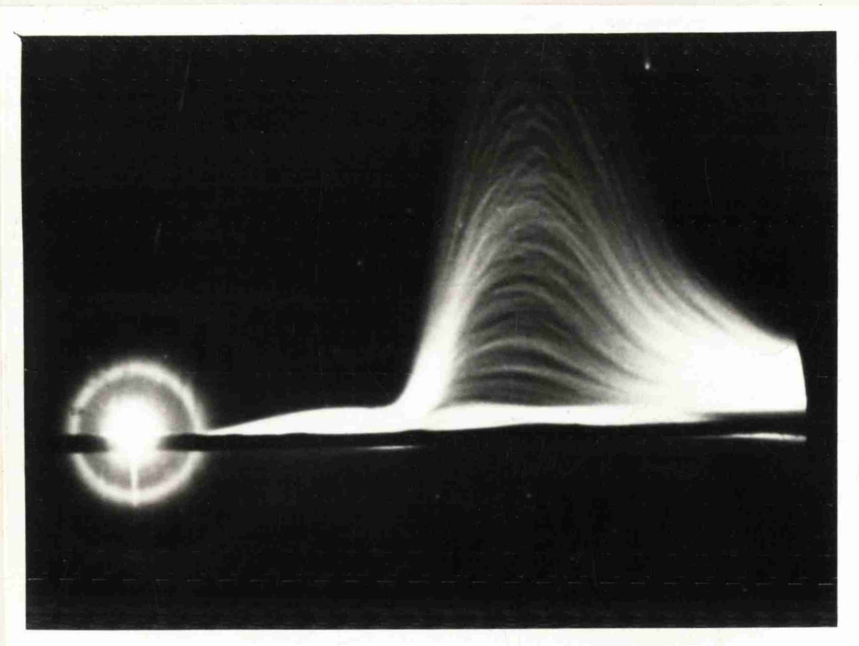


PLATE 5, Radiation from $Al^{27}(d,p)\ Al^{28}$

could then be analysed more fully by pulse analyser methods.

Typical results are shown in Plate 4, which illustrates the results using the gamma radiations from a RaD source in the region 10-20 Kev. Plate 5 shows how the radiation from the reaction Al^{27} (d,p) Al^{28} verifies the value of this technique. A rough comparison with a similar figure taken with Sn X-rays as a calibration gives the energy as between 30 and 35 Kev., which is an adequate degree of precision for the purpose for which this technique was to be used.

CHAPTER 5.

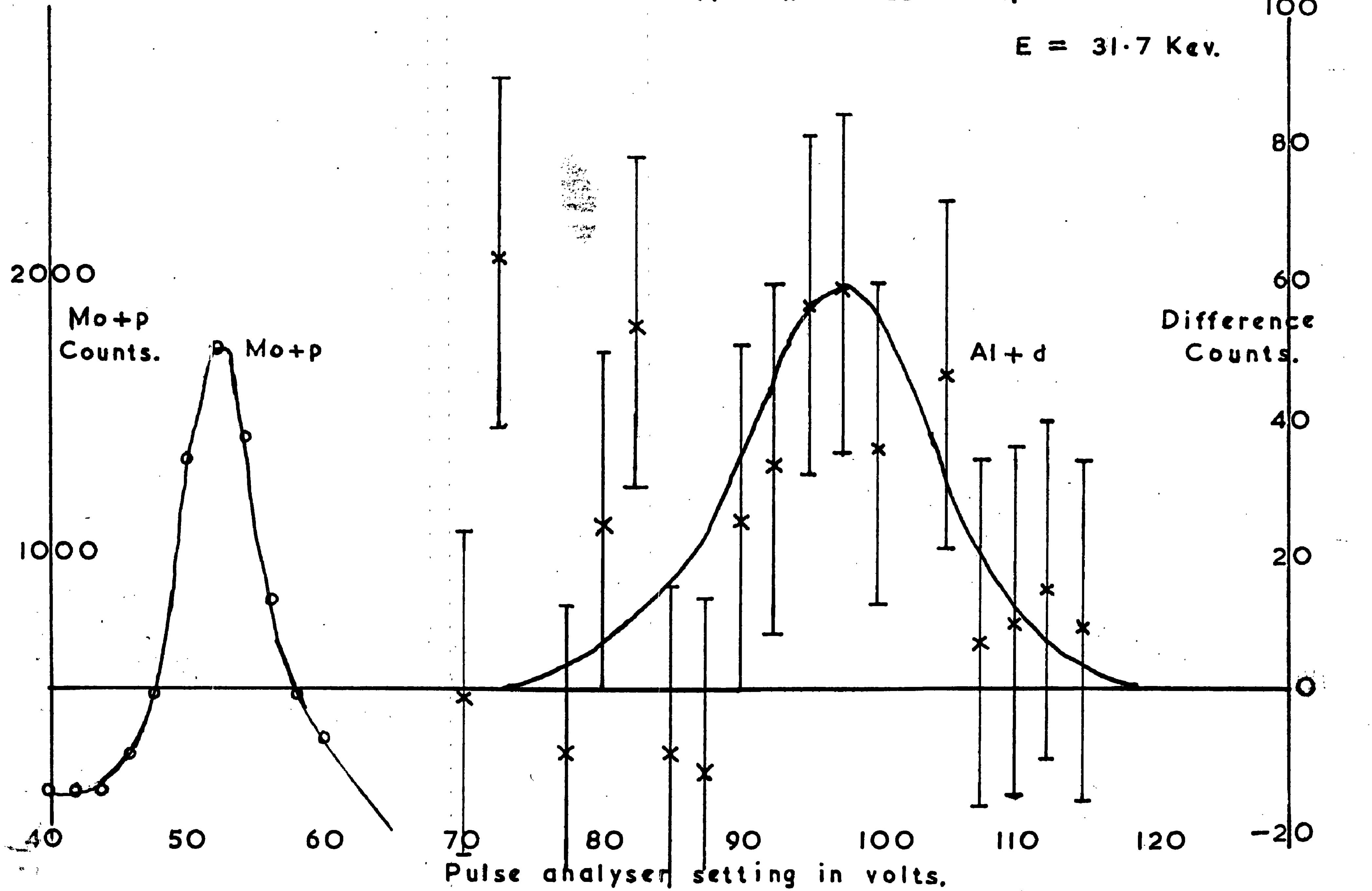
EXPERIMENTAL RESULTS

5. 1. THE DEUTERON BOMBARDMENT OF ALUMINIUM.

When this work was undertaken it had been intended to examine systematically reactions caused by protons and deuterons of energy up to 750 Kev. from the Glasgow Cockcroft-Walton accelerator. However, Enge, Buechner, Sperduto & Van Patter (1951) reported that a study of the e charged particles emitted in the reaction of Al^{27} (d,p) Al^{28}, carried out with a 180^{o} single-focussing magnetic spectrometer, had indicated that the proton group of energy about 5.5 Mev. going to the ground state of Al^{28} was, in fact, a doublet. This result suggested that there was a level of Al^{28} at 31.2 ± 2.0 Kev. with a yield of 55% of that of the ground state in this reaction. As this was the lowest level reported for such a light nucleus, it was felt that it would be well worth while attempting to detect radiation from the de-excitation of this level to the ground state, and to measure the energy and yield of such radiation, if detected.

The earlier experimental results obtained have errors due to uncertainties in the zero errors of the pulse analysers, and hence in the calibrations, and have larger background counts. The errors indicated in the figures are the square root of the total number of counts, including background and

Fig. 15 Al + d, No. 1, using proportional counter with ·017" Sn as absorber.



the figures given are the difference between the counts with the two different absorbing foils.

The position of the peak in the pulse distribution could be determined graphically, but the results quoted were obtained on the assumption that the distribution would be Gaussian, and the average was taken. When it was obvious that this asscumption was not justified, as, for example, when a scintillation counter was used, a "background" was taken from the experimental figures before this average was taken.

5.1.1. Proportional counter results using the single channel pulse analyser.

These were the first sets of results obtained on this reaction, before the background had been studied and reduced, and as only one calibration had been taken (with Mo X-rays from proton bombardment), this may be in error due to zero errors of the pulse analyser.

In the first of these, shown in Fig.15 there was no shielding and the beta-rays from the target were bent away from the counter by using the field of a large permanent magnet. A foil of thickness 0.017" of tin was used and the difference between counts with and without it in position between the target and counter was taken as due to soft-gamma-radiation. As shown the difference counts were at most 60 per channel. As mentioned before, each difference figure involves four counts.

The second and third had the counter shielded from background and used foils of 0.017" of tin and 0.048" of aluminium.

Fig. 16 Al + d, No. 2, using proportional counter with ·017" Sn and ·048" Al as absorbers.

E = 32·9 Kev.

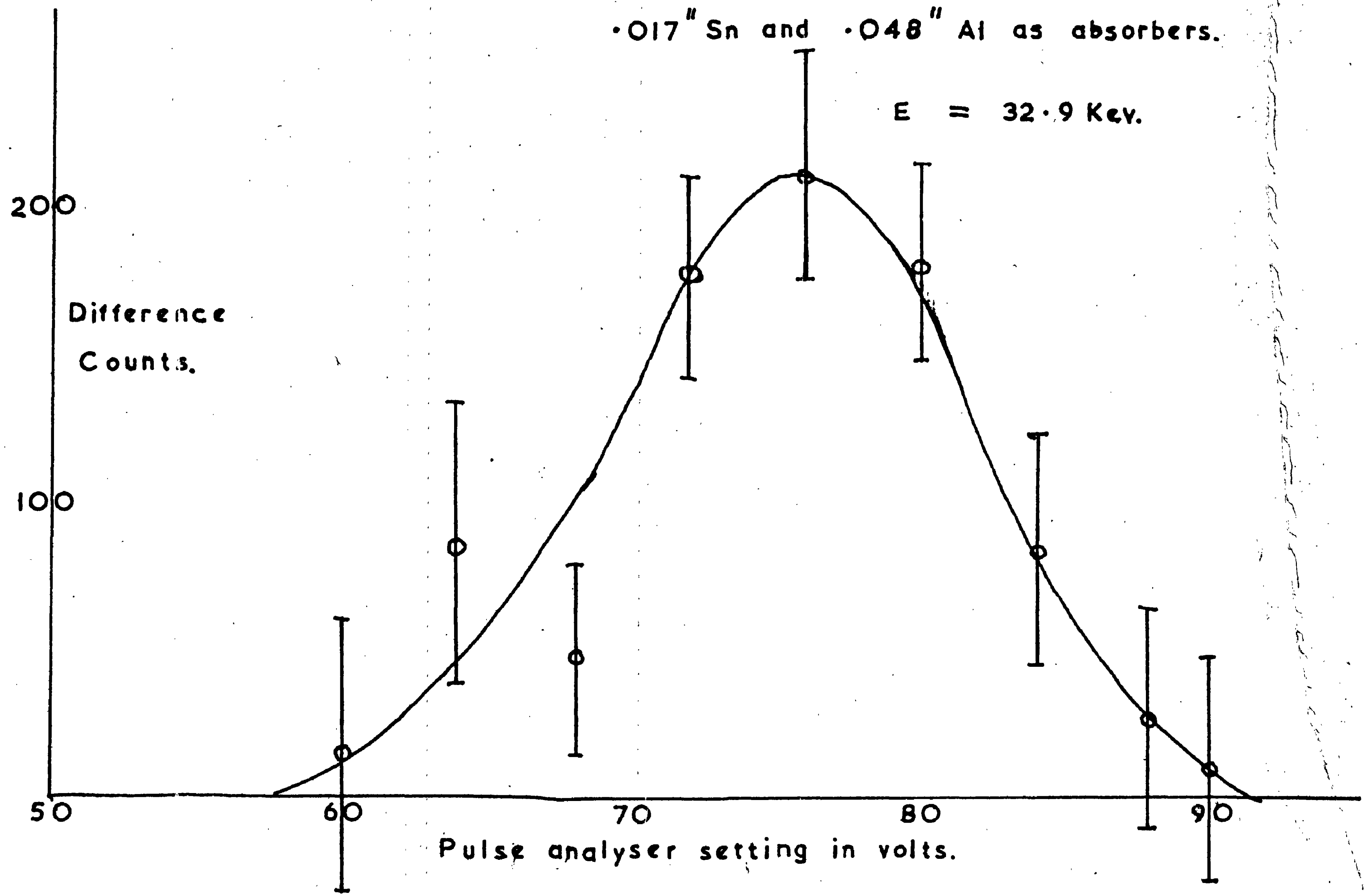
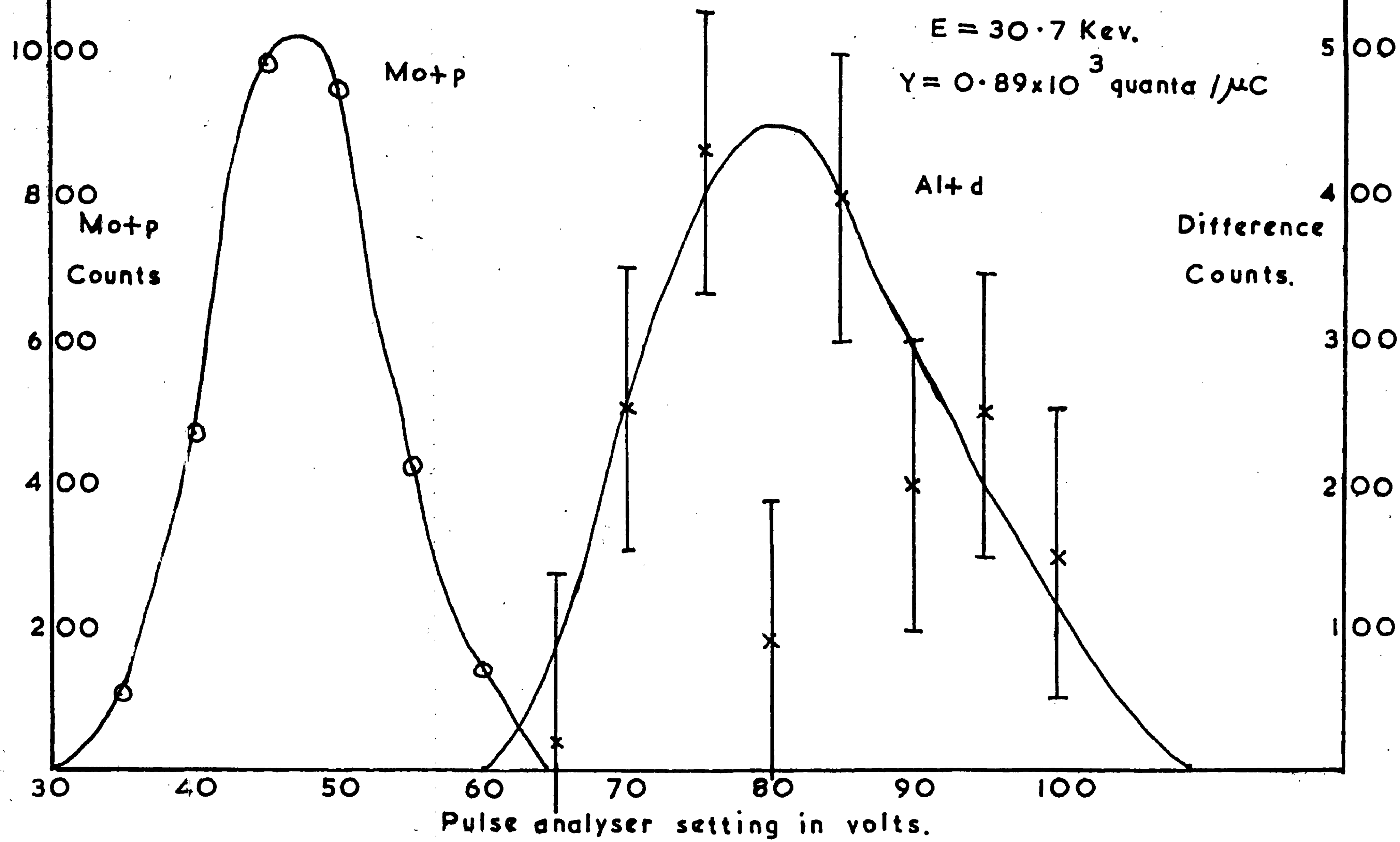


Fig. 17 Al + d, No. 3, using proportional counter with ·017" Sn and ·048" Al as absorbers.



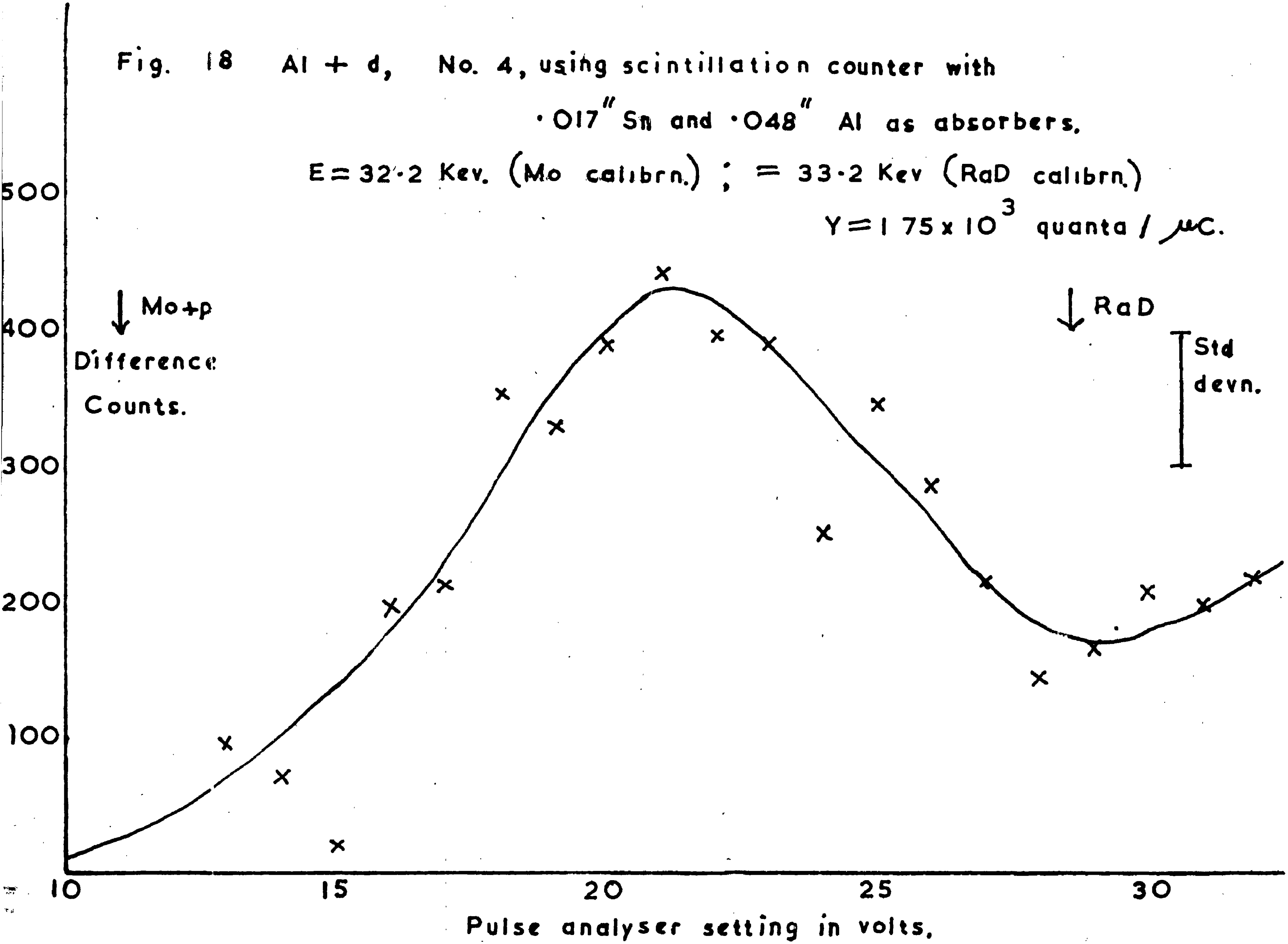


Fig. 18 Al + d, No. 4, using scintillation counter with ·017″ Sn and ·048″ Al as absorbers.
E = 32·2 Kev. (Mo calibrn.) ; = 33·2 Kev (RaD calibrn.)
Y = 1 75 x 10^{3} quanta / μC.

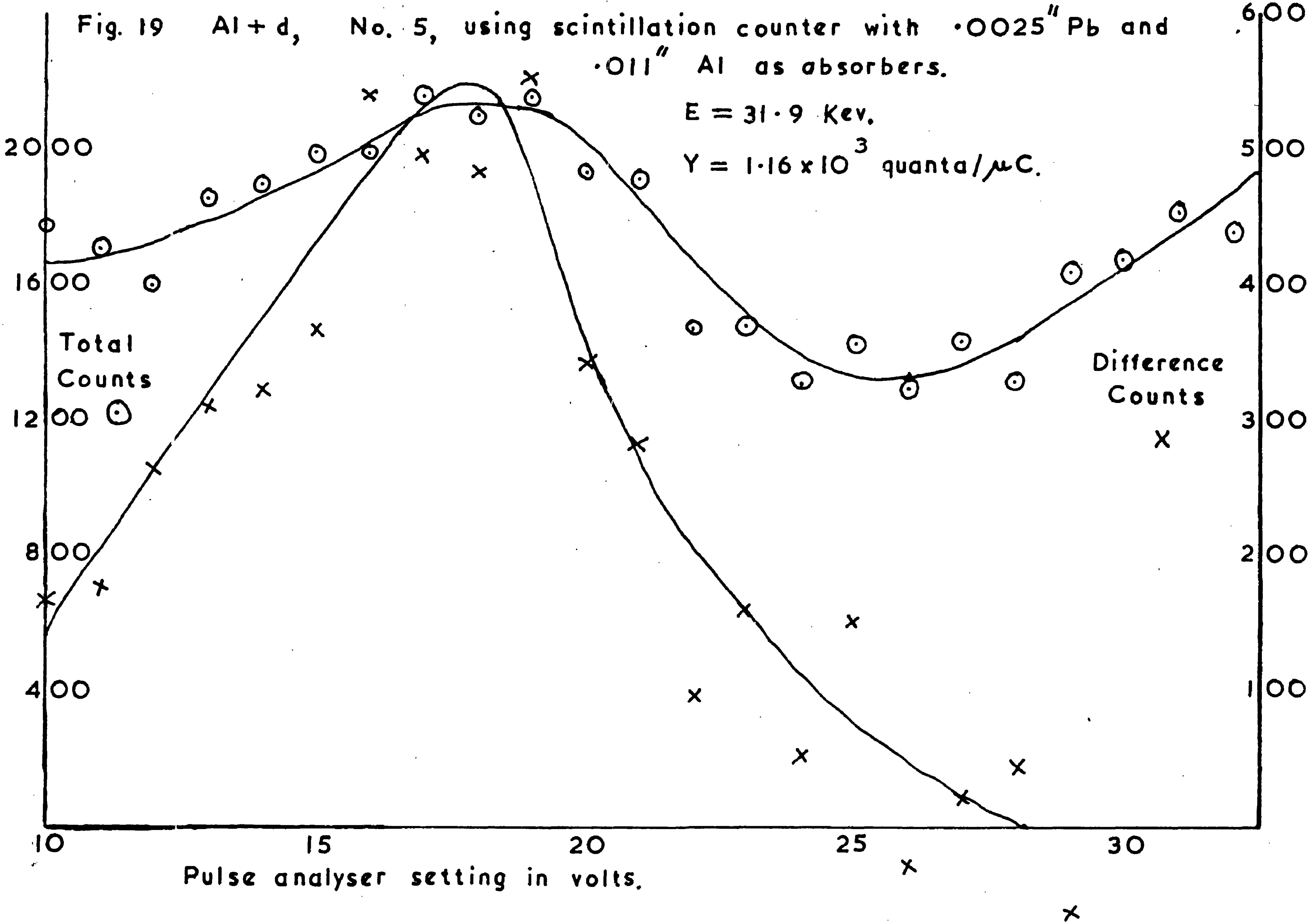


Fig. 19 Al + d, No. 5, using scintillation counter with ·0025" Pb and ·011" Al as absorbers.

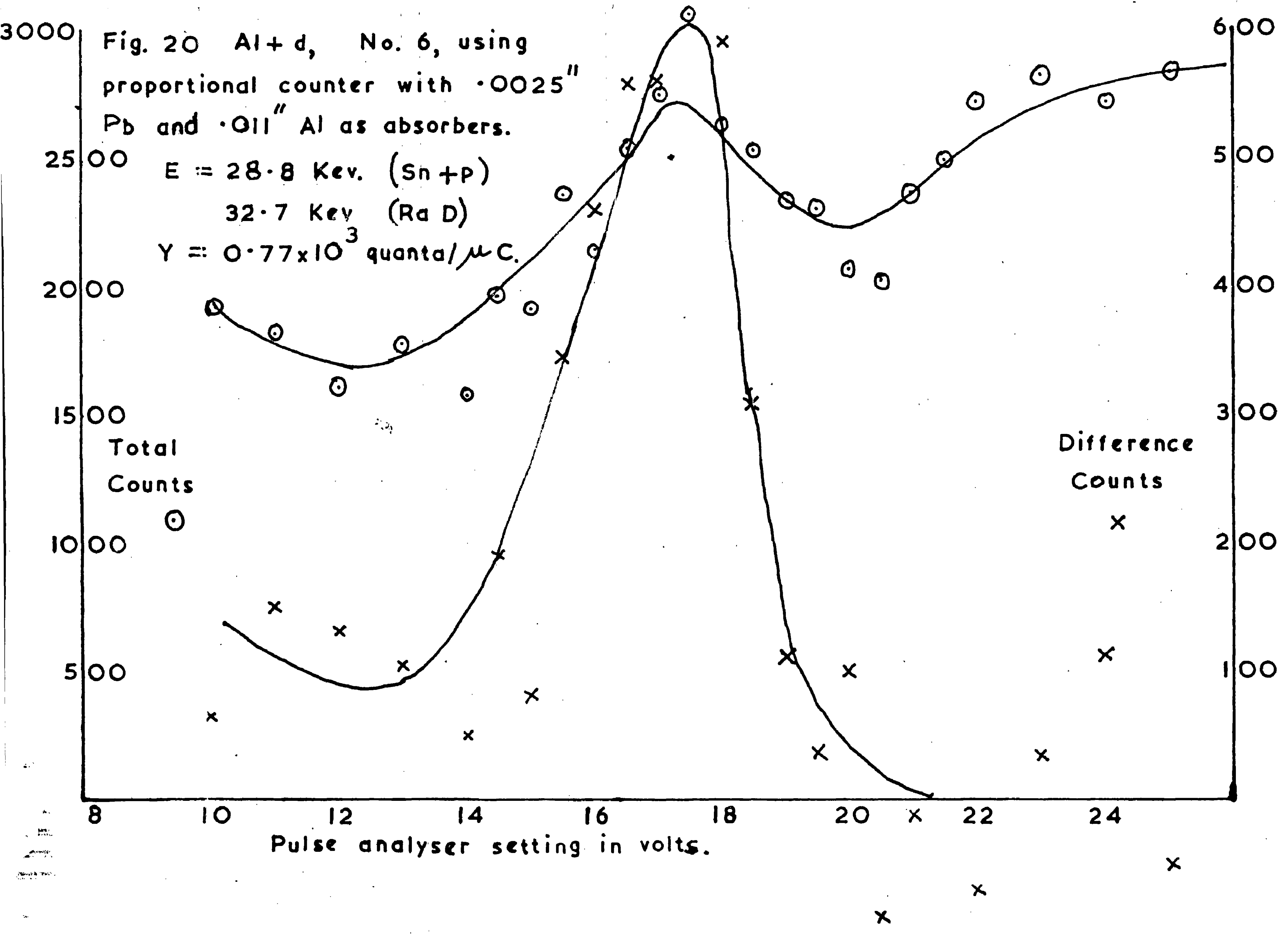


Fig. 20 Al + d, No. 6, using proportional counter with ·0025″ Pb and ·011″ Al as absorbers.

E = 28·8 Kev. (Sn + P)

32·7 Kev (Ra D)

Y = $0{\cdot}77 \times 10^3$ quanta/μC.

The second used the magnet to deflect the beta-radiation, the third absorbed them with a polythene absorber. The results are shown in Figs. 16 and 17. Rather longer runs were taken and background was reduced, giving better statistics, but there is uncertainty about the energy determination.

5.1.2. Scintillation counter results.

In obtaining these, the beta-radiation was absorbed with a polythene absorber, and two sets of results were obtained, one using foils of 0.017" of tin and 0.048" of aluminium, and the second foils of 0.0025" of lead and 0.011" of aluminium. The difference counts were about 500 in these results and the background was about 2,000. The low resolving power, however, renders the results less liable than those with the proportional counter. These results are shown in Figs. 18 and 19.

5.1.3. Further proportional counter results, using the 5-channel pulse analyser.

To obtain more precise measurements of the energy and intensity of the gamma-radiation in this reaction, the background was studied and reduced as described earlier, and the counter shielded, with both polythene and magnet placed to prevent beta-radiation reaching the counter. Following this three further sets of readings were obtained. In the first of these, shown in Fig.20, peak difference counts of 600 were obtained with a background rate of 2,000, which gave a very prominent peak which could be readily seen above background. Unfortunately, the calibration carried out for this run with tin X-rays and gamma radiation at 14 Kev. and 47 Kev. from RaD

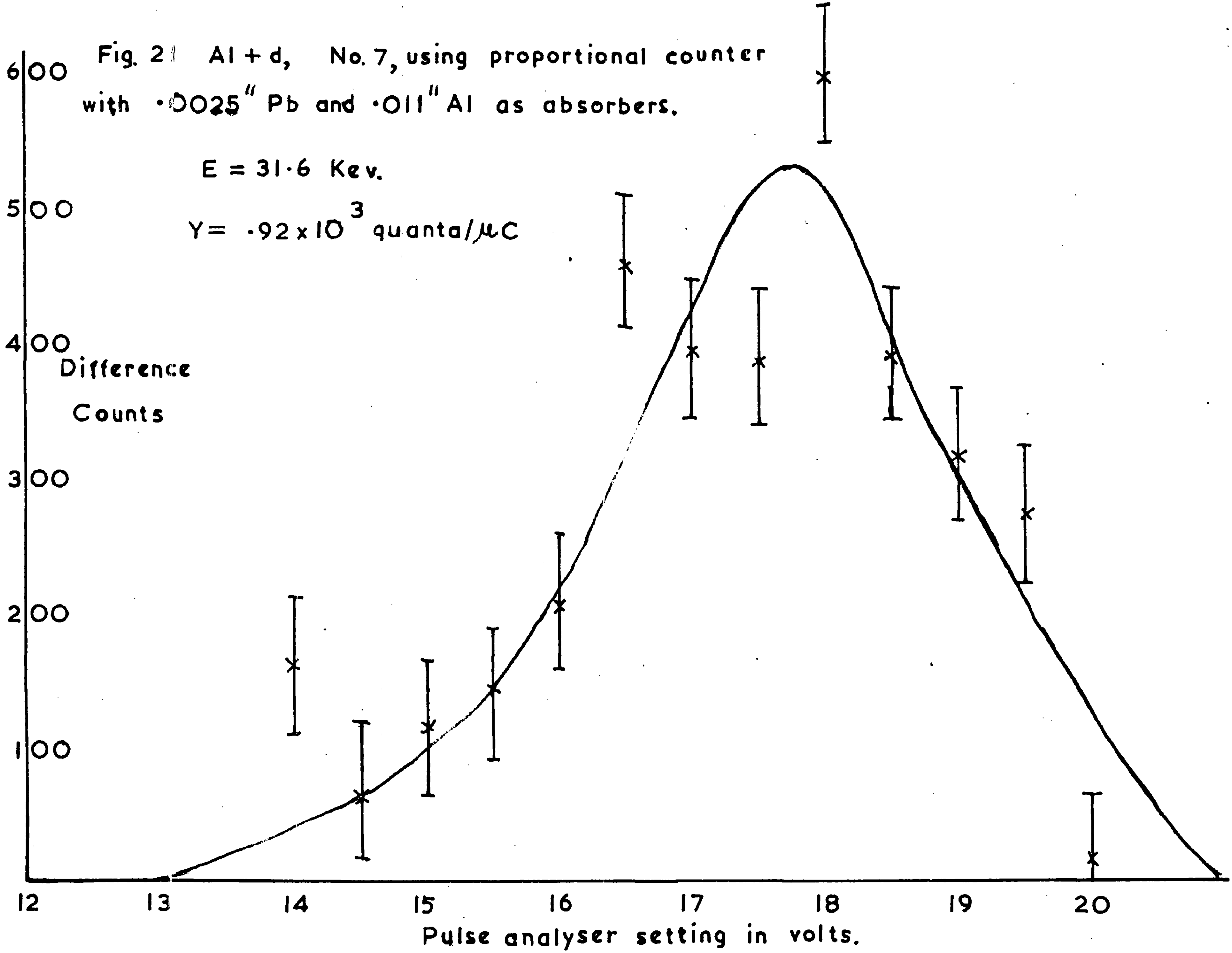


Fig. 21 Al + d, No. 7, using proportional counter with ·0025" Pb and ·011" Al as absorbers.

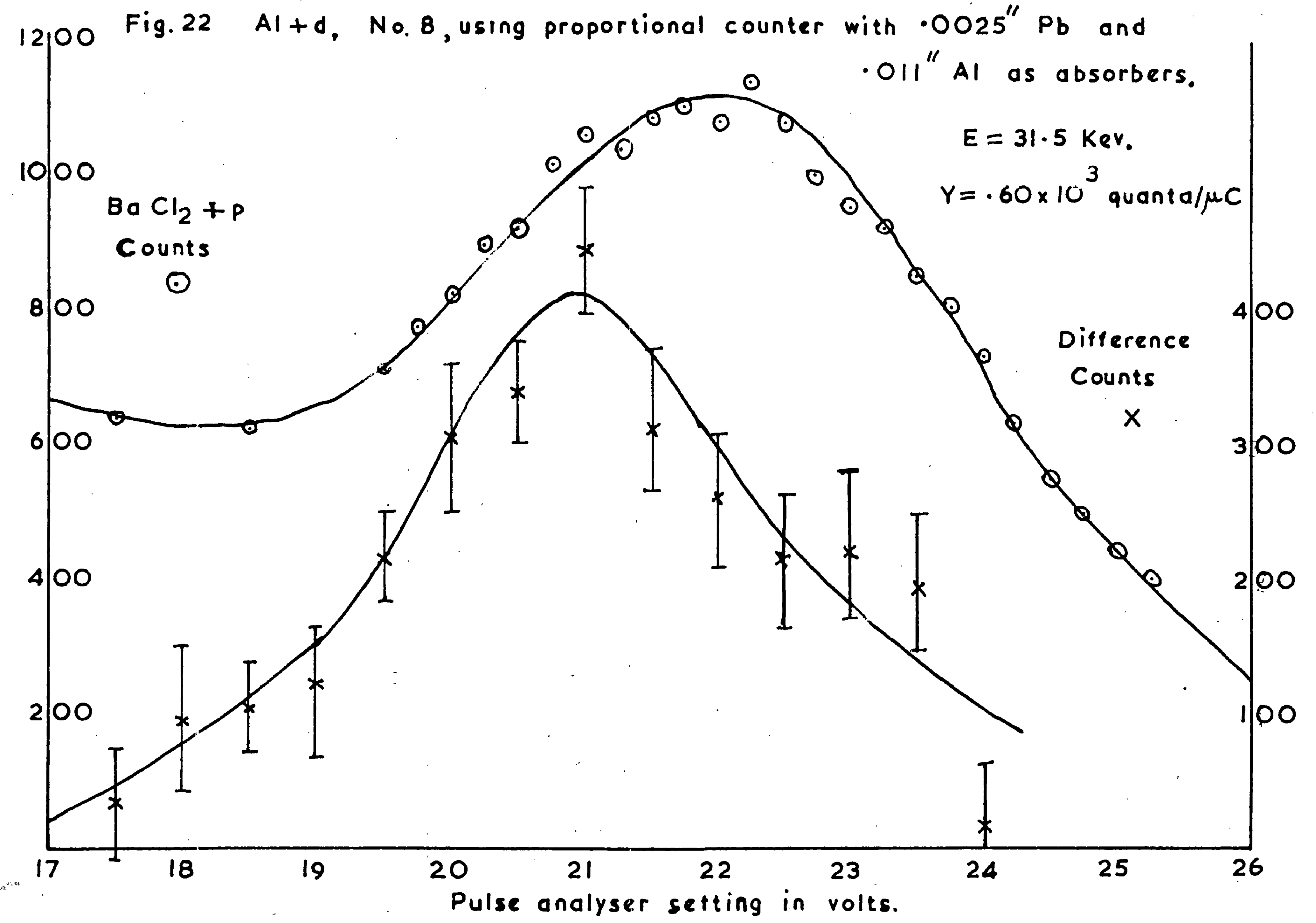


Fig. 22 Al + d, No. 8, using proportional counter with ·0025" Pb and ·011" Al as absorbers.
E = 31·5 Kev.
Y = ·60 x 10³ quanta/μC
Ba Cl2 + p Counts ⊙
Difference Counts ×
1200
1000
800
600
400
200
400
300
200
100
17
18
19
20
21
22
23
24
25
26
Pulse analyser setting in volts.

Solutions used	Absorption edge	Counts
1.49 gm. of tartar emetic (containing Sb.) in water, made up to 8.2 c.c.	30.5	10,640
0.875 gm. of Te dissolved in HNO_3 and HC1 and made up to 10 c.c.	31.9	11,270
1.07 gm. Na1 in water, made up to 10 c.c.	33.3	11,536

TABLE 4. Results of critical absorption experiment on radiation from A1 + d.

were not consistent, and the energy measurement is rather doubtful. This was before the cathode follower was added to the low-pass discriminator, and the output of the amplifier was found to be overloaded, giving distortion of the spectrum for large pulses. There was also an error due to the zero error of the single channel pulse-analyser, which has been used for calibration of the 5-channel analyser.

Finally, the last two runs taken were free from such calibration errors and had a low background rate. X-rays from a target of $BaCl_2$ fused on copper were used for the calibration and the results obtained are shown in Figs 21 and 22. The linearity of the calibration was verified using 47 Kev. gamma-radiation from RaD and X-rays from Sn and p.

5.1.4. Critical absorption results.

The solutions used, shown in table 4, had as constituents approximately equal concentrations of the absorbing elements, Sb, Te and I. They were held in perspex cells with a thickness of 5 mm., and using the figures given in Compton & Allison (1935) for the absorption co-efficient of iodine immediately above and below the absorption edge, these absorbers will reduce the intensity of gamma-radiation by about 25% if the energy is less than the absorption edge and by about 80% if it is greater. The results, shown in table 4, are consistent with the presence of a soft gamma radiation of energy between 30.5 Kev. and 31.9 Kev.

5.1.5. Subsidiary experiments.

The photographic technique was developed primarily for the detection of further low energy gamma lines, but the convenience made it useful for carrying out subsidiary experiments to obtain results which would not have justified the time involved with the more elaborate techniques.

As a check that the method using different absorbers was not giving rise to fallacious results, the photographic method showed the presence of radiation in the region 30-35 Kev. when there was no absorber between the target and the counter. The intensity of this radiation was substantially reduced by using a lead absorbing foil.

It was possible the radiation was coming, not from the reaction expected, but from excitation of characteristic X-rays by deuterons on impurities in the Aluminium targets used, although it is relatively improbable that sufficient Cs, which has characteristic radiation of the energy detected, would be present in the spectroscopically pure aluminium used for targets. It might also be conceivable that the radiation arose from background exciting characteristic radiation in the counter walls or window. To verify that these possibilities were not occurring, the target was bombarded with protons and the spectrum photographed. Proton excitation of characteristic X-rays would give greater intensities than deuteron excitation and the background would be expected to be similar to that in the deuteron case. However, no sign of radiation of the relevant energy was detected, and this would suggest that the radiation did, in fact, arise from the reaction suggested.

Expt. No.	Type of expt.	Calibration used	Energy of radiation (in Kev.)	Yield per uC of deuterons at 700 Kev.
1.	Proportional Counter	X-rays from Mo + p	31.7	---
2.	"	"	32.9	---
3.	"	"	30.7	0.89×10^3.
4.	Scintillation Counter	Ra 47 Kev. line	33.2	1.75×10^3
		Mo + p	32.2	
5.	"	Sn + p	31.9	1.16×10^3
6.	Proportional Counter	RaD 47 Kev.	32.7	
		Sn + p	28.8	0.77×10^3
7.	"	$BaCl_2$ + p	31.9	0.92×10^3
8.	"	"	31.0	0.60×10^3
9.	Critical absorption		30.5 -- 31.9	-------

TABLE 5. Summary of results on Al + d.

The radiation arising from deuteron bombardment may be due either to de-excitation of a low-lying excited state of Al^{28} or from an excited state of Si^{28}, following the beta decay. To test whether it could arise from the latter hypothesis, a set of photographs of the beta-spectrum, taken at the end of a run with the beam turned off, were examined. There was no indication of the presence of a low-energy gamma radiation.

Rae & Grant (1951), in the Dept. of Natural Philosophy, at Glasgow, have attempted to detect the conversion electrons arising from the transition giving this radiation, using a 180° magnetic spectrometer, but have been unable to do so. From the sensitivity of their apparatus and the experimental yield of the radiation, they conclude that the internal conversion co-efficient for the transition is less than 2.

5.1.6. Summary of results on Al^{27}.

The results of these experiments are summarised in Table 5. It is concluded that a radiation of energy 31.6 ± 0.4 Kev. with an intensity of $1.0 \times 10^{3} \pm 0.3 \times 10^{3}$ quanta per u C of deuterons of energy 700 Kev., is emitted in the deuteron bombardment of Al^{27}.

Fig. 23 Cu P + d, using scintillation counter, with lead shielding.

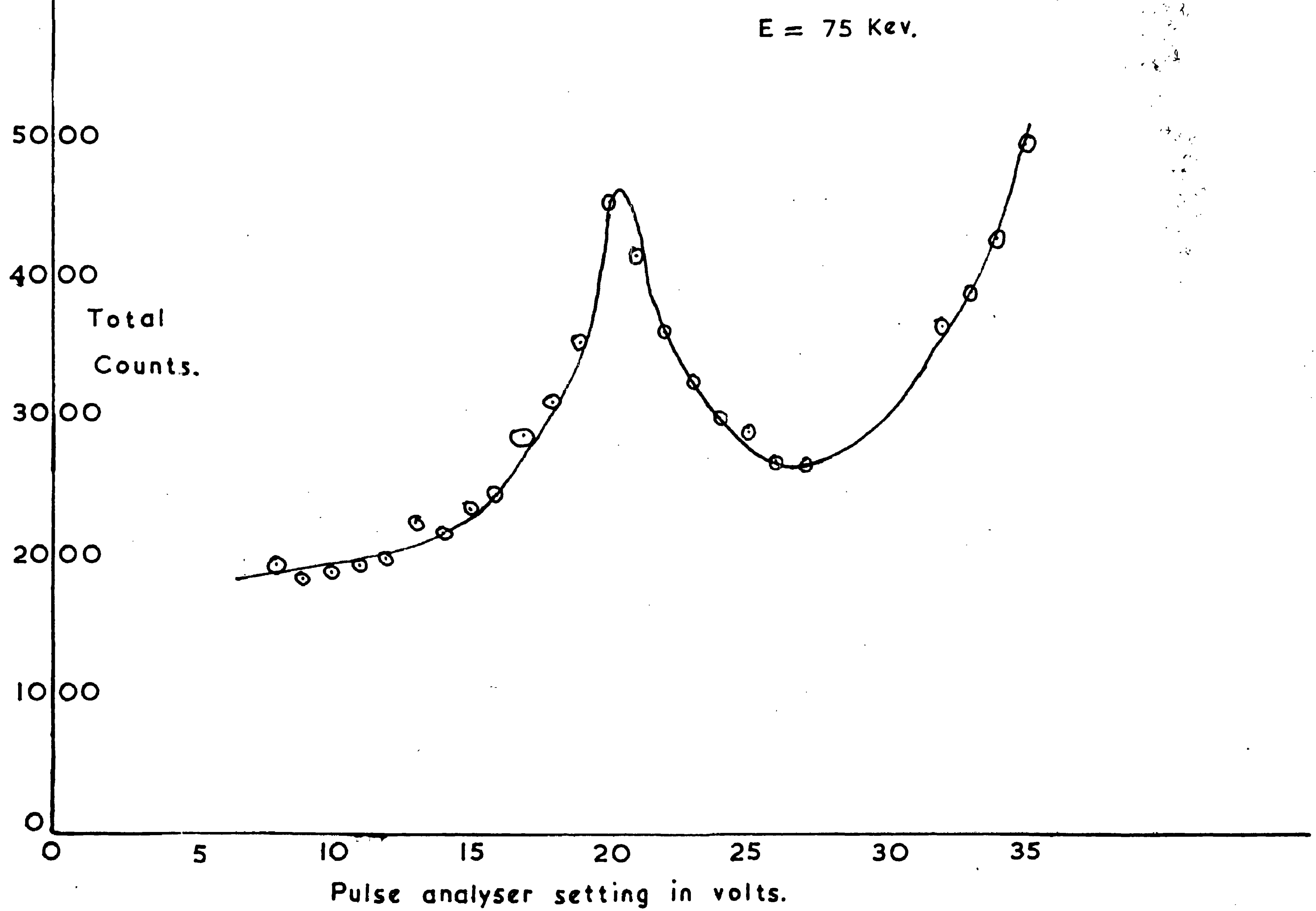
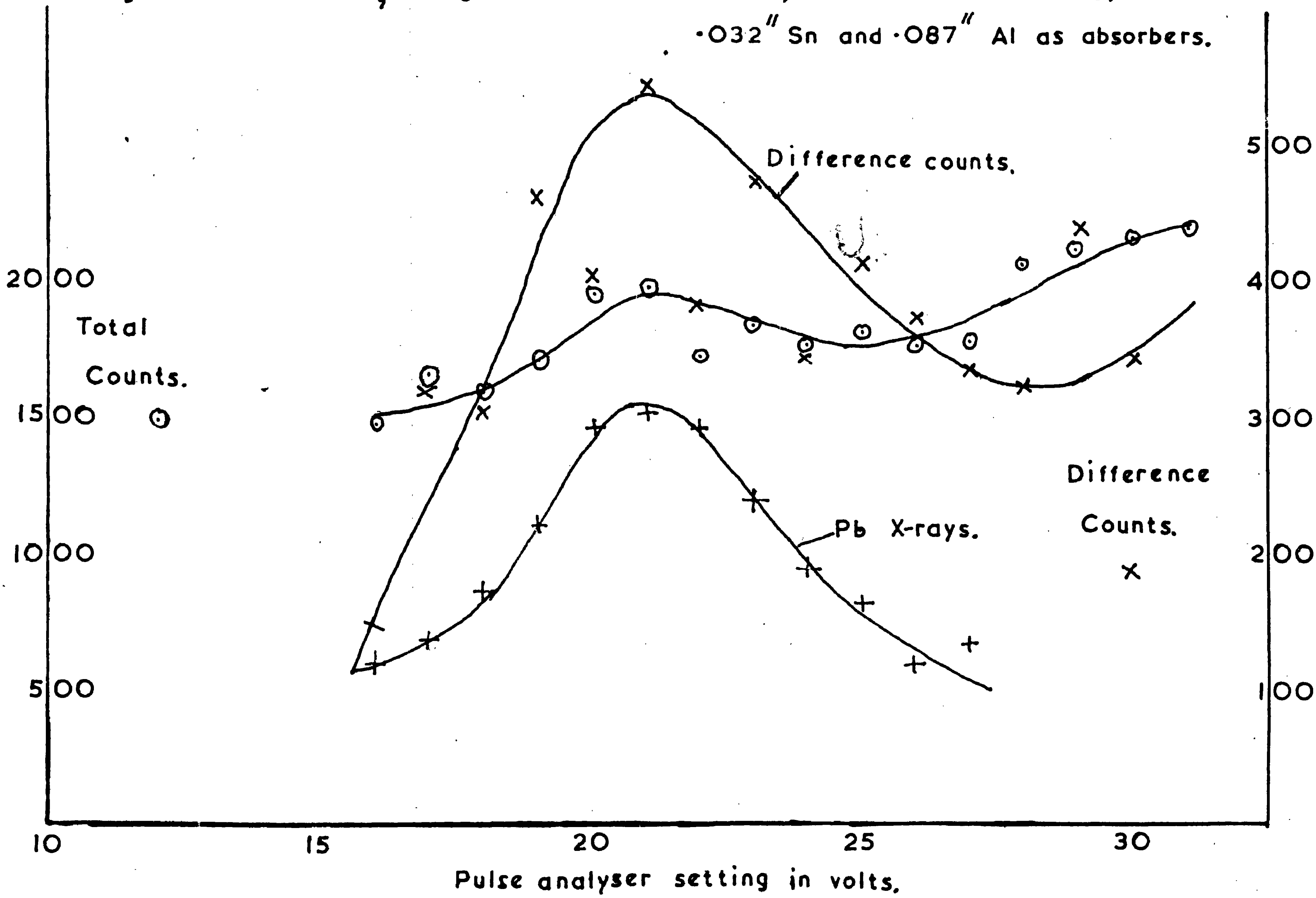


Fig. 24 Cu P + d, using scintillation counter, without lead shielding, with ·032″ Sn and ·087″ Al as absorbers.



5.2. THE DEUTERON BOMBARDMENT OF PHOSPHORUS.

Strait, Van Patter, Buechner & Sperduto (1951) also reported a low-lying state in P^{32} from the reactipn $P^{31}(d,p)P^{32}$. This was at 77 Kev. above the ground state. The proportional counter used for the aluminium reaction would be much reduced in sensitivity for radiation from such a level and therefore this reaction was examined with a scintillation counter. The results are described below.

A target of Cu P was used and the method of differential absorbers used, as in the aluminium experiments. The absorbers were 0.025" of lead and 0.105" of aluminium, to allow for the increased energy of radiation expected. In the first run which was carried out, the results shown in Fig.23 were obtained, indicating a peak in the radiation at 74 Kev. which could be observed above background. However, it was thought that this might be due to fluorescent X-rays of lead excited in the surrounding shielding by the background. Therefore a second run was carried out, in which the crystal was shielded from all lead by 0.032" of tin foil, and the absorbers used were 0.032" of tin and 0.087" of aluminium. The peak corresponding to radiation at 74 Kev. was reduced very considerably and, as shown in Fig 24, was coincident with lead X-rays which were excited by a strong RaD source to simulate the background. It was concluded from these experiments that it was not possible to detect radiation from the excited state of P^{32}, and, as the sensitivity of

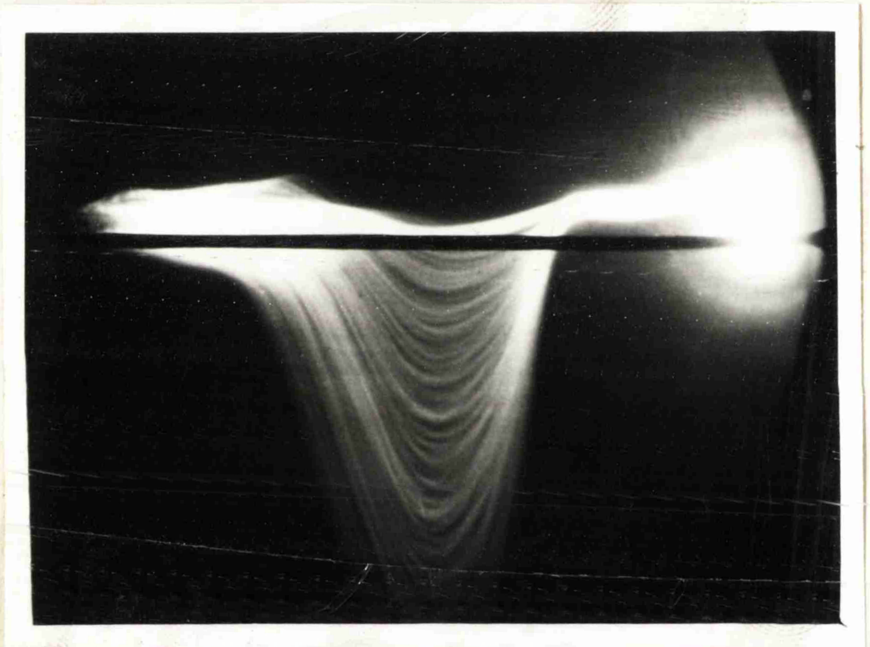


PLATE 6, Radiation from C + d.

the proportional counter for the required energy would be lower, no attempt was made to detect it using this method.

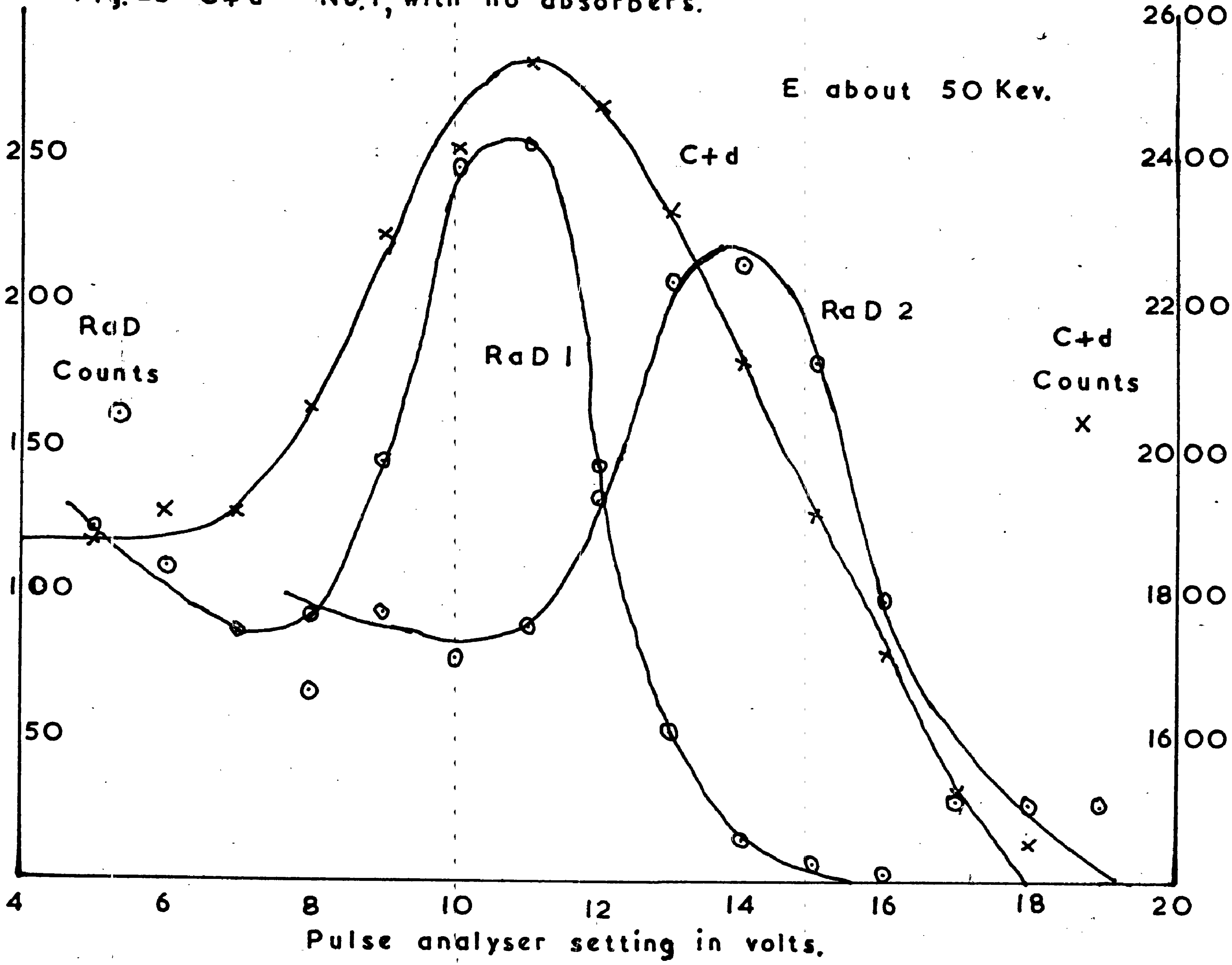
5.3. SEARCH FOR FURTHER SOFT GAMMA RADIATION FROM NUCLEAR REACTIONS

Following the investigation of the radiation from $Al^{27}(d,p)Al^{28}$, the photographic technique was developed to search for further such radiation, as described earlier. Targets of Cu, Sn, C, Al and B on a copper backing were placed in the rotating target chamber and series of photographs taken for proton and deuteron bombardment at 500 Kev. energy. Different attenuations in the amplifier were used and calibrations with RaD and Ge^{71} were also taken, and thus a wide coverage of energies was taken.

The results indicated the possibility of the following lines:- from C + p, a line at below the copper X-rays, i.e. from 6 to 8 Kev; from B + d, slight evidence for radiation of about 60 Kev. was found; and from C + d, there was a strong line at about 40 - 50 Kev., which appeared consistently in all the exposures covering this energy range, a typical exposure being shown in Plate 6. There was also a strong line about 90 Kev. which appeared in several cases, but it was suspected that this was due to excitation of characteristic X-radiation from lead shielding.

Of these results, the radiation from C + d appeared of most value to investigate further and therefore a further set of exposures was made, which verified the previous results with this reaction. To see whether or not the line was due to

Fig. 25 C+d No.1, with no absorbers.



electromagnetic radiation, rather than other types of radiation, the spectrum was taken without any foils between the source and counter, then with an aluminium foil and finally with a lead foil. The aluminium foil made very little reduction in the intensity of the line, but it was considerably weakened by the lead foil. The beta-spectrum was also examined at the end of a run, and showed no evidence of the radiation in question,

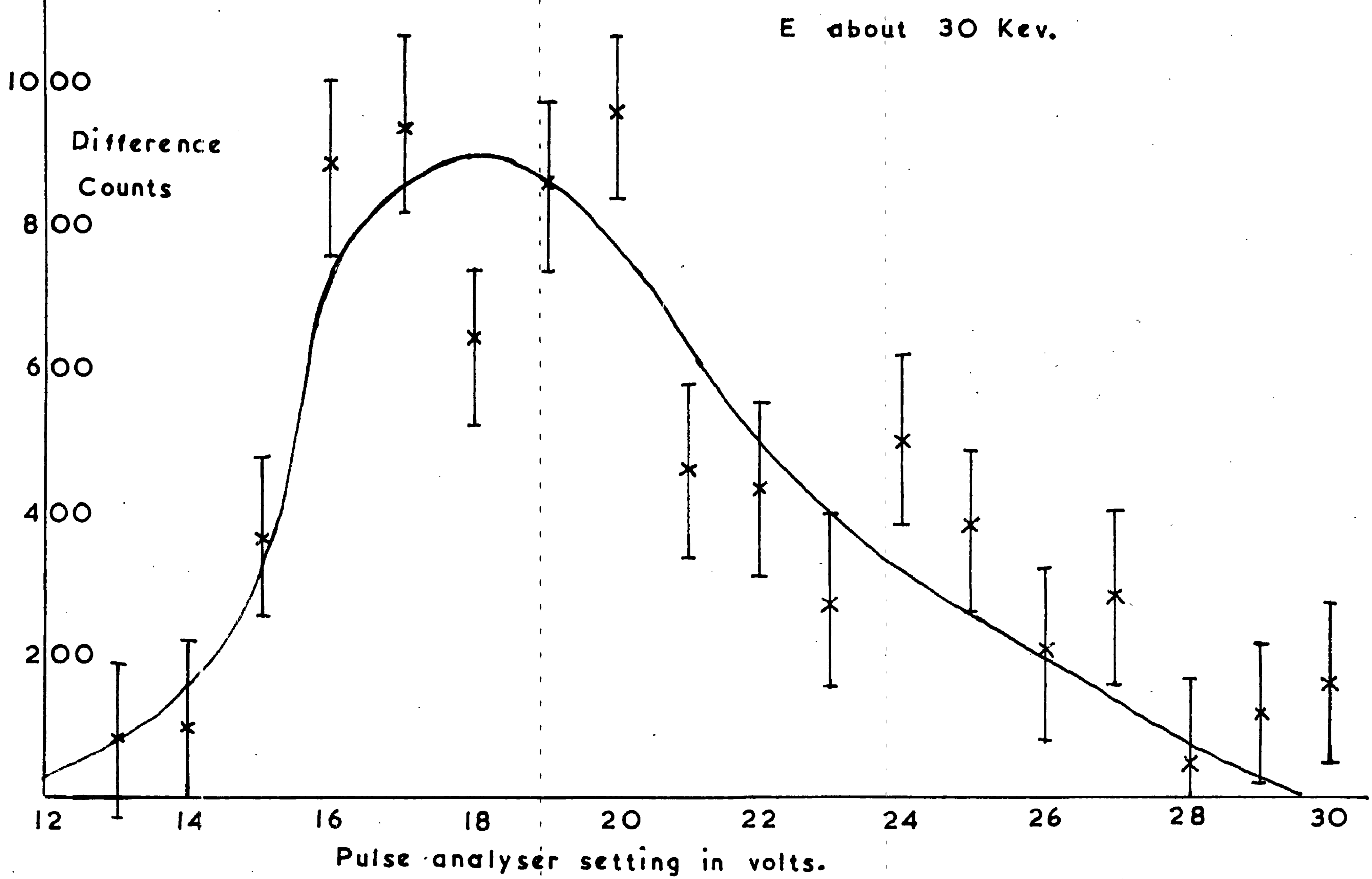
5.4. THE DEUTERON BOMBARDMENT OF CARBON

In view of the results obtained from the photographic methods, as discussed above, it was decided to investigate further the gamma-radiation from deuteron bombardment of carbon, using pulse analysis techniques. The energy and intensity were studied with proportional counter methods and later with a scintillation counter. Finally, the spectra from isotopic targets of C^{12} and C^{13} were examined photographically to find which isotope was giving rise to the soft gamma-radiation found.

5.4.1. Proportional counter results.

The first experiment was carried out as a straightforward analysis of the spectrum, using the T.R.E. five channel pulse analyser without any absorbers. The results, as shown in Fig.25, verified a line above the general background, but the latter was too large to enable any estimate of the energy or intensity of the radiation to be made. The calibrations carried out with RaD, using the 47 Kev.gamma

Fig.26 C+d No.2, with ·025″ Pb and ·105″ Al as absorbers.



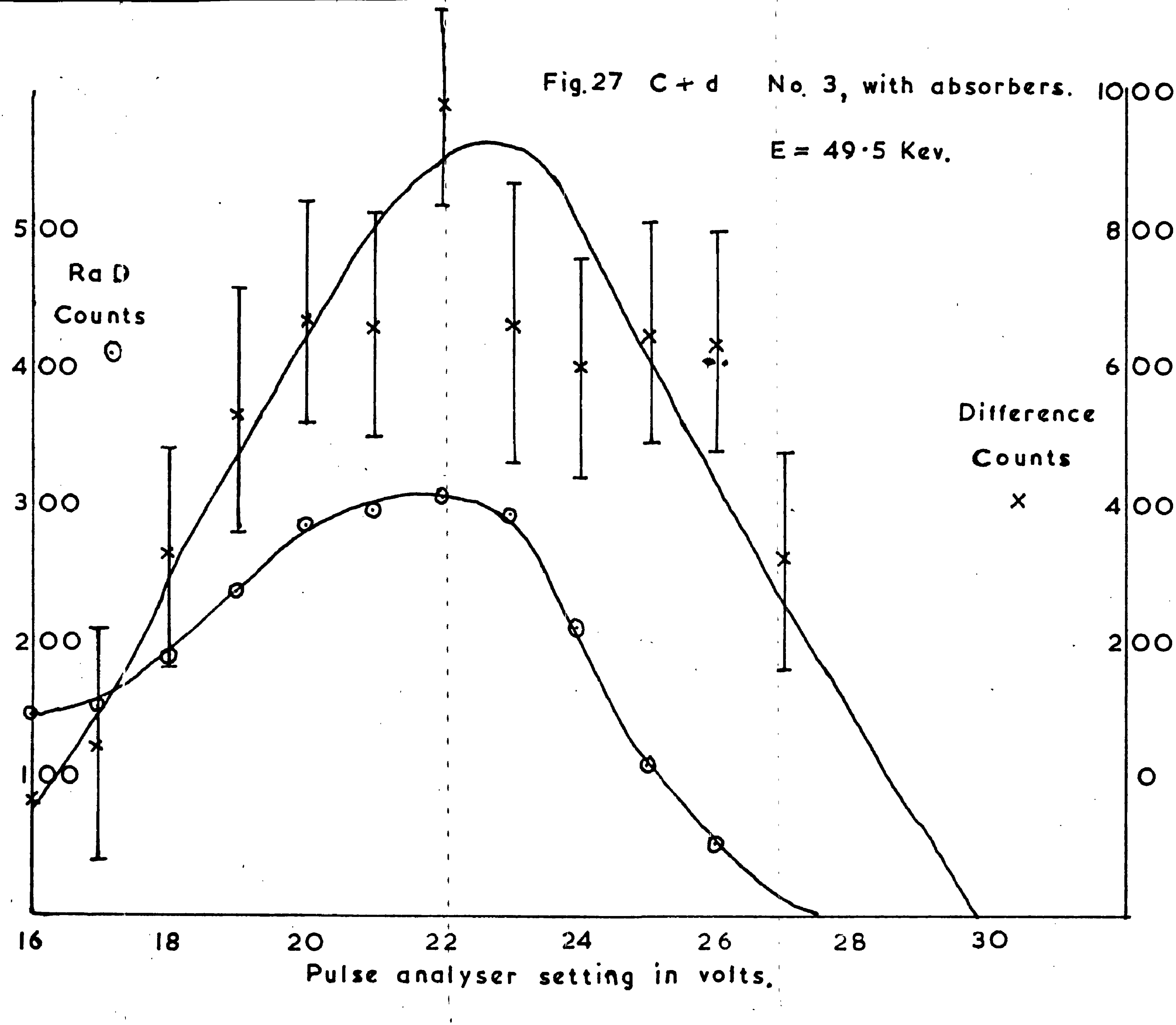
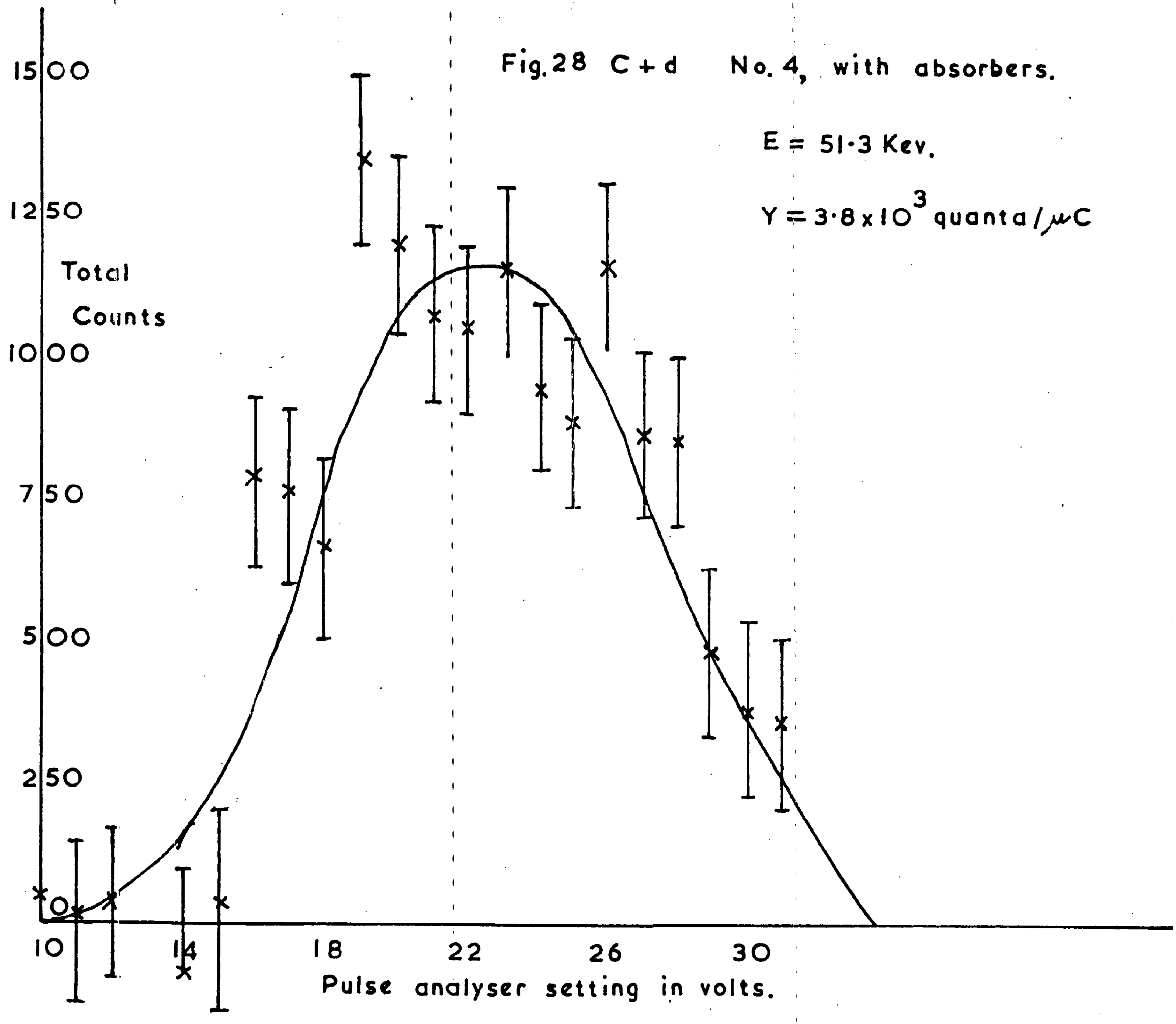


Fig. 27 C + d No. 3, with absorbers.

Fig. 28 C + d No. 4, with absorbers.



line were inconsistent, due to a small leak in the counter during the experiment.

Sets of readings were then taken using foils of 0.025" of lead and 0.105" of aluminium, and an absorber for beta-radiation of 1 cm. of perspex. As shown in Fig.26, this resulted in a well-defined peak corresponding to an energy of about 30 Kev. This result is much lower than any of the other determinations of the energy of this radiation made either before or after. It is suggested that an aluminium target had been used in the rotating target chamber instead of a carbon one, and that it was the radiation at 32 Kev. from $Al^{27}(d,p)Al^{28}$ which was detected.

The next experiments used about 2" of lead shielding round the counter, and a permanent magnet with ½" of polythene as a beta-particle absorber, as was done with the later experiments on the aluminium reaction. The first of these (Fig.27) gave an energy of the radiation of about 50 Kev., although the calibration from RaD was rather wide for an accurate determination of this. The second, however, used calibrations from X-rays from proton bombardment of Mo and Sn as well as the RaD radiation and gave the results of Fig.28, which gives the energy and intensity of radiation found.

With a view to obtaining better statistics and verifying this result, two further sets of readings were taken, in which the magnet and polythene were replaced by ½" of perspex as the beta-particle absorber. The first of these gave the

Fig. 29 C + d No. 5, with absorbers.

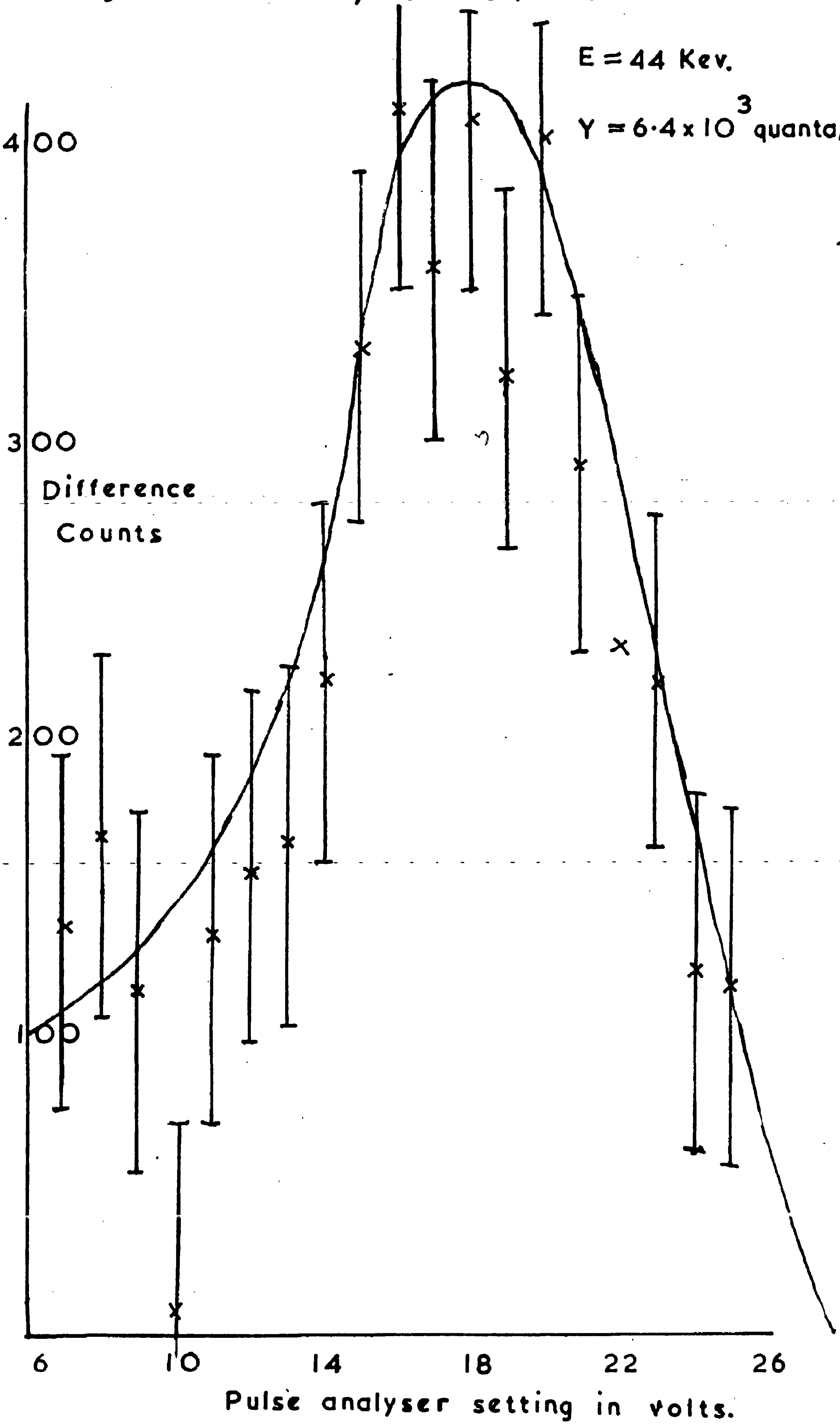
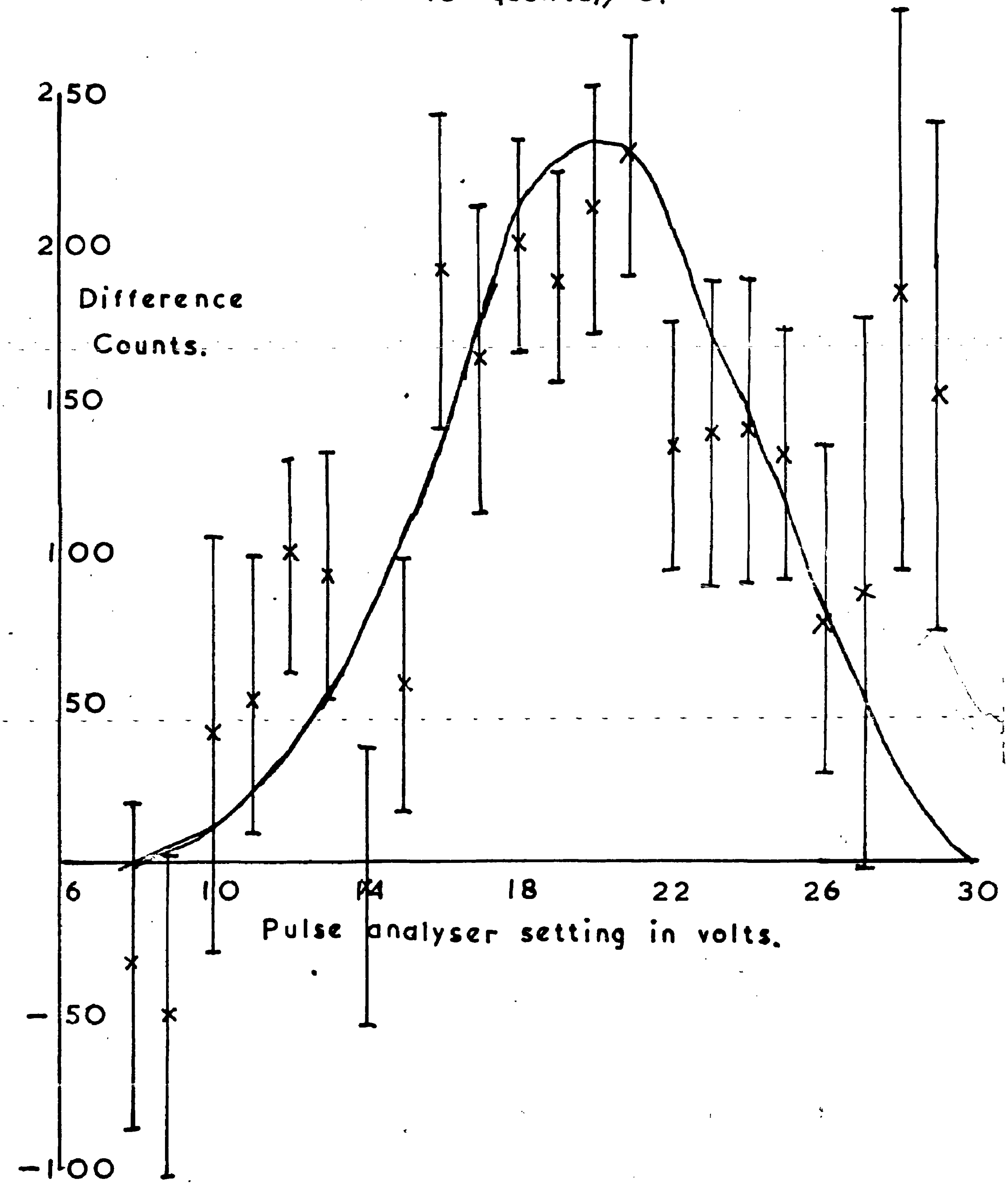


Fig.30 C + d No. 6, with absorbers.

E = 49 Kev.

Y = $3{\cdot}6 \times 10^3$ quanta/μC.



results of Fig.29, and the second, which involved many more readings than earlier ones and hence better statistics, gave those of Fig.30. After the latter a short analysis of the spectrum from the radioactive products of the reaction was performed and this gave no indication of the presence of the radiation.

5.4.2. Scintillation counter results.

Measurements similar to those with the proportional counter were carried out, using absorbing foils, but it was found that using a thick crystal of NaI(Tl), the background counts were too large to enable any peak in the distribution to be found, even taking difference counts. To try and reduce this background, the thin crystal, about 0.3 mm. thick was used. However, this still resulted in the soft radiation not being detectable, and it was decided that it was preferable to use the proportional counter.

5.4.3. Photographic results using separated $C^{12,13}$ isotopes.

As this work was being finished, targets of $C^{12,13}$ separated by the mass spectrometer at A.E.R.E., Harwell, were received. As it was desirable to determine whether the radiation was due to deuteron interaction with C^{12} or C^{13} the photographic technique, using the proportional counter, was used to study the radiation arising from these two targets on bombardment with deuterons. The exposures showed the rather surprising result that the radiation appeared to be present from both isotopes. Unfortunately time was not available to verify this result using the pulse

Expt. No.	Type of expt.	Calibration used	Energy of Radiation (in Kev.)	Yield per uC of deuterons at 700 Kev
1	Proportional counter	RaD 47 Kev.	50	---
2.	"	"	30	(?) ---
3.	"	"	49.5	---
4.	"	"	51.3	3.8×10^3
5.	"	"	44.0	6.4×10^3
6.	"	"	49.0	
		Mo + p	49.3	3.6×10^3

TABLE 6. Summary of results on C + d.

analyser method, but there would appear to be little doubt that this is the case.

5.4.4. Summary of results on C + d.

The bombardment of Carbon with deuterons therefore gives a soft gamma-radiation of energy 49 $\pm$ 2 Kev., with an intensity of $4.0 \times 10^3 \pm 1.0 \times 10^3$ quanta per uC of beam current. The results are summarised in table 6. There is also slight evidence for the presence of this radiation from the bombardment of both C^{12} and C^{13}.

CHAPTER 6.

DISCUSSION OF RESULTS

6.1. RADIATION FROM THE DEUTERON BOMBARDMENT OF Al.

The work of Buechner's group as reported in Strait, Van Patter, Buechner, & Sperduto (1951), Enge, Buechner, Sperduto, & Van Patter, (1951, a,b) and Enge, Buechner, & Sperduto (1952) indicates that the reaction $Al^{27}(d,p)\ Al^{28}$ gives proton groups, corresponding to transitions to the ground state and to an excited state at 31.2 ± 2.0 Kev. The group corresponding to the excited state had a yield of 55% of that to the ground state, using deuteron bombarding energies of 1.2 and 1.8 Mev. A search for radiation arising from transitions from this excited state to the ground state was made by this group but was unsuccessful, owing to the high background.

It seems reasonable to suppose that the radiation reported here did arise from de-excitation of this level, and this radiation has since been reported in studies of the decay of Mg^{28} (Sheline & Johnson, 1953, Wapstra & Veenendaal, 1953, and Sheline, Johnson, Bell, Davie, & McGowan, 1954). Mg^{28} decays with electron emission to Al^{28} and this work has verified that the radiation arises from decay of the excited state of Al^{28}.

The doublet represented by the ground and first excited states of Al^{28} is of some interest in the discussion of nuclear models and the polarity and parity change of the gamma-radiation is significant in this respect. These may be determined by a study of the internal conversion coefficients of the radiation or the lifetime of the excited state.

Table 2, facing page 25, gives figures for the K-shell conversion coefficient and effective lifetime of the state for various polarities. These have been derived from the formulae of Dancoff & Morrison (1939), for the conversion coefficients and Blatt & Weisskopf (1952) for the lifetimes. However, more recent calculations have been made by Spinrad & Keller (1951) and Rose, Goertzel & Perry (unpublished) and these are quoted by Wapstra & Veenendaal (1953) as leading to values for α_K for different types of radiation of 0.08 (M.1 0.22 (EI) 2.0 (M2) 4.1 (E2).

Rae & Grant (1951), using a 180° magnetic spectrometer at Glasgow, attempted to detect the conversion electrons arising from this transition but were unable to do so. From the sensitivity of their apparatus and the experimental yield of soft radiation given above, they concluded that the internal conversion coefficient is less than 2.

Since the yield of gamma-radiation is known, a value of the I.C.C. could be obtained if the number of transitions to the excited state was known. This could be obtained from the proton yield in the reaction $Al^{28}(d,p)Al^{27}$ only if the relative transition probabilities from the excited states to the ground and first excited state were known. Since the results in the literature for proton yields are rather uncertain and require extrapolation from the deuteron energies used to those at which this work was carried out, it was assumed that the mean transition probabilities to the ground and first excited state were the same. McMillan & Lawrence (1935) used deuterons of an energy of 2.2 Mev. and found a total yield of protons of 8 per 10^7 deuterons, corresponding to 5×10^6 per uC. Using the formula of Oppenheimer & Phillips (1935) for the excitation function for d,p reactions this gives a yield of 7.5. $\times 10^2$/uC at 700 Kev. though the extrapolation to low energies is rather uncertain. The final figure of about 4×10^2 transitions to the first excited state is slightly below the number of quanta found, but the uncertainties involved suggest that the figures are not inconsistent with a low internal conversion coefficient.

Later work of Allan & Wilkinson (1948) was carried out at 930 Kev., but it is difficult to determine the yield of protons from this paper, particularly in the short-range region of the proton spectrum. However, a yield of about 10^3 protons per uC per unit solid angle at a bombarding energy of 930 Kev., is indicated by the figures. At 700 Kev. bombarding energy this would be reduced by a factor of about 6, and hence the total number of transitions to the first excited state would be about 10^3/ uC. The approximations involved make this agreement with the number of quanta emitted somewhat fortuitous, but it indicates that these results agree with the internal conversion coefficient being small.

These values for the internal conversion coefficient suggest that the radiation must be electric or magnetic dipole, or possibly magnetic quadrupole, radiation. As we shall see later, shell model theory suggests that the transition between this low-lying doublet in Al^{28} would be by magnetic dipole radiation and the experimental results are thus in agreement with accepted theory.

The shell model, as described by Mrs. Mayer (1950), uses j-j coupling and describes heavy nuclei well but is not so successful for light nuclei. Inglis (1953) has suggested this is due to (LS) coupling and intermediate coupling, in a manner similar to the atomic case. However, he points out that complete j-j coupling is to be expected when a single s-nucleon spin is coupled to the j of a shell which is almost full.

In the case of Al^{28}, the order of filling of the energy states of the shell model is such that the 13 protons willbe in the states

$$(1\ s_{\frac{1}{2}})^2 \quad , \quad (1\ p)^6 \quad , \quad (1\ d_{5/2})^5$$

using the usual nomenclature. This is one short of the sub-shell of 6 $d_{5/2}$ nucleons, and hence may be written as $(d_{5/2})^{-1}$. Similarly the 15 neutrons will be in the states

$$(1\ s_{\frac{1}{2}})^2 \ , \ (1\ p)^6 \ , \ (1\ d_{5/2})^6 \ , \ (2\ s_{\frac{1}{2}})^1$$

Hence the ground state of Al^{28} will arise from the coupling of the $s_{\frac{1}{2}}$ neutron with what, in effect is a $d_{5/2}$ proton. If j-j coupling is assumed, this will lead to doublet consisting of d_3 and d_2 states, which will thus have $J = 3^+$, 2^+

If this is the case, the radiation from the transition between these states would be magnetic dipole, in agreement with the results given for the internal conversion coefficient. This assignment of J values to these states is further verified by the relative yields of protons to the two states found by Enge, Buechner, & Sperduto (1952), who showed that the yield to the excited state was 69% of that to the ground state for Ed = 2.1 Mev. Since the orbital angular momentum of the captured neutron is $l_n = 0$, as found by Black (1953) from a study of the angular distribution of the protons, for both states, the relative yield of protons should be in the ratio of (2J + 1). This agrees with the experimental result if the ground state is taken as $J = 3^+$, and the excited state as $J = 2^+$.

6.2. DISCUSSION OF RESULTS FROM DEUTERON BOMBARDMENT OF P^{31}

It was not found possible to detect any soft-gamma radiation corresponding to de-excitation of the excited state at 77 Kev. in P^{32} reported by Van Patter, Endt, Sperduto & Buechner (1952) from the analysis of the protons in the reaction $P^{31}(d,p)P^{32}$. This was largely due to the excitation of secondary X-rays of energy 75 Kev. in the surrounding lead shielding of the scintillation counter used, but it is probable that if the same intensity had been present as was the case with the 32 Kev. radiation from bombardment of Al, this would have been detected. Since the efficiency of the thick NaI crystal is similar for the two energies, this implies that the yield of the radiation must be less than 10^3 quanta per uC of deuterons. There appear to be no figures in the literature for the proton yield in this reaction, but, as it is fairly recently that this reaction was studied (Pollard, 1940, first measured the ground state protons and Allen & Rall, 1951, the protons to the excited state), the yield may well be low. This is also reported by Van Patter, Endt, Sperduto & Buechner (1952), who mention that the yield was lower than that from (dp) reactions with lighter nuclei. However, radiation of energy 77 Kev. has been reported from neutron capture in sulphur (Day, 1953), and this may well be following the reaction $S^{32}(n,p)\ P^{32}$, with subsequent de-excitation of the excited state of P^{32}. However, there is no available data to determine the nature of the radiation.

6.3. RADIATION FROM THE DEUTERON BOMBARDMENT OF CARBON.

As there is no previous evidence of levels following such bombardment that could account for this radiation, we will discuss possible reactions which might lead to it. It will not, however, be possible to make any definite assignment.

$C^{12}(d,p)C^{13}$. According to the review article of Ajzenberg & Lauritsen (1952), from which many of the figures given in this section are taken, the Q value for this reaction is 2.72 Mev. and hence the reaction is energetically possible and may also proceed via the excited state at 3.09? Mev. The energy levels in C^{13} and its "mirror" N^{13}, are in reasonable agreement with each other, and have been assigned values of J, and parities, on the shell-model, which agree with the experimental evidence. They both consist of the $1s_{\frac{1}{2}}$ shell containing 2 neutrons and 2 protons, and a full $1p_{3/2}$ shell with a single nucleon outside in the $1p_{\frac{1}{2}}$ shell.

Excited levels may be formed by excitation of the single nucleon from its $p_{\frac{1}{2}}$ state to a $s_{\frac{1}{2}}$ or $d_{5/2}$ level, corresponding to the levels at 3.09 Mev. in C^{13} (experimentally assigned as $\frac{1}{2}^{+}$) and at 3.89 Mev. ($5/2^{+}$). Alternatively, one of the shell of $p_{3/2}$ nucleons may be excited, to give a configuration $(p_{3/2})^{7}$, $(p_{\frac{1}{2}})^{2}$. Since either a neutron or a proton may be excited, and then the $p_{3/2}$ hole couple with the partial configuration $(p_{\frac{1}{2}})^{2}$, it appears that this excitation might give rise to a doublet of suitable separation.

However, this reaction has been studied, using magnetic analysis of the proton groups, by Buechner's group (Buechner, Strait, Sperduto & Malm, 1949) and there appears to be no evidence for a doublet group, corresponding to an excited state near the ground state. In view of the resolving powers obtained by these workers, it is probable that such a state would have been detected by them.

<u>$C^{12}(d,n)\ N^{13}$.</u> The Q of this reaction is -0.28 Mev. and therefore none of the reported excited states would be excited by the beam energy used. The three excited states which have been reported in this nucleus appear to correspond to those mentioned before for the mirror nucleus C^{13}. The excited levels at 3.511 and 3.558 Mev. are of some interest, their separation being similar to the energy of the radiation detected, though energetically it is not possible for this radiation to arise from a transition between these levels. It would appear, however that these levels do not form a true doublet, but their proximity is largely accidental, for the corresponding levels in C^{13}, as found by comparing the assignments of J and parity values, are separated by some 0.2 Mev. As mentioned in the discussion earlier, these levels, on the shell theory, arise from different modes of excitation, rather than any level splitting.

The literature gives no indication of magnetic analysis of charged particles in transitions to the ground state of this nucleus, and therefore it is feasible that this reaction might be responsible for the radiation arising from a transition between a low-lying excited state and ground.

<u>$C.^{12}(d,\alpha)B^{10}$.</u> Since the Q of this reaction is -1.35 Mev., this reaction is not energetically possible and need not be considered.

$C^{13}(d,p)C^{14}$. The Q for this reaction is 5.94 Mev. and hence the reaction is energetically possible and the reported 6.1 Mev. level may also be excited. The shell model gives a configuration of $(1p_{3/2})^8$ $(1p_{\frac{1}{2}})^2$, where the two nucleons outside the sub-shell are both neutrons. Thus the isobaric spin number will be given by T = 1, and the ground state should be given by $T_z = 0$ (j-j coupling) or $^1S_0$ (LS coupling) corresponding to an excited state of N^{14}. Excited states would be due to raising one of these nucleons to higher levels, or to raising one of the $p_{3/2}$ nucleons from the sub-shell to a $p_{\frac{1}{2}}$ state. This would give a fairly large value for the position of the first excited state, and little chance of splitting of the ground state. However, the anomalous long life of C^{14} is not in agreement with the shell theory, and it is possible that the assignments made to C^{14}, N^{14} are not accurate, and hence the possibility of a low-lying level in C^{14} is not completely ruled out. It is felt, however, more likely to be found in the N^{14} nucleus than in this as will be discussed later.

This reaction has been studied by Sperduto, Holland, Van Patter & Buechner (1950). They used a comparatively thick target about 90 Kev. thick, with the result that the peak in the spectrum corresponding to the ground-state protons was wide. Its shape, as given in curve 2 of their paper, would not be inconsistent with the existence of two closely spaced groups. It is therefore possible that the radiation was due to this reaction.

<u>$C^{13}(d,n)N^{14}$.</u> The Q-value for this reaction is 5.32 Mev., and hence the transition can occur to the ground and to several of the excited states. Shell theory predicts that there will be two nucleons (one proton, and one neutron) in the configuration $p_{\frac{1}{2}}$ outside the $p_{3/2}$ sub-shell. The ground states will be J=1, on j-j coupling, or $^3S_1$, on LS coupling, but higher levels will depend on the type of coupling. On simple j-j theory, the first excited state will be due to splitting of the state with two nucleons in the $p_{\frac{1}{2}}$ shell, and will give J = 0, or $^1S_0$, which is analogous to the ground state of C^{14}. Higher states will be due to excitation of one or two of the $p_{3/2}$ nucleons to the $p_{\frac{1}{2}}$ subshell, with subsequent coupling, between the "holes" for these cases. The first of such levels would, according to Inglis, (1953), be a state with J=0, on j-j coupling or ^3D state on LS coupling. If LS coupling occurs, this level will be depressed. It has been suggested by Feenberg & Hammack (1949) that the anomalous long lifetime of C^{14} might be explained if the ground-state of N^{14} was ^3D. However, if this were the case there would be two other low-lying states of the ^3D triplet, and these have not previously been reported, though Van de Graaf, Sperduto, Buechner, & Enge (1952) have studied the reaction $O^{16}(d,\alpha)N^{14}$, using a magnetic analyser to search for low-lying levels. Their target was such that groups appeared in the analyser as doublets, due to the reactions occurring on either side of the backing material, and the investigation was not searching for such low levels as would be required to account for this radiation. Their

published graphs also give an indication of a small group at the low energy edge of the main proton group to the ground state, though it is not possible to derive any quantitative results from this article. Thus, if the radiation does arise from this reaction, it would be compatible with LS coupling giving rise to ^3D ground and excited states. Such an assignment might also explain the long life-time of C^{14}.

<u>$C^{13}(d,\alpha)B^{11}$.</u> The Q for this reaction is 5.16 Mev., and thus the reaction could proceed to the ground state and also the excited levels of B^{11} at 2.14, 4.46 and 5.03 Mev. Shell theory would suggest that this nucleus is one short of the closed shell of 8 $p_{3/2}$ nucleons and thus may be represented as a $(p_{3/2})^{-1}$ configuration. Higher states would occur from excitation of one of these nucleons to an $s_{\frac{1}{2}}$ or $d_{5/2}$ state giving a configuration $(p_{3/2})^6$, $(s_{\frac{1}{2}})^1$. A study of this reaction was reported briefly by Strait, Van Patter, Sperduto & Buechner (1951), who do not mention any sign of a doublet state of the ground or low-lying levels. The reaction $B^{10}(d,p)B^{11}$, to the same final nucleus, has been studied more fully by Van Patter, Buechner, & Sperduto (1951,) and there appears to be no evidence in their work for doublets in any of these levels. It is, of course, possible that transitions to a low-lying excited level might occur in one reaction and not in another, but it appears that this reaction would not be the one from which the reported radiation arises.

CONCLUSION.

Unfortunately, the results obtained by using targets of separated isotopes of C^{12} and C^{13} were not sufficiently definite to be able to allocate the radiation to one or the other, but it would appear to be more probable that it was arising from the C^{13} target. If this were the case it would agree with the most probable allocation of the radiation on the discussion above- that it arises from a transition from an excited state of N^{14} to the ground state, following the reaction $C^{13}(d,n)N^{14}$. Other reactions which might lead to the radiation, by a transition from an excited state to the ground state of the final nucleus, would be $C^{12}(d,n)\ N^{13}$, and $C^{13}(d,p)\ C^{14}$.

REFERENCES

Ajzenberg, F., & Lauritsen, T., 1952, Rev.Mod.Phys.24,321.

Alburger, D.E., & Hafner, E.M., 1950, Rev.Mod.Pys.,22 373.

Allan, H.R., & Wilkinson, C.A., 1948, Proc.Roy.Soc.,A, 194,131.

Allen,R.C., & Rall, W., 1951, Phys.Rev., 81, 60.

Alvarez, F.W. & Bloch, F., 1940, Phys.Rev., 55, 322.

Bair, J.K., Mainschein, F.C., & Baker, W.B., 1951, Phys.Rev., 81, 283.

Bannerman, R.C., Lewis, G.M., & Curran, S.C., 1951, Phil.Mag., 42, 1097.

Benson, B.B., 1948, Phys.Rev., 73, 7.

Bethe, H.A., 1937, Rev.Mod. Phys.,9, 69.

Blatt, J.M., & Weisskopf, V.R., 1952, "Theoretical Nuclear Physics", Wiley, New York, ch.12.

Bohr, N., 1913, Phil.Mag., 26,1.

Breit, G., & Wigner, E., 1936, Phys.Rev., 49,519.

Brostrom, K.J., Huus, T., & Tangen, R., 1947, Phys.Rev.,71,661.

Buechner, W.W., Strait, E.N., Sperduto, A., & Malm,P.,1949, Phys.Rev., 76,1543.

Burcham, W.E., & Freeman, J.M., 1949, Phil.Mag.,40,807.

Burling, R.L., 1941, Phys.Rev., 60,340.

Cockcroft, A.L., & Curran, S.C., 1951, Rev.Sci.Instrum.,22,37.

Compton, A.H., & Allison, S.K., 1935, "X-rays in Theory and in Practice", MacMillan, London, p.365.

Cooke-Yarborough, E.H., Bradwell, J., Florida, C.D., & Howells, G.A., 1950, Proc.Instn.Electr.Engrs.,pt.1, 97,108.

Curran, S.C., Angus, J., & Cockcroft, A.L., 1949, Phil.Mag. 40,36.

Curran, S.C., & Craggs, J.D., 1949, "Counting Tubes", Butterworth's Scientific Publications, London, p.21.

Curran, S.C., & Strothers, J.E., 1939, Proc.Roy.Soc.,A, 172,72.

Dancoff, S.M., & Morrison, P., 1939, Phys.Rev.,55,122.

Day, R.B., 1953, Phys.Rev., 89,908.

De Benetti, S., & McGowan, F.K., 1946, Phys.Rev.,70,569.

Delbruck, M., & Gamow, G., 1931, Z.Phys., 78,16.

Ellis, C.D., & Skinner, H.W.B., 1924, Proc.Roy.Soc.,A, 105,165.

Elmore, W.C., & Sands, M., 1949, "Electronics", McGraw-Hill, London, pp.43,133.

Enge, P.M., Buechner, W.W., & Sperduto, A., 1952, Phys.Rev., 88,963.

Enge, P.M., Buechner, W.W., Sperduto, A., & Van Patter, D.M.,
1951 a, Phys.Rev.,81,317.
1951 b, Phys.Rev.,83,31.

Feenberg, E., 1950, Phys.Rev., 77,771.

Feenberg, E., & Hammack, K.C., 1949, Phys.Rev., 75,1877.

Ghoshal, S.N., 1950, Phys.Rev., 80,939.

Gibson, W.M., Green, L.L. & Livesey, D.L., 1947, Nature, Lond., 160,534.

Goutsmit, S., & Uhlenbeck, G.E., 1926, Nature, Lond.,117,264.

Grove, G.R., Cooper, J.N., & Harris, J.C., 1950, Phys.Rev. 80,107.

Hebb, M.H., & Morrison, E., 1940, Phys.Rev., 58,486.

Heitler, W., 1936, Proc.Camb.Phil, Soc., 32,112.

Helmholtz, A.C., 1941, Phys.Rev., 60,415.

Henneberg, W., 1933, Z.Phys., 86,592.

Hornyak,W.F., & Lauritsen, T., 1948, Rev.Mod.Phys.,20,191.

Hornyak, W.F., Lauritsen, T., Morrison, P., & Fowler, W.A., 1950, Rev.Mod.Phys., 22,291.

Inglis, D.R., 1953, Rev.Mod.Phys., 25,390.

Livingstone, M.S,Genevese, F., & Konopinski, E.J.,1937, Phys.Rev., 46,542.

McMillan, E., & Lawrence, E.O., 1935, Phys.Rev., 47,343.

Mayer, M.G., 1950, Phys.Rev., 78,16.

Mitchell, A.C.G., 1950, Rev.Mod.Phys., 22,36.

Moseley, H., 1914, Phil.Mag., 21,669.

Oppenheimer, J.R., & Phillips, M., 1935, Phys.Rev., 48,500.

Peters, O., 1936,Ann.d.Physik, 27,299.

Plain, G.P., Herb.,R.G., Hudson, C.M., & Warren, P.R., 1940, Phys.Rev.,57,187.

Pollard, E., 1940, Phys.Rev., 57,1086.

Rabi, I.I., 1937, Phys.Rev., 51,652.

1939, Phys.Rev., 55,526.

Rae, E.R., & Grant, P.J., 1951, Private Communication.

Rasetti, F., 1936, "Elements of Nuclear Physics", Prentice Hall, Inc., New York, p.68.

Rose, M.E., Goertzel, G.H., & Perry, (unpublished), Oak Ridge National Laboratory Report ORBL 1023 (cited in Wapstra & Veenendaal, 1953).

Rose, M.E., Goertzel, G.H., Spinrad, B.I., Harr, J., & Strong, P. 1951, Phys. Rev., 83,79.

Rosenblum, S., 1930, J. phys.et radium, 1,438.

Rutherford, E., 1911, Phil.Mag., 27,703.

Rutherford, E., Chadwick, J. & Ellis, C.D., 1930, "Radiations from Radioactive Sources", Cambridge University Press, London, p.378.

Rutherglen, J.G., Rae, E.R. & Smith, R.D., 1951, Proc.Phys. Soc., Lond.,64,906.

Sachs, R.G., 1940, Phys.Rev., 57,194.

Sheline, R.K., & Johnson, N.R., 1953, Phys.Rev.,90,325.

Sheline, R.K., Johnson, N.R., Bell, P.R., Davie, R.C., & McGowan, F.K., 1954, Phys.Rev.,94,1642.

Smith, R.D., 1950, Private Communication.

Sommerfeld, A., 1916, Ann.Phys.,Lpz., 51,1.

Sperduto, A., Holland, S.S., Van Patter, D.M., & Buechner, W.W., 1950, Phys.Rev., 80,769.

Spinrad, B.I., & Keller, L.B., 1951, Phys.Rev., 84,1056.

Strait, E.N., Van Patter, D.M., Buechner, W.W., & Sperduto, A., 1951, Phys.Rev., 81,747.

Swann, C.P., Mandeville, C.E., & Whitehead, W.B., 1950, Phys. Rev., 79,598.

Tangen, R., 1947, K.Norske Vidensk. Selsk.Skr., no.1,p.91.

Van de Graaf, R.J., Sperduto, A., Buechner, W.W., & Enge,P.M. 1952, Phys.Rev., 86,966.

Van Patter, D.M., Buechner, W.W., & Sperduto, A., 1951, Phys. Rev., 82,248.

Van Patter, D.M., Endt, P.M., Sperduto, A., & Buechner, W.W.1952 Phys.Rev., 86,502.

Walker, R.L., & McDaniel, B.D., 1948, Phys.Rev., 74, 315.

Wapstra, A.H. & Veenendaal, A.L., 1953. Phys.Rev., 91, 426.

Weiszacker, C.F. von, 1936, Naturwiss, 24, 813.

Wiedenbeck, M.L., 1945, Phys.Rev., 68, 237.

1947, Phys.Rev., 72, 429.

Wilkinson, D.H., 1950 a. Helv.Phys.Acta, 23, supplement 3.

1950 b, "Ionisation Chambers and Counters", Cambridge University Press, London, p.90.

Wilson, H.A., 1950, Phys.Rev., 77, 516.

1952, Proc.Roy.Soc., A, 214, 446.