THE PHOTODISINTEGRATION OF NEON AND OXYGEN

BY

G. I. CRAWFORD

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CONTENTS

PREFACE

This thesis contains an account of research conducted at the University of Glasgow between October 1953 and September 1956.

The introductory chapter contains a summary of the results of experiments on photonuclear reactions in light nuclei; a critical review of experimental techniques used in such investigations; a review of theories of photonuclear processes; and a discussion of selection rules based on the concept of charge independence of nuclear forces, and their influence on photonuclear reactions.

In Chapter II the experimental technique used by the author is described, special mention being given to certain improvements introduced by the author to the system of operation of the cloud chamber. The development of an analysis technique, which was used in the experiments described in the later chapters, is discussed. The author's contributions to this process were experimental, rather than theoretical. The system was originally designed by Messrs. I.F. Wright and D.R.O. Morrison, and is based on microscope measurements made on the film negatives.

Chapter III contains an account of an experiment on the photodisintegration of neon. New results are presented for the (γ,p), (γ,α), $(\gamma,\alpha\alpha)$ and $(\gamma,\alpha p)$ reactions, only the second of which had previously been studied, and that at only a few photon energies. The author assisted Mr. D.R.O. Morrison in the experimental work, and early analysis; he was responsible for the later analysis, of the events of the (γ, p) reaction and certain of the $(\gamma, \alpha\alpha)$ and $(\gamma, \alpha p)$ events, in which he was assisted by Mrs. M.B. Lambie and, later, Mr. I. M. H. Preston. The interpretation of the results has inevitably been influenced by frequent discussions with the other members of the group, but the presentation is as original as possible.

Chapter IV describes an experiment on the photodisintegration of oxygen. The author was responsible for the planning of this experiment and was assisted in its execution and in the analysis of the photographs by Mr. I. M. H. Preston. The presentation and discussion of the results is entirely original.

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CHAPTER ONE

INTRODUCTION

1.1 A Review of Experiments on Photonuclear Reactions.

The term "photonuclear reaction" can be applied to a much wider range of reactions than those included in this survey. However, in view of the extent of the subject, severe limitations have been imposed and only reactions, in light and medium weight nuclei, induced by photons with energies below 30 MeV, will be considered. Further, the photo-disintegration of the deuteron will be omitted.

With these restrictions, the first photonuclear reaction to be observed was that in which neutrons were emitted when beryllium was exposed to the gamma-rays from Th C" (Szilard and Chalmers 1934). The study of photonuclear reactions, however, requires photons of much higher energy than are available from naturally radioactive sources. The discovery of the high energy gamma-rays which are emitted when lithium is bombarded with protons provided a very important tool which was utilized in 1937 in a study of many reactions (Bothe and Gentner 1937). This source of gamma-rays is, of course, of only limited application, since only three photon energies are present, and one of these is of very low intensity (Walker and M^c^Daniel 1948).

The development of the betatron (Kerst, 1941) overcame this difficulty and led to rapid progress in the study of photo-disintegration. Such a machine was first used in a study of the yield, near threshold, of a number of elements (Baldwin and Koch 1943). Cross-section curves, deduced from the yield curves for the reactions $C^{12}(\gamma, n) C^{11}$ and $Cu^{63}(\gamma, n)Cu^{62}$ established the existence of the giant resonance (Baldwin and Klaiber) 1948). The beta activity induced in copper as a result of the latter reaction has frequently been measured, and provides a convenient standard by which to monitor gamma-ray doses.

The first photonuclear reaction in which a charged particle was emitted was observed in 1943 (Huber et al. 1943, 1944). The first (γ, α) and $(\gamma$, star) events were observed in a cloud chamber (Baldwin and Klaiber 1946). The first study of a (γ, p) cross-section as a function of energy came much later (Mann and Halpern 1950), when it was shown that cross-section for the reaction $C^{12}(\gamma, p)B^{11}$ was very similar to that for the (γ, n) reaction on the same nucleus.

An early attempt to compare the yields of (γ, p) and (γ, n) reactions (Hirzel and Waffler 1947) suggested the ratio of photoprotons to photoneutrons was much larger than would be expected for the statistical decay of a compound nucleus. The reliability of the experimental evidence on which this conclusion was based is, however, rather dubious. The data was not extensive, and was based on measurements at only one photon energy. Further, it was not always possible to compare yields for the same isotope of a particular element. The conclusion, that the (γ, p) yields are anomalously high, is, however, supported by later work (Weinstock and Halpern 1954) in which the systematics of (γ, p) reactions in several elements were investigated.

If compound nucleus formation is assumed, the yield Y of photo-protons from a given nucleus may be expressed as

$$Y = \int SGP(E)dE$$

where S is the cross-section for the absorption of a photon of energy E.

G is the probability of proton emission from the compound nucleus.

P(E) is the number of photons with energies between E and E + dE. Weinstock and Halpern estimated values of S from work on (γ, n) reactions and calculated G using standard theory (Blatt and Weisskopf 1952 page 340). The values of Y so calculated were then compared with the experimental results (Butler and Almy 1953; Toms and Stephens 1951, 1953). For nuclei with atomic number below fifty the observed and calculated values agree well. However, the yields for heavier nuclei were several orders of magnitude greater than the theory predicted. (It is noteworthy that, in fact, the actual yields are only of the order of one thousandth of those for the (γ, n) reactions).

Probably the most significant feature of the experimental results on photo-nuclear reactions is the existence of the "giant resonance". This peak in the graph of cross-section against photon energy occurs, for the range of nuclei with which this review is principally concerned, at about 20 - 22 MeV, with a value of about 10 mb. (i.e. 10^{-26} cm^2) and a width at half maximum of about 5 MeV. (The figures refer to either (γ, p) or (γ, n) reactions.)

Early attempts to explain the variation of cross-section with energy were based mainly on competition between several reactions.

For example, it was suggested that the decrease in (γ,n) cross-section at energies above that of the giant resonance was due to an increase in the $(\gamma,2n)$ cross-section. However, when it was demonstrated that the (γ,p) and (γ,n) yields approached the 'sum rule' limits (Levinger and Bethe 1950), it came to be accepted that the resonance in the reaction cross-section was due to a resonance in the absorption process rather than to variations in the particle emission. Two experiments (Marshall 1951; Koch, McElhinney and Cunningham 1951) demonstrated that the photon absorption cross-sections, and not merely the photoneutron yields, were peaked.

It was then suggested (Blatt and Weisskopf 1952 page 651) that only electric quadrupole and magnetic dipole absorption took place below about 15 MeV, and that the rapid increase in cross-section above this energy was due to the onset of electric dipole absorption. There is little experimental evidence to support these suggestions. That the giant resonance corresponds to electric dipole absorption is generally accepted; but the majority of the evidence suggests that photon absorption may well be electric dipole in character at lower energies. The results of one experiment (Spicer 1955) favour the hypothesis, since a resonance in the $O^{16}(\gamma,p)N^{15}$ cross-section at 14.7 MeV is reported which would appear to correspond to electric quadrupole absorption. However, Spicer's results are not supported by those of other workers (Johansson and Forkman 1955). In particular, the angular distribution reported by these workers is completely different from that of Spicer, from which the nature of the absorption was deduced. (The $O^{16}(\gamma, p)N^{15}$ reaction is discussed in more detail in Chapture IV). It has been established that the photon absorption in nitrogen in the energy region 7.5 - 10.5 MeV is electric dipole in character (Wright et al 1956). Three resonances in the (γ, p) reaction in this energy range were observed, which corresponded to absorption into known levels, thus establishing the nature of the transitions. The reliability of the experiment is demonstrated by the excellence of the agreement - as shown by "detailed balancing" - with the results of the inverse reaction C^{13} (p,γ) N^{14}. The author can find no justification for believing, as has been assumed (Strauch 1953), that the low energy regions of the (γ, n) excitation curves for carbon, nitrogen and oxygen (Katz and Cameron 1951; Johns et al 1951; Haslam et al. 1951) represent quadrupole absorption.

The papers mentioned in the previous paragraph reported fine structure in the (γ, p) cross-section in the energy region between the threshold for the reaction and the giant resonance. Recent work on the photo-disintegration of oxygen at 23, 25 and 26 MeV (Johansson and Forkman 1956; Stephens et al. 1955, 1956) discovered fine structure in the giant resonance region also. This is in accord with earlier work on the $O^{16}(\gamma, n)O^{15}$ reaction (Katz et al. 1954; Penfold and Spicer 1955) in which "breaks" in the activation curve were attributed to resonances in the cross-section.

The angular distributions of photo-protons and photo-neutrons are of considerable theoretical interest (see 1.3) Compound nucleus theory favours an isotropic distribution, such as was found in several experiments (e.g. Toms and Stephens 1951, Diven and Almy 1950). However work on the $C^{12}(\gamma, p)B^{11}$ reaction has produced a variety of anisotropic results, including "$1 + 3\sin^2\theta$" (Gaerttner and Yeater 1951).

'a pronounced forward peak' (Levinthal and Silverman 1951)

"$1 + (\sin\theta + \frac{1}{4}\sin\theta\cos\theta)^2$" (Mann, Halpern and Rothman 1951)

"$1 + \frac{3}{2}\sin^2\theta$" (Mann, Stephens and Wilkinson 1955)

(This later conclusion being based on the experimental results of the previous paper).

In the author's opinion the experimental information on angular distributions is rather unsatisfactory. An insufficient number of reactions has been studied and the available results are not as reliable as one would desire. In particular, a much larger number of events must be studied, to reduce the statistical uncertainties in the results.

1.2 A Comparison of Experimental Techniques.

Experiments on photonuclear reactions are difficult to perform. In this section some of the techniques which have been used in the study of (γ, p) reactions are discussed. The four main problems facing the experimenter are:-

(a) The protons are produced in a heavy photon background which is liable to interfere with the proton detector.

(b) The cross-sections involved are very small - not more than a few tens of millibarns (mb. = 10^{-27} cm^2).

(c) Not all of the possible techniques have high detection efficiencies. Where, in addition, the solid angle subtended, at the target, by the detector is small the number of events which are recorded may be prohibitively low.

(d) Unless a very thin target is used, energy losses in the target may seriously reduce the resolution of the experiment.

The use of scintillation counters - normally one of the most powerful techniques in particle detection - is rendered virtually impossible by the fact that they overcome none of these difficulties. In particular, the solid angle subtended at the target is inevitably low. The proportional counter has obvious advantages in this respect, and it may even be possible to use the counter gas as the target. However, it must be difficult to ensure that all the protons stopped in the counter; and any which did not would produce pulses which could not be distinguished from those of photo-protons of lower energy which did. Further it would be impossible to identify pulses due to other reactions in which charged particles were emitted. (These last two points assume that a gamma-ray source with a continuous energy spectrum was used, such as a synchrotron or betatron. It might well be possible to overcome the difficulties by using essentially monochromatic sources e.g. (p,γ) reactions, but these are limited in number, and the results are of only limited value.)

Photographic emulsions have extensively been used in the study of photonuclear reactions (Titterton 1955). Two distinct ways of using the emulsions exist, and will be considered in turn.

(i) When the emulsion is used as the target.

An obvious restriction on this technique is the limited number of elements which can be included in the plates. However, a much more serious difficulty is that certain elements e.g. carbon oxygen silver bromine are inevitably present and it is extremely difficult to separate reactions in the different nuclei. In principle this can be done by measuring the ranges of the residual nuclei but these are, in general, too short to permit of accurate measurement. With (γ,α) reactions of fairly high energy this is possible (Millar and Cameron 1953) but it is almost certain that many real events must be rejected because the recoil cannot be measured. It is significant that the cross-section for the $O^{16}(\gamma,\alpha)C^{12}$ reaction as measured by Millar and Cameron is an order of magnitude smaller than that reported by other workers. (Waffler and Younis 1949; Nabholz et al. 1952) who used gamma-rays from the $Li^7(p,\gamma)$ reaction and were able to identify the $O^{16}(\gamma,\alpha)$ events by measuring only the alpha-particle ranges.

(ii) When the target is outwith the emulsions.

This technique has been used more frequently for studies of (γ,p) reactions than has the previous one. It possesses two main advantages over the use of counters; the detection efficiency is higher, and the effect of gamma-radiation is negligible. The chief disadvantage of the technique is that low energy protons fail to reach the emulsions, or to make measurable tracks therein. For example, those workers who used this technique to study photo-proton emission from oxygen (see chapter IV) were unable to detect protons with energies below about 1.5 MeV and are almost certain to have 'lost' many events whose energies lay between 1.5 and 2 MeV.

The development of bubble chambers has not yet reached a stage which justifies their inclusion in this discussion, although they seem likely to be of considerable value in the future. The chief disadvantage of expansion and diffusion chambers is the long cycling time which, inevitably, involves long irradiation periods. This is not a severe restriction in itself, since in any case the irradiation time is much shorter than that required for analysis of the photographs, but demands a considerable amount of indulgence from those who are responsible for the operation of the gamma-producing machine.

Although the diffusion chamber is, normally, continuously sensitive the dense cloud formed when the X-ray beam of a synchrotron passes through removes so much vapour that some time must elapse before a state of supersaturation is restored. In practice a cycling time of about 45 seconds is required (Balfour 1956) which is approximately one half of the cycling time of an expansion chamber of similar dimensions working at a similar pressure. It is possible that the use of "fast recompression" or "over-compression" techniques would allow a reduction in cycling times. In the author's opinion however, a more valuable application of such techniques would be to permit an increase in working pressure. If a cloud chamber were operated at a pressure equivalent to 20 - 30 atmospheres almost all photo-proton tracks would stop in the chamber. It might not, however, be possible to distinguish proton tracks in the dense background of electron tracks if so high pressures were used, but if even 5 - 10 atmospheres were attainable a worthwhile extension of the technique would be achieved.

For, in the author's opinion, cloud chambers possess outstanding advantages over the other possible techniques. In particular all events in which charged particles are emitted can be identified and, when the particle stops in the chamber, all the track is visible and the energy can be determined with more certainty than is possible with other techniques in which the position of the origin of the event is uncertain. Further protons, and alpha-particles, of very low energy can be detected - photo-protons of energy below 0.5 MeV were measured in an experiment on the photo-disintegration of nitrogen (Wright et al. 1956) whereas the lower limit of the photographic plate technique is about 1.5 MeV.

One further difficulty, common to all techniques, lies in assigning the correct photon energy to each event. For all methods measure only the energy of the proton, from which the kinetic energy of the residual nucleus can be calculated. However, the excitation energy - if any - of this nucleus cannot be determined and hence the total energy of the disintegration is uncertain. In some cases, if the first excited state of the product nucleus lies at a reasonably high energy there may be a fairly large range of photon-energies in which only ground state transitions are possible. Also, if (p,γ) radiation is used, only a few transitions are possible, and it may be possible to identify them. However, such gamma-sources are few in number and limited in application. Hence the only solution lies in varying the peak energy of the synchrotron (or betatron) and comparing the energy spectra of the photo-protons at the different energies.

Conclusions.

It is suggested that the ideal approach to a study of photonuclear reactions would be to combine the following experiments for each nucleus which is chosen for study:-

(a) The use of activation techniques to study the (γ,n) reaction.

(b) The use of a conventional cloud chamber to study multiparticle events, and those in which photoprotons of energies below 2 MeV are emitted (the operating pressure being 1 - 2 atmospheres).

(c) The use of a high pressure cloud chamber to study photoprotons of higher energy.

(d) The use of photographic emulsions if the maximum working pressure of the cloud chamber is insufficient to ensure that an adequate number of high energy protons stop in the chamber.

(e) Both (b) and (c) (and (d), if required) should be carried out at several peak energies so that any groups of protons which were found could unambiguously be assigned to the appropriate photon energy. The pressures in the chamber should be chosen to provide a reasonable region of overlap in the proton energies which are measured in each. If photographic emulsions are used, then experiment (c) should still be carried out, to provide a link between experiments (b) and (d). It has been assumed above that a gas target is available, which is more convenient than a solid target for either cloud chamber or emulsion techniques. Solid targets, in the form of thin foils, have been used with emulsions in other experiments however and, despite some loss in energy resolution, would permit a considerable increase in the number of nuclei which are available for study. There seems no reason why foils should not be used, with equal success, in conjunction with a cloud chamber.

1.3 Theories of Photonuclear Reactions.

(a) Introduction.

The basic theory of photonuclear reactions is an application of quantum mechanical principles to the interaction of charged particles with the electromagnetic field. The photon absorption cross-section for nuclei has been calculated by two methods. Firstly the dipole matrix element may be calculated for the absorption of photons, if explicit assumptions are made about the ground state and excited state wave functions. (Either an independent particle model or a collective model may be used). Secondly sum-rules may be used, based only on the properties of the nuclear ground state wave function. Potentials, such as the neutron-proton exchange potential, which do not commute with position will, in general, be different for excited states and the ground state. However, it is still possible to use only the ground state wave function, with the results changed by an amount proportional to the strength of the exchange force.

The complexity of the interaction of electromagnetic radiation with nuclei, and the incomplete comprehension of the nature of nuclear forces, precludes the formulation of any full account of photonuclear processes. The theories which have been advanced to date have been based on broad assumptions and models which are freely admitted to be both extreme and crude. Most of these can be made to give reasonable agreement with the broad trends of experimental results. It is surprising, in fact, that so extreme models can yield such similar results.

It is unfortunate that some of the experimental results which these theories have been called upon to explain are based on not very reliable evidence. Even the "giant resonance", which is probably the most firmly established of the results, has recently been shown (e.g. Stephens et al. 1955) not to be continuous in nature - as had been supposed - but to be composed of several narrow resonances.

The experimental evidence, upon their accordance with which the theories have been judged, can be summarised (Levinger 1954) as;-

(i) The cross-section $\sigma(W)$ for nuclear absorption of photons of energy W has the general appearance of a rather broad peak at about 20 MeV (Em), with a peak cross-section of about 0.1 barns.

(ii) Em decreases with mass numbers A as $E_m \propto A^{-0.2}$

(iii) The full width of the peak at half maximum, Γ, is about 5 MeV (except for "magic" nuclei, for which Γ is about 2 - 3 MeV).

(iv) The area under the $\sigma(W)$ curve, $\sigma_{INT.} = \int \sigma(W)\,dW$, is proportional to A, with proportionality constant about 0.02 MeV-barns.

(b) <u>Sum Rules.</u>

The first photonuclear sum rule appeared in 1950 (Levinger and Bethe 1950). In this paper it was shown that quadrupole transitions can account for only a small proportion of the observed integrated cross-section. The integrated cross-section for electric dipole transitions was evaluated as:-

$$\int \sigma(W)\,dW = 0.06\,(1 + 0.8x)\,\frac{NZ}{A} \text{ MeV-barns} \quad \text{—— (A).}$$

where x is the fraction of attractive exchange force for the neutron-proton potential. A reasonable value for the mean energy for photon absorption was found, and it was claimed that qualitative agreement with a resonance peak could be obtained by consideration of the alpha-particle model. The unexpectedly high yields of photo-protons were also explained on the basis of a photon interacting with a single proton in an alpha-particle sub unit of the nucleus. It was claimed that the ratio of photo-proton to photo-neutron emission was "qualitatively understood".

These sum-rules are independent of any nuclear model - except in so far as the exchange forces are concerned - and are based solely on a knowledge of the ground state wave functions.

More recently a second sum rule, for all multipole transitions, has been obtained (Gell-Mann, Goldberger and Thirring 1954). No nuclear model is assumed, but two assumptions are made about the interaction between nuclei and electromagnetic fields.

(i) Photons of energy greater than the threshold for meson production μ ($\doteqdot 150\,\mathrm{MeV}$) contribute only to mesonic processes.

(ii) The forward scattering amplitude for a nucleus approaches that of Z free protons and N free neutrons as the photon energy tends to infinity.

With these assumptions the integrated cross-section up to the meson threshold is

$$\int_0^{\mu} \sigma(W)\, dW = 0.06 \frac{NZ}{A}\left(1 + 0.1\frac{A^2}{NZ}\right) \quad \text{—— (B)}$$

where the final term has been evaluated from the results of photon-nucleon interactions at high energies and is estimated, by the authors, to be accurate to about 30%.

The chief advantage of sum rule (B) over (A) is that the upper limit of integration is specified. In each the first term is the integrated cross-section if mesonic interactions and, hence, exchange forces are neglected. The second term is that due to such effects. Although, properly, the magnitudes cannot directly be compared (since (A) is based only on dipole absorption whereas (B) contains all multipolarities) the comparison is made not unreasonable by the calculation of Levinger and Bethe (loc.cit.) that quadrupole transitions can amount to only about 6% of dipole transitions. Scattering experiments suggest that "x" lies between 0.5 and 0.7. If such a value is assumed (A) reduces to

$$\int \sigma(W)\, dW \doteq 0.06 \frac{NZ}{A} (1 + 0.5)$$

whereas (B) is $$\int \sigma(W)\, dW \doteq 0.06 \frac{NZ}{A} (1 + 0.6)$$

Hence the sum rules are consistent within the accuracy of their evaluation.

(c) Nuclear Models.

As mentioned in section (a) many nuclear models have been suggested in attempts to explain certain of the observed features of photonuclear reactions. Some of these will be summarised here.

The earliest considered the nucleus as a 'liquid drop' (Bohr 1938)in which there is no ordered array. A projectile shares its energy with the whole drop. Subsequently enough energy may be concentrated in one particle to eject it from the nucleus.

An extreme shell model (Mayer 1950) in which only nucleons outside closed shells take part, with the assumption that nuclear properties may be deduced by neglecting closed shells, is diametrically opposed to certain more recent models (Reifman 1953, Wilkinson 1954).

When the resonance nature of photonuclear cross-sections was discovered a model based on an ordered dipole vibration of protons and neutrons in the nucleus was suggested (Goldhaber and Teller 1948). Three possible potentials were suggested, the most successful being that in which the protons and neutrons move against each other as two incompressible fluids. With not unreasonable choices of two arbitrary perameters it can be shown that E_m varies as $A^{-\frac{1}{6}}$ and $\sigma_{INT.}$ = 0.015 A MeV-barns.

A second Goldhaber-Teller model (Steinwedel and Jensen 1950) is based on a vibration of compressible neutron and proton fluids within a well-defined spherical shell, with a constant nucleon density (although the neutron or proton densities in any region may vary i.e. ρ_N and ρ_P may vary, but $(\rho_N + \rho_P)$ is constant). The cross-section on these two models is resonant over an energy range because the well-ordered vibration lasts for a finite time before the energy is transferred to other nucleon motions through nucleon-nucleon interactions. The value of E_m on this latter model is about 30% lower than the experimental values, but the value for the integrated cross-section agrees well with the sum rule value (Levinger and Bethe 1950). It is noteworthy that this model predicts that photon scattering will make a large contribution to the integrated cross-section.

One common feature of all these models is that a photon, absorbed near an eigen-energy of some collective motion, sets up a well-ordered motion whose vibrations are damped due to the transfer of energy through nucleon interactions. Thus a compound nucleus is formed from which nucleons may be emitted in accordance with statistical theory (Blatt and Weisskopf 1952 Chapter VIII).

Since the experimentally measured ratio of photo-protons to photo-neutrons was greater than suggested by statistical theory it was suggested (Courant 1951) that if a photon interacted with a nucleon near the surface of the nucleus the nucleon might be emitted directly without interacting with the residual nucleus. The results, though larger than those of the statistical theory, were still lower than the experimental values.

A somewhat similar model, based on Weisskopf's "cloudy crystal ball" (Feshbach, Porter and Weisskopf 1954), in which an excited nucleon moves in an orbit within the nucleus with a mean free path (λ) of about 2×10^{-12} cm, has been suggested (Wilkinson 1954). On this model, a nucleon is raised to an excited orbit by absorption of a photon. After a finite time $\Delta t = \frac{\lambda}{V}$ (where V is the velocity of a typical nucleon) the energy is transferred to other nuclear motions forming a compound nucleus, which decays in the usual way. The target nucleus is assumed to be satisfactorily described by the shell model, and only transitions from a closed shell are considered. Many transitions which are allowed on the single particle model are forbidden on the shell model owing to the Pauli exclusion principle. Similarly certain transitions which might be small in the single particle model may well be large in a real nucleus (Lane and Radicati 1954). The giant resonance is attributed to these "enhanced" transitions.

The nucleon in the excited orbit may, at any time up to Δt (when the compound nucleus state is formed), escape from the nucleus, thus providing the anomalously high yield of photo-protons. Wilkinson's model predicts the emission of a greater number of "direct" protons since the excited orbit exists for a longer time than in Courant's model, in which a compound nucleus is formed immediately if direct emission has not occurred.

Wilkinson's model successfully predicts the shape of the cross-section including the existence of several narrow resonances within the "giant resonance" region. The correct ratio of photo-proton to photo-neutron yields is obtained, but the values of E_m, the resonance energy, are rather low. One feature, which offers hope of experimental verification, is the prediction of non-isotropic angular distributions for the emitted nucleons. In fact, for ejection from the l-orbit, the expected distribution is

$$(\theta) = 1 + \frac{1}{2}\left(1 + \frac{2}{l}\right)\sin^2\theta \, .$$

Compound nucleus theory, on the other hand, suggests that s-wave proton emission - leading to an isotropic distribution - will predominate.

1.4 Isotopic Spin Selection Rules.

The isotopic spin formalism was introduced many years ago (e.g. Heisenberg 1932) and, without introducing anything which was fundamentally new, led to simplifications in certain calculations in few body problems. Basically it consists of treating the neutron and the proton as alternative states of the same particle, rather than as distinct particles; they are distinguished by the value of isotopic spin co-ordinate i.e. the component of the isotopic spin matrix, which has value $\frac{1}{2}$ for neutrons and $-\frac{1}{2}$ for protons. It has been found possible, rather more recently, to apply the concept to many body problems. In particular, when linked with the hypothesis of charge independence of nuclear forces, it has led to selection rules which are of considerable interest in many branches of nuclear physics including photo-disintegration, beta and gamma decay, as well as in meson reactions. In view of the dependence of the rules on charge independence it is well to consider the justification for that hypothesis before continuing with the discussion of the rules themselves.

Firstly, it must be conceded that the existence of Coulomb Forces means that the hypothesis can never be completely justified - though it may well be a good approximation. That it is a reasonable supposition is suggested by the evidence that the specifically nuclear forces are, to a large degree, charge independent. This includes the equivalence of the singlet scattering lengths for n - n, n-p and p-p interactions and the similarity between the singlet effective ranges for n-p and p-p interactions. Further evidence is obtained from a comparison of n-d and p-d scattering and from a comparison of the level schemes of isobaric nuclei of odd mass. It may reasonably be accepted, therefore, that the hypothesis is reasonably sound, and that the selection rules may be of useful validity. The selection rules for photonuclear reactions may be derived as follows.

If it is assumed that the forces between nucleons are independent of charge then the total isotopic spin $T = \sum_i t^{(i)}$ of a system of "i" nucleons is a constant of the motion, and hence a definite eigenvalue $T(T + 1)$ of T^2 can be assigned to each nuclear stationary state.

The interaction between a nucleus and an electromagnetic field can be represented by a Hamiltonian H which may be written

$$H = H_0 + H_1 = H_0 + \sum_i f_i \, t_z^{(i)}$$

where H_0 represents that part of H which is independent of isotopic spin and is, therefore, a scalar with respect to rotations in isotopic spin space. H_1 transforms like the z - component of a vector in that space.

It follows that

1. Transitions induced by H_0 obey $T - T^1 = 0$ (since, otherwise H_0 vanishes).
2. Transitions induced by H_1 obey $T - T^1 = 0, \pm 1$ when $T_z \neq 0$ $\left(T_z = \frac{N-Z}{2}\right)$
   $T - T^1 = \pm 1$ when $T_z = 0$

The most significant fact arising from this is that, for self-conjugate nuclei (i.e. those with $T_z = 0$), electromagnetic transitions which take place without change of isotopic spin must arise from H_0 alone. (This subject is treated in more detail by Trainor (1952) and Radicati (1952))

Hence for photonuclear reactions in self-conjugate nuclei, we have the rules

1. For electric dipole transitions $T - T^1 = \pm 1.$
2. For other transitions $T - T^1 = 0, \pm 1.$

Thus electric dipole absorption by self conjugate nucli is forbidden unless a T = 1 state of the nucleus is excited.

The total isotopic spin T of a system is obtained from the isotopic spins of the constituent nucleons, following the usual rules for the addition of angular momenta. The behaviour of the component along the z - axis is generally trivial. The 2T + 1 different nuclei which can be formed - subject to the Pauli conclusion principle - from a given nuclear wave-function by changing neutrons into protons (and vice versa) without changing the wave-function form what is known as an "isotopic spin multiplet", characterized by the 2T + 1 values of T. Obviously these members of such a multiplet must have the same spin and parity; their masses will also be equal if allowance is made for the neutron-proton mass-difference, and for the Coulomb interaction. The identification of such multiplets provides strong evidence in favour of the theory of charge independence (Wilkinson 1953).

The impurities to be expected, on the basis of a Coulomb perturbation of a charge independent Hamiltonian, have been estimated (Radicati 1953, MacDonald 1954, 1955). Many experiments have been performed with the object of measuring the effectiveness of the selection rules, and results in accord with these predictions have been obtained (Wilkinson et al 1953 - 6). From this work we may expect that, in light nuclei ($A \lesssim 20$), for excitation energies below about 15 MeV the impurity of any particular state will lie between a few tenths of a per cent and a few per cent. Thus, instead of the traditions being completely forbidden as demanded by the rules, we may expect that "forbidden" reactions will be inhibited by a factor ranging from say, 20 - 500, depending on the particular states involved. If therefore, a state may de-excite by the emission of either of two particles, and one of these transitions is "allowed" whereas the other is "forbidden" by the isotopic spin rules, and if the two transitions are, otherwise, equally probably then that one which is in accord with the rules may be expected to predominate. However, the emission of a particle in violation of the rules would be expected to compete more than favourably with the emission of a gamma ray.

The selection rules are mainly of interest when applied to the photo-disintegration of self conjugate nuclei. Even in such cases, however, the influence on the (γ,p) and (γ,n) reactions is likely to be slight, since the states of the residual nuclei following such reactions are of half-integral isotopic spin. The selection rules are, therefore, of major importance only when α-particle emission is considered. It has been noted (Gell-Mann and Telegdi 1953) that the selection rules, if strictly valid demand that (γ,α) reactions in self conjugate nuclei follow electric quadrupole absorption alone, unless enough energy is available to leave the residual nucleus in a T = 1 state. For electric dipole absorption must form a T = 1 state and Alpha particle transitions have Δ T = 0; also alpha-particle emission from the 1 + state, formed by megnatic dipole absorption, to the 0+, 2+ and 4+ low lying states of the product nucleus is impossible. It is suggested, however, (Gell-Mann and Telegdi loc. cit) that there may be an energy region between the lowest T = 1 state of the parent nucleus and the threshold for neutron or proton emission in which alpha particles may be produced as a result of the impurities of the isotopic spin states.

The following paragraph from the Gell-Mann Telegdi paper is quoted, almost verbatim, because of its importance in a discussion of the reaction Ne^{20} ($\gamma,\alpha\alpha$) C^{12} (see Chapter III).

"The charge independent perturbations contribute also to the fate of a residual T = 1 state produced by alpha-particle emission in accordance with the selection rules. Again if gamma-ray emission is the only process which competes effectively, further alpha-decay to a T = 0 state may occur. It should be noted that such an α-α cascade through a level with T = 1 will prevail not only over a corresponding cascade through a T = 0 level, but also over the direct emission of two alpha-particles. For these "forbidden" modes of decay of initial T = 1 states we expect the smallness of the isotopic spin impurity not to be compensated by phase-space factors. In the allowed mode of decay of the initial T = 1 state, the residual nucleus may find itself unable to do anything but violate the conservation law.

The isotopic spin selection rules are based on the assumption of charge independence. It has been shown (Kroll and Foldy 1952) that the less stringent requirement of charge symmetry (i.e. the assumption that n-n and p-p forces are equal but that these are not necessarily equal to n-p forces) provides selection rules for self-conjugate nuclei, which are, in fact, identical to isotopic spin selection rules. All the experimental evidence about the selection rules has, so far, referred to self conjugate nuclei with $T < 2$ and, hence, satisfies either set of selection rules. There are, however, reasons for believing in the fuller concept of charge independence (Wilkinson 1953).

It has been suggested (Peaslee and Telegdi 1953) that experiments with light nuclei having $A = (4n + 3)$ may provide evidence in favour of one theory or the other. States with $T = \frac{1}{2}$ and $T = \frac{3}{2}$ will be formed following photon absorption. After neutron emission, the residual nucleus will have both $T = 0$ and $T = 1$ low lying levels while the available states in the daughter nucleus following triton emission must be $T = 0$. From $T = \frac{1}{2}$ states neutron and triton transitions to $T = 0$ or $T = 1$ states are allowed. However, from $T = \frac{3}{2}$ states only neutron emission - to $T = 1$ states - is allowed. Thus, in the energy region up to the threshold for triton emission to a $T = 1$ state in the product nucleus, a comparison of the levels appearing in the (γ, n) and (γ, t) reactions will distinguish the $T = \frac{1}{2}$ and $T = \frac{3}{2}$ states.

The experimental evidence on the photo-disintegration of Li^7 supports the hypothesis of charge independence. For 5 neutron-emitting levels are reported (Goldemberg and Katz 1953) but only 2 which emit tritons (Titterton and Brinkley 1953).

CHAPTER TWO

EXPERIMENTAL TECHNIQUE

II.1 The Operation of the Expansion Chamber.

In chapters three and four are described experiments in which the photo-disintegration of neon and oxygen were studied by passing the bremsstrahlung from a synchrotron through an expansion chamber filled with the appropriate gas saturated with water vapour. Photographs were taken after each expansion, and the films were analysed by a technique which is described in the second part of this chapter. This first section describes the operation of the chamber proper.

The cloud chamber used was of conventional design. The 'Perspex' cylinder, which was 12 inches in diameter, $2\frac{1}{2}$ inches high and $\frac{1}{4}$ inch thick, rested on a brass plate, the centre of which was perforated. The volume was defined by a diaphragm of butyl rubber which was free to move between two brass plates, the first of which has already been mentioned and the second of which was movable. (This permitted the variation of the expansion ratio). The position of the diaphragm was controlled by the pressure of the gas which filled the bottom part of the chamber. A significant reduction in the number of electron tracks in the chamber was achieved by reducing the thickness of the chamber wall to 0.09 inches at the regions of entrance and exit of the X-ray beam. The chamber was placed one metre from the target of the synchrotron; a lead collimator was used to produce a rectangular beam 10 cm. wide and $2\frac{1}{2}$ cm. high, at the chamber. The bottom of the chamber was covered with black velvet, which was found to be the most suitable background for photographic purposes. A 'grid' of fine wire, 0.002 inches in diameter, which was stretched just above the surface of the velvet, provided a reference frame which was used in the analysis of the photographs.

The chamber was carefully positioned so that the X-ray beam passed through the centre of the illuminated region and along the direction of the control grid wire. This was carried out in two stages:-

(a) The collimator was positioned so that the beam passed centrally through.

(b) The cloud chamber was then placed in the correct position relative to the collimator.

The position of maximum intensity of the uncollimated beam was found by irradiating an array of copper rods and measuring the induced beta-activity. The collimator was then placed so that the position of maximum intensity coincided with the centre of the hole in the face of the lead block which was nearer the synchrotron. Lead plates each containing a row of three pinholes with the central one at the centre of the collimator were then placed over the front and rear faces. Examination of the pattern produced when an X-ray plate on the chamber side of the collimator was exposed then enabled the latter to be correctly aligned. That the chamber was correctly positioned was verified visually by shining a light through the collimator and, also, by exposing X-ray plates at the entry and exit windows.

In the period between expansions the diaphragm was held in its highest position by connecting the bottom section of the chamber to a reservoir of compressed air which was maintained at a pressure of approximately 8 pounds per cubic inch above that of the gas in the chamber proper. An expansion was caused by releasing the compressed air to the atmosphere through an orifice which was approximately one inch in diameter. This was normally sealed by a rubber-capped brass disc, mounted coaxially on a rod the lower half of which was of steel. This was held in place by the action of a D.C. solenoid through which was passed the cathode current of a pair of type 6L6 output tetrodes which were connected in parallel and normally conducting. A fast expansion was caused by applying a large negative pulse to the control grids of these valves thus cutting them off. After the expansion the valve was reset by applying a sudden voltage to a second solenoid, situated below the first. This impelled the rod upwards into its original position, where it was held in place by the field of the first solenoid.

It is of great importance, in the study of photonuclear reactions, that good track quality be obtained, since it may be necessary to measure the tracks of protons, alpha-particles and residual nuclei the densities of ionisation of which are markedly different. For operation with the cloud chamber the output of the synchrotron was reduced to single bursts of X-rays which were of very short duration (about 40 microseconds). Once the expansion ratio had been correctly adjusted the most important factor which governed track quality was the time delay between the expansion of the chamber and the passage of the X-rays.

The magnet of the synchrotron was permanently energized and the "single shots" of output were obtained by applying single pulses to the gun, via a push-button switch. When the button was pressed a pulse, derived from one of the magnet coils, was passed to a flip-flop circuit, in the cloud chamber control unit, which produced the negative pulse which caused the fast expansion. After the cloud chamber pulse a finite delay occurred before the pulse was fed to the synchrotron gun. During the preliminary stages of each experiment this delay was varied, in steps of 5 milliseconds, between 30 and 70 milliseconds and the shortest delay consistent with good track quality was adopted for the subsequent work. A too short delay produced tracks which were very diffuse, whereas an unnecessarily long delay resulted in an increase in chamber background without any significant improvement in track quality.

One further variable delay was the time which elapsed between the expansion of the chamber and the flashing of the lamps by which the photographs were taken. Here, again, the minimum delay was selected so that, although sufficient condensation had occurred along the tracks which were of interest, the tracks of electrons had not reached maximum intensity nor had the densest tracks had time appreciably to diffuse. Since very short exposures were required, it was convenient to open the camera shutters before expansion and obtain the desired exposure time from the short duration of the flash of light from the lamps. These were discharge tubes filled with xenon gas to a pressure of 10 centimetres of mercury. These were fed from a bank of condensers, of 600 microfarads total capacity, charged to approximately 1 kilovolt. (The optimum voltage was found for each experiment). The condensers discharged through the lamps when the gas was rendered conducting by the application of the output from an automobile type ignition coil.

An ionisation chamber mounted on the wall of the synchrotron room behind the cloud chamber was used for monitoring purposes. The output pulses were amplified by conventional equipment and displayed on the screen of a cathode ray oscilloscope. The pulse height was noted each time that an expansion was made. The monitoring system was calibrated by noting the pulse height during the irradiation of a standard copper foil. The radiation dose during this irradiation was found by measuring the beta-activity of the foil. The copper activity was subsequently compared with the response of a Victoreen thimble mounted at the centre of a Perspex cylinder.

The operations which have been considered were associated directly with the fast expansion of the chamber and with the exposure of the film on which the results were recorded. Many other things must be done if the chamber is successfully to be operated. For instance the condensation nuclei which remain in the chamber after an expansion must be removed before the next expansion can take place. This is accomplished by performing several 'slow' or 'clearing' expansions between successive 'fast' expansions. The original method was to open and close manually at the appropriate times, a tap which was connected to the bottom section of the chamber. For the neon experiment, however, a second magnetic valve was fitted with a smaller orifice than that used for the fast expansions. Also the action of this valve was much slower than the first since the solenoid, in opening the valve, had to overcome the resistance of the spring which, normally, held the valve closed. Since it was considered that greater uniformity of track quality might be achieved if the cycle of slow expansions were performed more regularly than was previously possible, it was decided that the valve should automatically be controlled by an electronic unit which was designed also to perform the other functions which the operation of the chamber entailed.

The basic component of this unit is a uniselector mechanism which is, essentially, a switch of eight banks each containing twenty-five contacts. These were selcted, in turn, by the eight wiper arms which were caused to move round, from one contact to the next, by energizing the coil of a control solenoid. The coil, which actually is in two sections which may be connected either in parallel or in series, was placed in the cathode circuit of a thyratron, whose grid was maintained at a fixed negative potential. The anode was connected to the positive terminal of a large (thirty microfarads) condenser which was charged through one of a number of resistors from a stabilized high tension supply. When the voltage on the anode of the thyratron reached the critical value the valve became conducting, and the condenser discharged through it thus energizing the uniselector solenoid. The time interval between successive discharges was controlled by the time constant of the condenser and charging resistor and, hence, the delay in each uniselector position was dependent on the particular value of resistor which was in circuit. Thus, by using one bank of contacts to select the resistor of the appropriate value, it was possible to make the uniselector control the timing of its own cycle.

The other banks of contacts were used to perform the other operations associated with the expansion cycle viz:-

(a) Open, and close, the camera shutters.

(b) Operate the reset solenoid.

(c) Wind the film onto the take-up spool after each exposure.

(d) Provide a delay of about 35 seconds after the final slow expansion to allow the gas in the chamber to regain its equilibrium conditions.

(e) Operate warning buzzers which indicated that the chamber was ready for the next fast expansion.

The clearing expansions consisted of a period of five seconds during which the chamber was allowed slowly to expand followed by a period of eight seconds when the diaphragm was slowly forced back up. The unit normally provided the maximum number - five - of slow expansions, which were required when the chamber was used in the densely ionising γ-ray beam. Provision was made for having a smaller number of expansions, if the operating conditions warranted a reduction.

Once the expansion ratio has correctly been adjusted for any particular chamber gas it is not necessary to alter it, so long as the temperature of the gas, before expansion, remains constant. Since each "run" occupied a period of six hours some form of temperature control was necessary. This was provided by a water-cooled aluminium cylinder which surrounded the chamber, and was clamped to the brass plates which formed the main part of the chamber. Windows were, of course, left to permit the passage of the beam and the light from the flash lamps, which were mounted horizontally, in a direction parallel to that of the X-rays. The shield was so constructed as to prevent light from the lamps striking on the edge of the Triplex plate which formed the top of the chamber. Otherwise a shadow pattern which obscured much of the chamber was formed in the glass plate. It was important also to prevent direct light striking the velvet which covered the chamber bottom since this produced, on the photographs, an array of spots corresponding to the weave of the cloth.

Stereoscopic photographs were taken by using two, or three, cameras. The film used was Ilford type 5G91 which was found to combine the necessary qualities of sensitivity, contrast and fineness of grain. The film was sixty centimetres wide, unperforated, and was supplied in twenty-five feet rolls, which provided one hundred and twenty exposures. It was usual to take one complete roll of film in each "run".

II.2. The Development of an Analysis Technique.

In the strict sense of the word, an event has been "analysed" when, as a result of measurements of the individual tracks, its nature has conclusively been established, and all possible information about the energies of the particles and the excitation energies involved has been extracted, by calculations based on these measurements. The word "analysis" is used in a rather more restricted sense in this chapter, however, and is applied to the extraction, from the photographs, of the required information about the positions, lengths and angles of the relevant tracks.

The first step in such a process, is, therefore, a preliminary scanning of the films, when the positions of tracks are noted and, where possible, a preliminary separation of the events is made into the various classes (stars, collinear and non-collinear flags etc.) Several scanning techniques are available. In that which has most frequently been adopted, the films after processing, were passed over an illuminated ground glass screen and examined under a simple magnifying glass (a watchmaker's eyeglass was found to be very suitable). For the experiment on the photo-disintegration of oxygen (see Chapter IV) images of the films were projected onto a flat table and examined by the naked eye. When this preliminary scanning has been completed measurements of the tracks is commenced.

The information which is normally required comprises

(a) The position of the origin of the event, and of the end points of any tracks which stop in the chamber.

(b) The angles of all tracks.

(c) The lengths of all of the tracks which lie wholly within the illuminated region of the chamber.

Co-ordinates are measured relative to the reference grid on the chamber bottom; angles are measured relative to the grid wire which was placed in the direction of the gamma-ray beam. (This is simply for convenience in later work; any fixed direction could have been selected).

The most direct analysis technique is that which usually is known as "reprojection". The films are replaced in the appropriate cameras, whose backs are removed so that lights placed above them cast, through the camera lenses, images of what is recorded on the films onto a movable table which is placed approximately in the position of the chamber. The table is then moved until all the images of the track coincide, when they correspond exactly, in position and magnitude, to the original track. The co-ordinates, lengths and angles are then measured directly using protractors, dividers and rulers.

When the tracks to be measured are reasonably long - greater in length than one centimetre, say - this technique is very effective. However, in the study of photonuclear reactions, it is frequently necessary to measure the tracks of recoiling nuclei which are, almost invariably, much shorter than this and, hence a new technique is required. One solution (Wright et al. 1956) is to measure directly, on the films, the lengths of these short tracks, using a binocular microscope of fairly low magnification (about X 40). It is then possible, in principle at least, to calculate the true track length, using the known geometry of the camera system. However, unless this is chosen carefully, the calculations are unduly complicated. (In fact Wright et al. found it practical to use only that one of the three cameras which was positioned centrally above the chamber).

The calculations can be considerably simplified by suitably designing the camera system. For this reason a new system was adopted for the Neon experiment (see Chapter III), in an attempt to provide a more uniform analysis procedure based on microscope measurement of all tracks. The three cameras are mounted on a horizontal board with the lenses at the vertices of an isosceles triangle. The lenses are off-set so that the films may run horizontally. With this system it is possible to calculate the co-ordinates, angles and length of a track from the values of these quantities as measured, using a microscope, on the film negatives. The calculations are based on the following principles:-

1. The image of a track on any film is a horizontal projection of that track.
2. The height of a point above the grid is proportional to the displacement, from the grid, of its projection from a fixed point which is not vertically above it. Consequently the height of a point is defined by the measurement of the displacements from two fixed points.

The procedure, in measuring a track by this technique, is as follows:-

(a) The co-ordinates of each end of the track (x_i, y_i) are measured, relative to the nearest point on the central grid wire, on each of two films (denoted by the suffices i ,j).

(b) The angle between the track and the central grid wire, which lies in the direction of the gamma-beam, (ψ_i) is measured for each film.

(c) The length of the track (l_i) is measured on each film.

(It has been assumed, here, that the track stopped in the chamber. If it did not then, obviously, the co-ordinates of only one end could be measured, and no length measurement would be possible.)

The co-ordinates (x,y,z) length (l) and angles (θ, α) of the original track are then obtained from the following formulae:-

$$Z = \frac{A}{h - z} \left\{ | x_i - x_j | + | y_i - y_j | \right\}$$

$$X = m \; x_1 \left(1 - \frac{z}{h} \right)$$

$$Y = m \; y_1 \left(1 - \frac{z}{h} \right)$$

$$\tan \alpha = \frac{h - z}{B} \times \frac{\cos \beta \, (\tan \delta_1 - \tan \delta_i)}{1 - \frac{q}{B} \, (\tan \delta_1 - \tan \delta_i)}$$

$$\tan\beta = \frac{1}{2}\left(\tan\vartheta_1 + \tan\vartheta_i\right)\left(1 + \frac{q}{h-z}\,\frac{\tan\alpha}{\cos\beta}\right) - \frac{p}{h-z}\,\frac{\tan\alpha}{\cos\beta}.$$

$$l = \frac{C\,l_i}{\cos\alpha} \times \frac{\cos\psi_i}{\cos\theta} \times \frac{1 - \frac{z}{h}}{1 + \frac{x - X_i}{h-z}\,\frac{\tan\alpha}{\cos\beta}}$$

where A,B,C,m are constants which depend on the dimensions of the camera system.

h is the height of the camera lenses above the grid.

p and q are co-ordinates relative to horizontal axes defined, for each pair of cameras, so that the p-axis is the line joining the projections of the camera lenses and the q-axis is the line, perpendicular to the p-axis, through the orthogonal projection of the origin of the track.

β is the angle between the orthogonal projection of the track and the q axis.

ϑ_i is the angle, measured on film "i", between the track and the q-axis.

Xi is the x-co-ordinate of the lens of camera "i".

α is the angle between the track and a horizontal plane; θ is the angle between the projected track and the gamma-beam.

As can be seen from the formulae, measurements on only two films are required for the measurement of either the co-ordinates or angles of a track. In practice, however, the choice of cameras is restricted for:-

(i) the projection of the camera lens of one camera is chosen as the origin of the $(x,y,z,)$ co-ordinate system (the x-axis is the direction of the gamma- beam and the y, z axis complete an orthogonal set). The formulae for the co-ordinates assume that this film is always used; the second is chosen as the one whose camera was nearest to the track. (Thus lens distortion is the lowest possible).

(ii) the films for the angular measurements are chosen so that angle is less than 30°. (There is always one, and only one pair of cameras which satisfies this condition). Hence it is easily possible to obtain α and ψ by successive approximations. In fact, since these angles are calculated to the nearest half-degree, it is usually possible to estimate $\cos\beta$ with sufficient accuracy to make a second approximation unnecessary.

As can be seen from the formulae, very many arithmetical operations are involved in the measurement of each track, and this is the main disadvantage of the system. For, not only are the calculations tedious, but they are very liable to "human errors", which are not easily detected. Hence, although the accuracy of the system is satisfactory when correctly carried out it is not, in practice, sufficiently reliable. Assuming that no arithmetical errors have been made, the accuracy is

$\pm 1^{\circ}$ in θ

$\pm 2^{\circ}$ in α

$\pm$ 0.05 cm. in l.

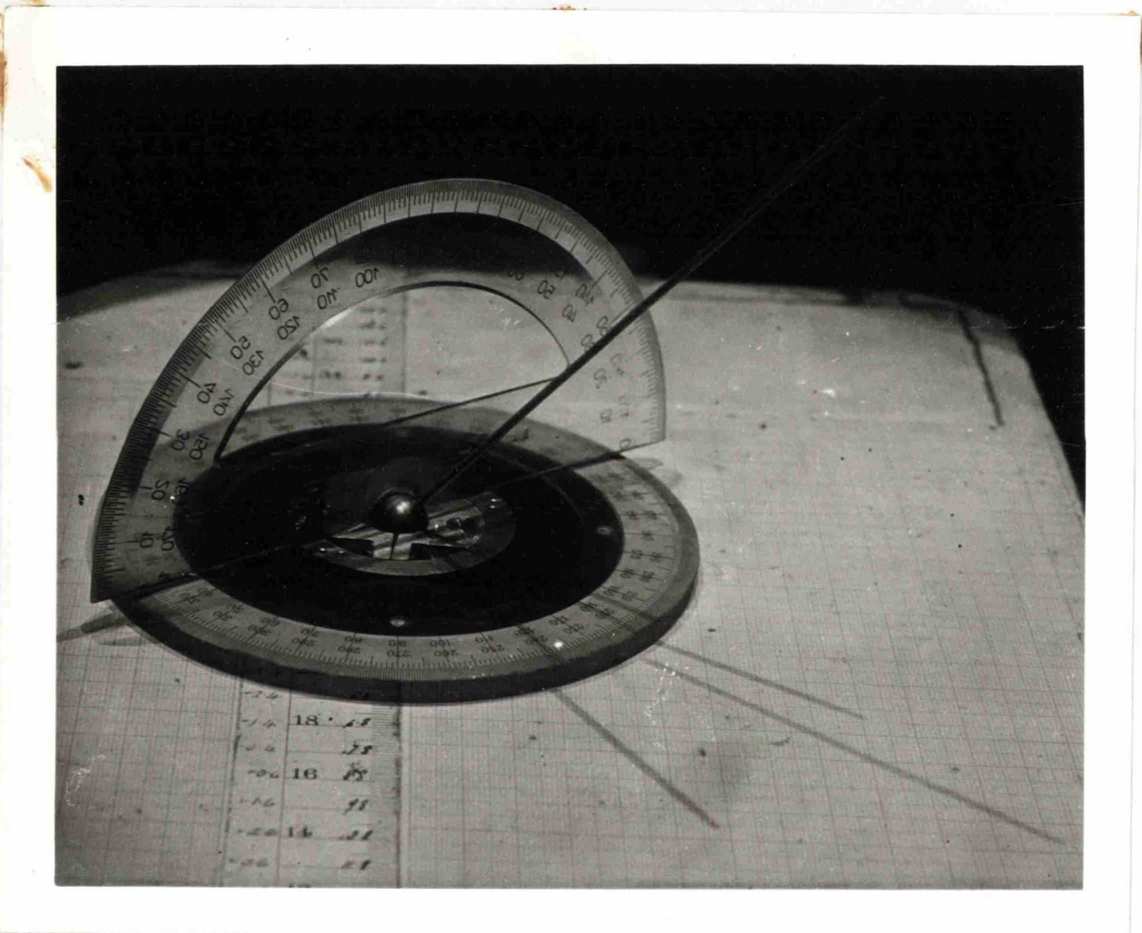


Figure 1.

which compares not unfavourably with the corresponding figures for reprojection, with the advantage that the lower limit of accurate length measurements is much less.

To retain the advantages of the above technique while reducing the number of arithmetical processes would obviously be a useful advance. Two possible solutions are the use of nomograms or of a mechanical analogue. Unfortunately the calculations are not well suited to the application of the first of these techniques, and a very large number of graphs and tables would be required. However the second solution has proved to be very practical.

The mechanical device consists of a needle, which is six inches in length, mounted in a ball and socket at the centre of a 360° protractor. If this is placed beneath the cameras and illuminated by lights shone through the lenses, three shadows are cast by the needle (see fig.1.) The angles between these shadows and a fixed direction then correspond exactly to those which would be recorded on the films if the needle were photographed in this position. If, therefore, the fixed end of the needle is placed in the position, relative to the cameras, of one end of a track, and if the needle is rotated until the angles of shadow (as measured on the protractor) correspond to those of the track as measured on the film negatives, then the needle must lie in the direction of the track. The angle which the needle makes with the fixed direction which is, therefore, that between the track and the gamma-ray beam can then be measured.

If the needle is now moved, without rotation, until the end of the shadow cast by any one light is in the position of the topmost point of the track, a simple relation exists between the true track length, the length of the shadow, and of the track as measured on the corresponding film. In fact

$$l = M\, l_{FILM} \left(1 - \frac{Zo}{h}\right) \frac{l_{NEEDLE}}{l_{SHADOW}} \quad \ldots\ldots\ldots\ldots\ldots(A)$$

where Zo and h are the heights above the grid of the lower end of the track and the camera lens respectively.

M is the factor required to convert measurements in the arbitrary units of the eyepiece scale of the microscope into lengths in centimetres.

The analysis of a track is, therefore, carried out as follows:-

(a) The co-ordinates, lengths and angles on the films are measured, as before.

(b) The co-ordinates of the end points of the track which lie in the chamber are calculated.

(c) The needle is placed in the position, relative to the cameras, of the lower point of the track. A reprojection table, fixed in a horizontal plane but free to move vertically, is used to support the device.

(d) The angles θ and α are measured, using the horizontal protractor and a second 180° one which rotates about a vertical axis through the centre of the ball.

(e) The needle is moved as required, the three shadow lengths are measured, and three values of the track length are calculated using formula (A).

The angles (ψ_i) which are measured, using the goniometer head of the microscope, on the films are the angles made by the positive direction of the track with the direction of the photon beam. If the track is inclined upwards i.e. if the origin is the lowest point of the track, then the shadow angles measured on the protractor are made equal to the corresponding ψ_i. However, if the origin is the highest point of the track, the needle must be placed in the position of the other end of the track and the shadow angles are made equal to ($\psi_i + 180^\circ$). When the needle is correctly orientated its angles, as measured by the protractors, are ($\theta + 180^\circ$) and ($-\alpha$).

In addition to being much less tedious to apply, this technique is much more reliable than that which depended solely on microscope measurements and calculations. Each stage in the procedure is automatically verified, for

1. If the measured co-ordinates are incorrect it is not possible to make the shadow angles coincide with those measured on the films.
2. It is impossible to make all three angles agree unless all have correctly been measured. (In principle only two angles are required to define the direction of the track and, in fact, only

two are used in the earlier calculations. There is no safeguard against an error in one of these).

3. Three values are obtained for the length of the track, instead of one as previously. (It would have been possible to calculate three values but the time required would have been excessive).

One restriction on the technique is that the mechanical design of the device impedes its use for tracks which are close to horizontal, since the minimum inclination of the needle is ten degrees. However, in practice, the angle α is sufficiently well defined if it is known to be less than ten degrees, since the most significant angle is γ which is defined by

$$\cos \gamma = \cos \theta \, . \, \cos \alpha$$

and the error introduced in γ is small since cos 10° is close to unity. Further the effect on the measurement of lengths is small also, for

$$l \propto \frac{l_{FILM}}{\cos \alpha}$$

and the error introduced by assuming, for all tracks with angle α less than ten degrees, that $\cos \alpha = 0.995$ is less than one half of one per cent and, in consequence, negligible.

The accuracy of this technique is similar to that attainable by calculations based on the microscope measurements. This has been verified by measurements of artificial tracks and, also by comparing the results of measurements of real tracks using each of these methods and, also reprojection.

CHAPTER THREE

THE PHOTO-DISINTEGRATION OF NEON

III.1 Introduction

Two papers describing photonuclear reactions in neon had been published at the time when this experiment was commenced. The first of these (Ferguson et al. 1954) presented a graph showing the variation with energy of the cross-section for the reaction $Ne^{20}(\gamma, n)Ne^{19}$. This was obtained by moderating the neutrons in paraffin wax and detecting them in BF_3 counters. A typical "giant resonance" was found at 21.5 MeV with a peak cross-section of 8 mb. The second (Erdman and Barnes 1953) presented results for the reaction $Ne^{20}(\gamma, \alpha)O^{16}$ obtained by exposing an ionisation chamber filled with neon to the radiation from the $Li^7(p, \gamma)$ reaction. It was claimed that, at 17.6 MeV, transitions which left the O^{16} nucleus in one of the excited states at 6 - 7 MeV were much more frequent than ground state transitions.

It was hoped that useful information about three types of reaction would be obtained from the experiment to be described. These were:-

(a) the (γ, p) reaction, which had not previously been studied.

(b) the (γ, α) reaction, which had been studied at only three energies.

(c) the $(\gamma, \alpha\alpha)$ and $(\gamma, \alpha p)$ reactions which had not been studied but which had unusually low thresholds.

It was anticipated that the (γ, p) reaction would exhibit a "giant resonance" but, in view of the low stopping power of neon it was not expected that any fine structure in the cross-section would be detected except, possibly, in the region immediately above the threshold for the reaction. Since the thresholds for the (γ,p) and (γ,n) reactions are high (12.87 and 16.908 MeV respectively) it was expected that many (γ,α) events (threshold 4.746 MeV) would be observed since this is the only reaction, in which a particle is emitted, which is energetically possible below about 13 MeV.

$(\gamma,\alpha\alpha)$ and $(\gamma,\alpha p)$ events are to be expected if, in a (γ,α) or (γ,p) reaction the residual nucleus is left in an excited state above the threshold for further particle emission. The values of the cross-sections for the (γ,α), $(\gamma,\alpha\alpha)$ and $(\gamma,\alpha p)$ reactions should be governed, to some extent, by the isotopic spin selection rules (see chapter 1.4). It was hoped that the validity of these rules might be confirmed by the experimental results.

III.2 Experimental Method.

The expansion chamber was filled with "spectrally pure" neon, saturated with water vapour, to an expanded pressure of 1.2 atmospheres. The operation of the chamber and the associated equipment was controlled electronically, as discussed in chapter II.1. During the irradiations the peak energy of the synchrotron was 23 $\pm$ 0.5 MeV. The radiation dose, which was measured by the method described in the previous chapter, amounted to 0.1 Roentgen. In all, ten series of irradiations were carried out in addition to those performed while the operating conditions were being adjusted. A total of approximately nine hundred exposures were made.

The thresholds for neutron-induced events in neon are:-

$$Ne^{20}\ (n, p)\ F^{20} \ldots\ldots\ldots\ldots 6.27\ \text{MeV}$$

$$Ne^{20}\ (n, \alpha)\ O^{17} \ldots\ldots\ldots\ldots 0.603\ \text{MeV.}$$

The neutrons which always accompany the photon beam are produced chiefly by (γ, n) reactions in the synchrotron target and in the collimator. In an attempt to moderate the faster neutrons, paraffin blocks which totalled four inches in thickness were placed in front of the chamber.

It was not found necessary to take elaborate precautions in processing the films, which were Ilford 5G91, and were developed in Ilford ID 33 developer. The effect of shrinkage of the films was negligibly small. It was, however, found necessary to take steps to ensure that the film remained reasonably taut between the camera gate and the feed spool. This was satisfactorily achieved by using a modified feed spool in place of the plain cardboard one supplied by the makers. One end of a strip of paper, slightly less broad than the film, was fixed to the spool and the end of the film was wound underneath the paper when the film was respooled.

The isotopic composition of neon gas is, approximately:

Ne^{20}	-	91%
Ne^{21}	-	$\frac{1}{4}$%
Ne^{22}	-	$8\frac{3}{4}$%

Hence, although the events observed in this experiment corresponded predominantly to the photo-disintegration of Ne^{20}, some certainly arose from the volume of Ne^{22}; the contribution of Ne^{21} may reasonably be neglected. Although, in principle, events from each of these isotopes can be distinguished, by applying the principle of momentum conservation, in practice the accuracy of measurement which would be required cannot be achieved. However since, in general, the thresholds for reactions in Ne^{22} are higher than those for the corresponding reactions in Ne^{20} and since the proportion of that isotope in the gas is small, it is reasonable to ascribe the observed events to reactions in the main isotope, Ne^{20}.

III.3 <u>The analysis of the Photographs.</u>

(A) <u>Preliminary Analysis</u>

The tracks which were observed when the photographs were scanned under a pocket magnifying glass were divided into a number of classes, the two most important of which were referred to as "flags" and "stars'.

A "flag" was the name given to an event in which two tracks were observed, one corresponding to a fragment (proton, deuteron or alpha-particle) and the other to the recoiling nucleus. Events in which three tracks were visible were referred to as "stars". As a result of the scanning 333 flags and 60 stars were noted. The events were then further classified according to whether or not the individual tracks stopped in the illuminated region of the chamber. In all cases the recoil did so stop.

The events were analysed in the following order:-

(1) stars in which both fragments stopped.

(2) stars in which one fragment stopped but the other did not.

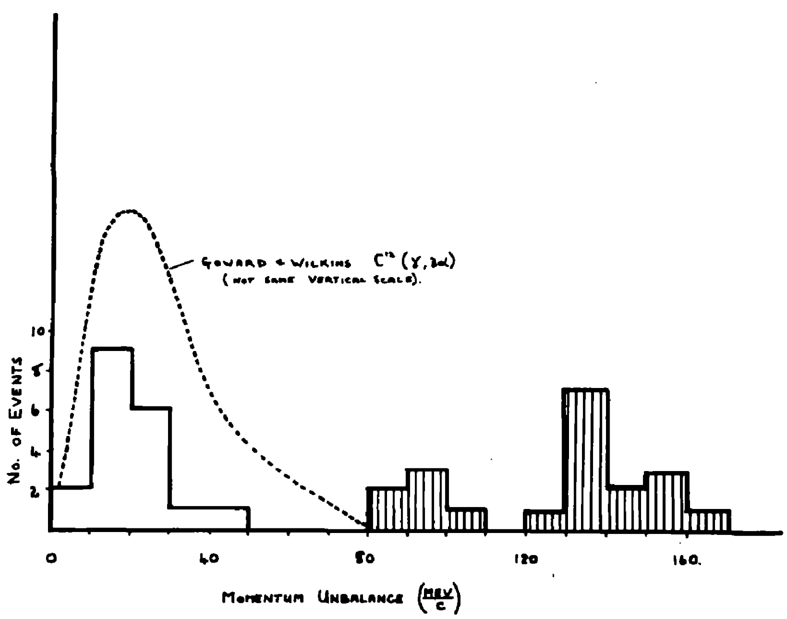
(3) flags in which the fragment stopped.

(4) flags in which the fragment failed to stop.

There were three reactions which would be observed as "stars".

(a)	$Ne^{20}(\gamma,\alpha\alpha)C^{12}$	Threshold	11.895 MeV
(b)	$Ne^{20}(\gamma,\alpha p)N^{15}$		16.856 MeV
(c)	$Ne^{20}(\gamma,pp)O^{18}$		20.825 MeV.

Each event of class (1) was assigned tentatively to one of these reactions after consideration of the density of ionisation and multiple scattering of the tracks, but the final classification was based on a more positive identification. After the lengths and angles of the three tracks of each event had been measured, by the technique described in the previous chapter, the momenta of the three particles were calculated, assuming initially that the visual identification



GOWARD + WILKINS C[12] (γ, 3α)
(NOT SAME VERTICAL SCALE).
No. OF EVENTS
2
4
6
8
10
0
40
80
120
160.
MOMENTUM UNBALANCE (MEV/C)

Figure 2.

was correct. The vector sum of the momenta of the three particles was then subtracted from the momentum of the incident gamma-ray, whose energy was obtained from the sum of the energies of the particles and the threshold energy. In principle, if the event had been identified correctly, this "momentum unbalance" would be zero. However, in view of the probable errors in the measurements, it would be unreasonable to expect the momentum unbalance to be exactly zero. In practice, values up to 50 $\frac{\text{MeV}}{\text{c}}$ were found, although only exceptionally was a value greater than 30 $\frac{\text{MeV}}{\text{c}}$ accepted. (The recoil track of this event had been badly scattered near the origin and, in consequence, its direction was less well defined than was usual). The second most reasonable assignation of each event was then adopted, and the corresponding momentum unbalance evaluated. Figure 2 shows the values of momentum unbalance obtained for the stars in which all tracks stopped in the chamber on each of the two assignations. In every case the value based on the classification which was considered to be the most probable was found to be very much less than the other which, in turn, was smaller than any other possibility. In fact all of the "first choice" values were lower than the least of the others. Also shown in figure 2 is a sketch of similar results obtained by workers who used photographic emulsions to study the reaction $C^{12}(\gamma,3\alpha)$ (Goward and Wilkins 1953). This is included to illustrate the similarity in criteria for acceptance of an event.

As will be shown later, it was possible to calculate the photon energy for each of these events without using the measurements of the recoil track. It is then possible to deduce the energy of the recoil with greater certainty than the measured value, which is limited in accuracy by range straggling and by possible uncertainties in the range-energy relation which was used. However, it was shown, by comparing the calculated energies and the measured ranges, that the relation which had been used was, in fact, accurate. This fact, together with the success of the visual identification of the events (as verified by the separation of "first choices" from "seconds"), provided the justification for the technique used in analysing the stars in which only one of the fragment tracks stopped in the chamber. These events were classified as a result of a visual examination, and the momentum of the particle which did not stop was calculated from the momenta of the two which did and of the gamma-ray. Successive approximations were, of course, necessary since the calculations of the photon energy depends on a knowledge of the energy of the particles. This technique was less reliable than that used for the first group, since it was dependent on measurements of the recoil tracks which were much shorter than the others. In fact, only fourteen of the thirty-eight stars of this class could be analysed; in the other events the recoil was either so short or so badly scattered that a sufficiently accurate measurement was not possible. However, in view of the low values of momentum balance obtained for the first group of stars, it was believed that the results for these fourteen events were sufficiently reliable to be included with the others.

'Flag' events may correspond to any of the following reactions:-

$Ne^{20} (\gamma, p) F^{19}$	Threshold	12.87 MeV
$Ne^{20} (\gamma, \alpha) O^{16}$		4.75 MeV
$Ne^{20} (\gamma, d) F^{18}$		21.1 MeV
$Ne^{20} (\gamma, pn) F^{18}$		23.0 MeV
$Ne^{20} (\gamma, \alpha n) O^{15}$		20.34 MeV

All of the 'flags' observed in this experiment were "collinear" (i.e. the angle between the fragment and the recoil lay between 170° and 190°) and must, therefore, correspond to one of the first three reactions. If a flag is "non-collinear" the momenta can only be balanced if the emission of a neutron, in addition to the charged fragment is assumed.

It is possible that some of the flags were neutron-induced events (e.g. $Ne^{20} (n, p) F^{20}$ or $Ne^{20} (n, \alpha) O^{17}$), but it is unlikely that many (n, p) or (n, α) events occurred. That the precautions (described in section III.2) were effective is indicated by the small number of events whose origin lay without the known dimensions of the photon beam. Since the volumes of the chamber which were "in" and "out" of the beam were approximately equal, the number of events which occurred "out of the beam" - and must, in consequence, have been neutron-induced - was a measure of the number of neutron-induced events which occurred "in the beam". In fact only two of the events which were observed did not originate within the beam.

It was assumed therefore, that all the flags were photonuclear events. Events corresponding to the (γ,α) and (γ,p) reactions could be distinguished visually, since the recoil tracks of (γ,α) events were much longer than the recoils of (γ,p) events. Also there were marked differences in the density of ionisation and multiple scattering of the tracks. When the fragment stopped in the chamber, momentum balancing provided a more certain identification. Unfortunately, however, only three proton tracks stopped.

It is possible that some of the flags corresponded to (γ,d) events but, in view of the high threshold for this reaction, it is believed that few of the events did so correspond. Since the maximum energy of the gamma-rays was only a few MeV above the threshold for the reaction any photodeuterons which were emitted must have been of low energy and a large proportion would, in consequence, have stopped in the chamber. Any which did so would certainly have been identified by momentum balancing but, in fact, none were found. It could reasonably be assumed, therefore, that all of the 'flags' corresponded to (γ,α) or (γ,p) events.

(B) <u>Events in which two alpha-particles were emitted</u>.

The energies of the gamma-rays which caused such events, which were attributed to the reaction $Ne^{20}(\gamma,\alpha\alpha)C^{12}$, were obtained initially, on the assumption that the residual nuclei were formed in the ground state, by adding the energies of the three particles to the threshold energy for the reaction i.e.

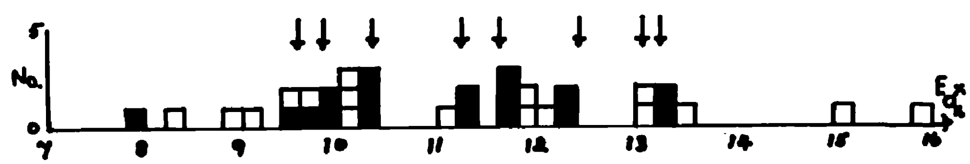
$$(E_\gamma)_{G.S.} = E_{\alpha_1} + E_{\alpha_2} + E_{C_{12}} - Q$$

If the excitation energy of the product nucleus was E^1 then the true photon energy was $E_\gamma = (E_\gamma)_{G.S.} + E^1$. Since the first excited state of C^{12} lies at 4.43 MeV it was possible, in several cases, to be certain that the transition was to the ground state for, since the maximum quantum energy was 23 MeV any events for which $(E_\gamma)_{G.S.}$ was greater than 19 MeV could only be ground state transitions. Further, it has been reported (Ajzenberg and Lauritsen 1955) that in only a small proportion of events do alpha-particle transitions leave a C^{12} nucleus in that excited state. It was assumed, therefore, (at least initially) that all the $Ne^{20}(\gamma,\alpha\alpha)$ events did leave the product nucleus in the ground state.

It was assumed, also that such events represent the formation and two-stage decay of compound nuclei i.e. that they followed the scheme

$$Ne_{20} + \gamma \rightarrow Ne_{20}^{x} \rightarrow \alpha_1 + O_{16}^{x} \;;\; O_{16}^{x} \rightarrow \alpha_2 + C_{12}.$$

The excitation energy of the intermediate compound nucleus state, in oxygen 16, was calculated from the energies and directions of the two



<u>Figure 3.</u> Excitation Energies of O^{16} Nuclei, from $(\gamma,\alpha\alpha)$ events.

alpha-particles and the incident photon. Since, however, it was not possible to determine which alpha-particle was first to be emitted, two values of excitation energy (E^x) were obtained for each event. The calculations were carried out as follows, assuming that one alpha-particle, then the other, was first to be emitted.

(1) The momentum of the recoiling intermediate nucleus was obtained from the momenta of the photon and first fragment. The corresponding (kinetic) energy E_{R_1} was calculated, as was the angle between this recoil and the second fragment.

(2) The momentum of the product nucleus was calculated from those of the intermediate recoil and the second fragment. The (kinetic) energy E_{R_2} of this final recoil was also obtained.

(3) The excitation energy of the intermediate nucleus was then computed from:-

$$E^x = E_{R2} + E_{F_2} - E_{R_1} - Q^1$$

where Q^1 is the binding energy of the second fragment (F_2) in the intermediate nucleus.

(4) The energy of excitation of the first compound nucleus which was, of course, the energy of the incident photon, was obtained from:-

$$E\gamma = E^x + E_1^x - Q^{11}$$

where $E_1{}^x = E_{R_1} + E_{F_1}$

and Q^{11} is the binding energy of F_1 in the target nucleus.

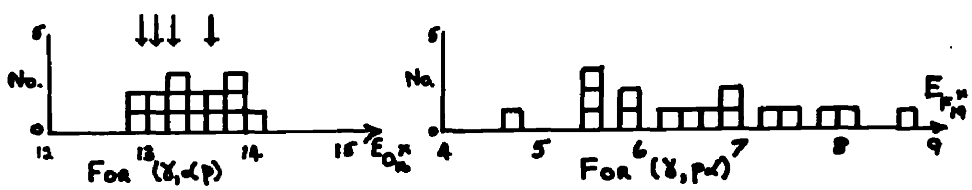


Figure 4. Excitation Energies of O^{16} and F^{19} Nuclei, from $(\gamma,\alpha h)$ events.

The values of E^x so calculated are shown in figure 3.

(C) Events in which an alpha-particle and a proton were emitted.

Such events belonged to one of the reactions Ne^{20} (γ,α p) N^{15} and Ne^{20} (γ,pα) N^{15}. It was assumed that such events corresponded to the two stage decay of a compound nucleus, but it was clearly impossible to distinguish between the two possibilities.

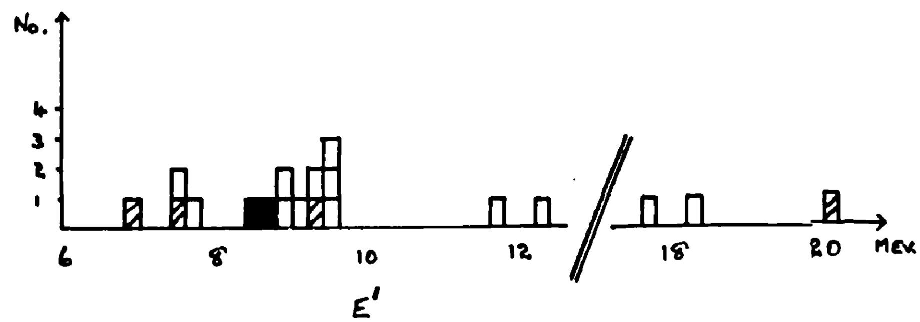
$$\text{(i)} \quad Ne_{20} + \gamma \rightarrow Ne_{20}^{x} \rightarrow O_{16}^{x} + \alpha$$
$$O_{16}^{x} \rightarrow N_{15} + p$$

$$\text{(ii)} \quad Ne_{20} + \gamma \rightarrow Ne_{20}^{x} \rightarrow F_{19}^{x} + p$$
$$F_{19}^{x} \rightarrow N_{15} + \alpha .$$

Consequently both possibilities were considered and the excitation energies in the appropriate intermediate nuclei were calculated in a manner similar to that described above for the (γ,$\alpha\alpha$) events. The results are shown in figure 4.

(D) Events in which a single alpha-particle was emitted.

The results for these events, which were attributed to the reaction Ne^{20} (γ,α) O^{16}, are included because they have an important place in a full picture of the photo-disintegration of neon. The author was, however, not responsible for the analysis of these events. Figure 5 shows values of E^1 which is defined by:-



<u>Figure 5.</u> Results from (γ,α) Reaction in Ne^{20}.

$$E^1 = E_R + E_\alpha - Q$$

Three of the events were analysed by direct measurement of the ranges of the recoil and alpha-particle. In fourteen others the momentum of the alpha-particle (which did not stop in the chamber) was obtained from that of the recoil, by equating the components of the respective momenta at right angles to the direction of the incident gamma-rays. In two cases, although the event had the appearance of a (γ,α) event in which both of the fragments stopped in the chamber, it was not possible to define the origin with sufficient accuracy to permit accurate range measurements. In these two cases the total range, of both tracks, was measured and proportion contributed by each particle was calculated. The three categories are indicated, in figure 5, by the extent of the shading.

(E) Events in which a single proton was emitted.

Since only 3 of the 303 proton tracks which were observed stopped in the chamber, the energy measurements of the majority of such events, which were attributed to the reaction $Ne^{20}(\gamma,p)F^{19}$, were based on the ranges of the recoil tracks. These recoil tracks were very short - seldom longer than 4 mm. - and it was not anticipated that the resulting energy spectrum would be very accurate, but it was hoped that the general nature of the energy dependence of the cross-section for the reaction would be obtained. (It was estimated that the calculated energy of any individual track might be in error by as much as 1 MeV).

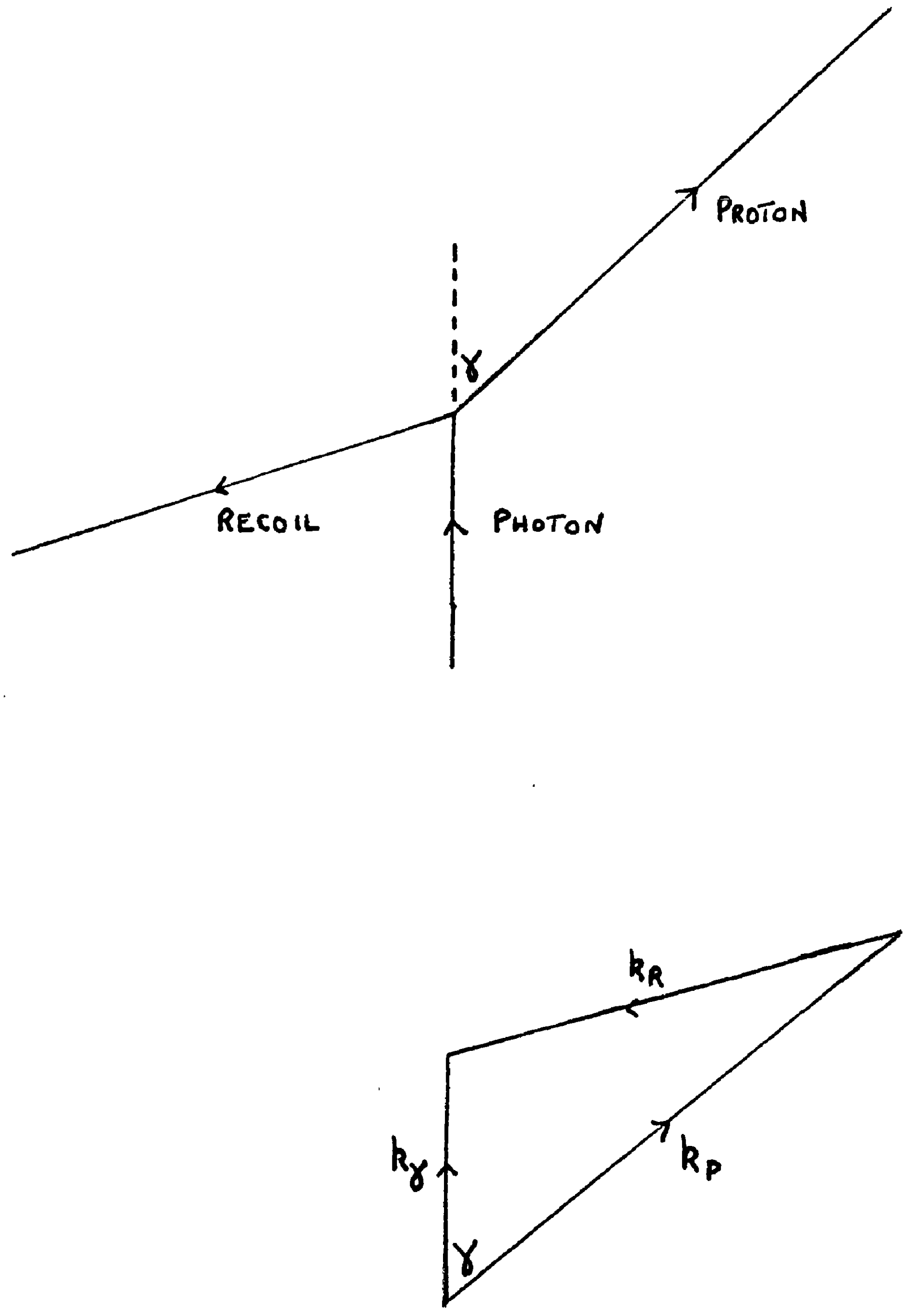


Figure 6.

For each (γ, p) event the length of the recoil and the angles of the proton track were measured. The energies of the protons were then calculated from the energies of the recoils, which were obtained from the measured ranges using a range-energy relation which had been derived from published data (Morrison 1954). When this range-energy curve was drawn it was necessary to extrapolate downwards in energy from the region of experimental measurements. The exact shape of the curve in the region of extrapolation was chosen to agree with the points obtained from those (γ, p) events of this experiment in which the proton energy could be directly measured.

Although there was reason (see later) to believe that the assumption was invalid, it was convenient to assume that, in each event, the product nucleus was formed in the ground state. Then, in the obvious notation,

$$E_{\gamma} = E_p + E_{F_{19}} - Q.$$

The method of calculation is illustrated in figure 6. The momentum of the recoil (k_R) and the angle (γ) between the gamma-ray and proton were known. The proton momentum (k_P) and gamma-ray momentum (k_{γ}) could be calculated by a method of successive approximations but, in practice a series of graphs of recoil range against photon energy were prepared, for a sufficient number of values of angle γ to permit reasonably accurate interpolation. These graphs were obtained by using

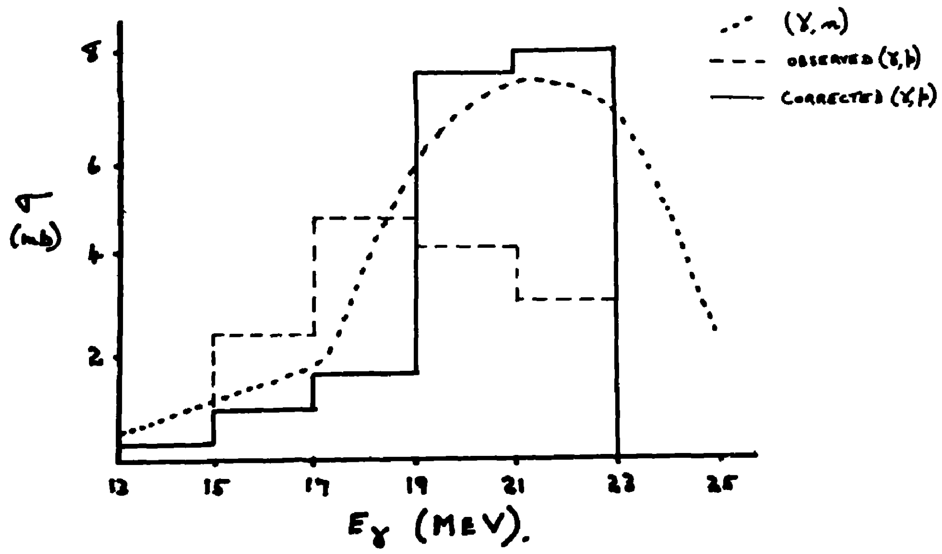


Figure 7. Results for (γ, p) Reaction in Ne^{20}.

the method of calculation outlined above.

If it were possible to measure accurately the angle between the recoil and fragment tracks it would be possible to obtain the photon energy more directly. However, since this angle lies between 170° and 190°, and since the measurement of the angle between two arbitrary directions is inevitably difficult to perform, a sufficiently accurate determination to justify this approach to the problem is not possible.

In order to illustrate the variation of the cross-section for the reaction with the energy of incident photons it was necessary to make allowance for the varying numbers of gamma-rays of different energies which were emitted by the synchrotron. It was assumed that the output spectrum of the Glasgow synchrotron was similar to that of the Saskatchewan machine (Katz and Cameron 1951). The histogram of cross-section against photon energy which was obtained is shown by the dashed line in figure 7. The dotted curve represents the results for the (γ, n) reaction (Ferguson et al. 1954). As can be seen the (γ, p) results show no sign of the expected giant resonance. Careful checks of the calculations and tests of consistency in the analysis of the events failed to reveal any errors, and it was concluded that the assumption that, in all the events, the F^{19} nucleus was formed in its ground state was invalid. If a nucleus were left in a state of excitation energy E, then the true photon energy E_γ would be related to the value calculated as above, E_γ' say, by

$$E_\gamma = E_\gamma' + E.$$

(The error in Ep introduced by using the incorrect value of k_γ in the calculation of kp would have been negligible, since $kp = 43.3\sqrt{Ep}$ and the error in k_γ and, hence kp could have been but a few units of $\frac{MeV}{C}$)

As was mentioned earlier, there was reason to expect that many of the transitions in the higher energy regions would leave the F^{19} nucleus in excited states. Workers (Arthur et al. 1952) who studied the reaction F^{19} (p,p^1) F^{19} reported that several resonances in the energy spectrum of the scattered protons corresponded to transitions in which the fluorine nucleus was left in one of several excited states of energies up to 4 MeV. The energy of the incident protons in this experiment was 8 MeV, which corresponds to the giant resonance region of the reaction $Ne^{20}(\gamma,p)F^{19}$ if these reactions involve the formation of compound nuclei. It is an essential feature of compound nucleus theory that the decay of the compound nucleus is independent of the mode of formation. Hence it may be concluded that the proton energy spectrum of the photoprotons from neon in the 'giant resonance' region will be similar to the spectrum of the protons which were inelastically scattered from fluorine.

The results of the fluorine experiment may be summarised, very generally, by stating that the protons fell with approximately equal frequency into three energy groups corresponding to transitions which left the F^{19} nucleus in

(a) the ground state.

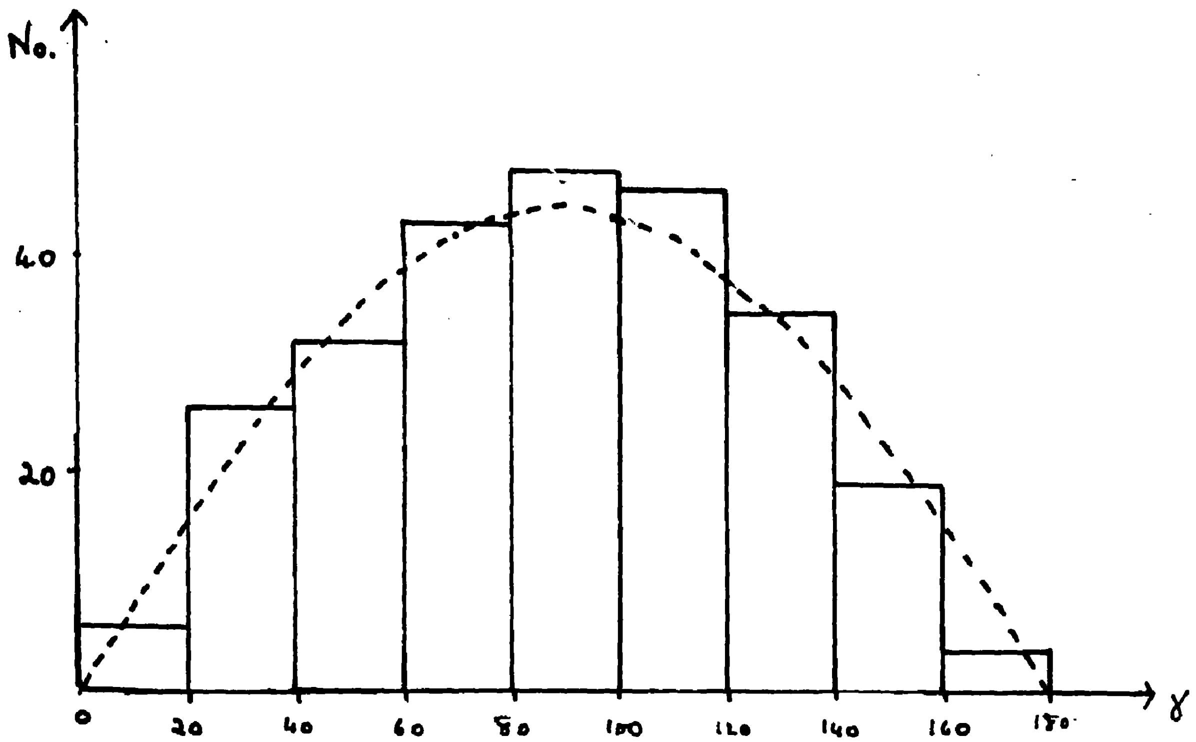


Figure 8. First Angular Distribution.

(b) excited states at about 2 MeV.

(c) excited states at about 4 MeV.

It was tentatively assumed, therefore, that this applied also to the photodisintegration of neon in the corresponding energy region. Hence those events which were observed to correspond to the photon energy range 21 - 23 MeV represented only one third of the events which occurred in this range, the other two thirds being observed equally in the 17 - 19 and 19 - 21 MeV regions. It was then possible to reconstruct the histogram, as shown by the unbroken line in figure 7.

(F) The Angular Distribution of the Photoprotons.

An attempt was made to measure this distribution before the fuller analysis of the (γ,p) events was commenced. This attempt was prompted by the controversy aroused by certain theoretical models (e.g. Wilkinson 1954) which predicted an angular distribution which is markedly different from that which is the most probable on a compound nucleus interpretation of photodisintegration.

It was obvious that, for statistical reasons, it would be necessary to group the results into broad angular intervals and, hence, that the previous accuracy of angular measurements was not necessary. Therefore certain simplifications in the analysis procedure were introduced. Instead of accurate co-ordinate measurements being made, the position of each track in the chamber was estimated visually, by reference to the grid system, an average value of z-co-ordinate being assigned to each event. The needle and protractors were then positioned similarly with respect

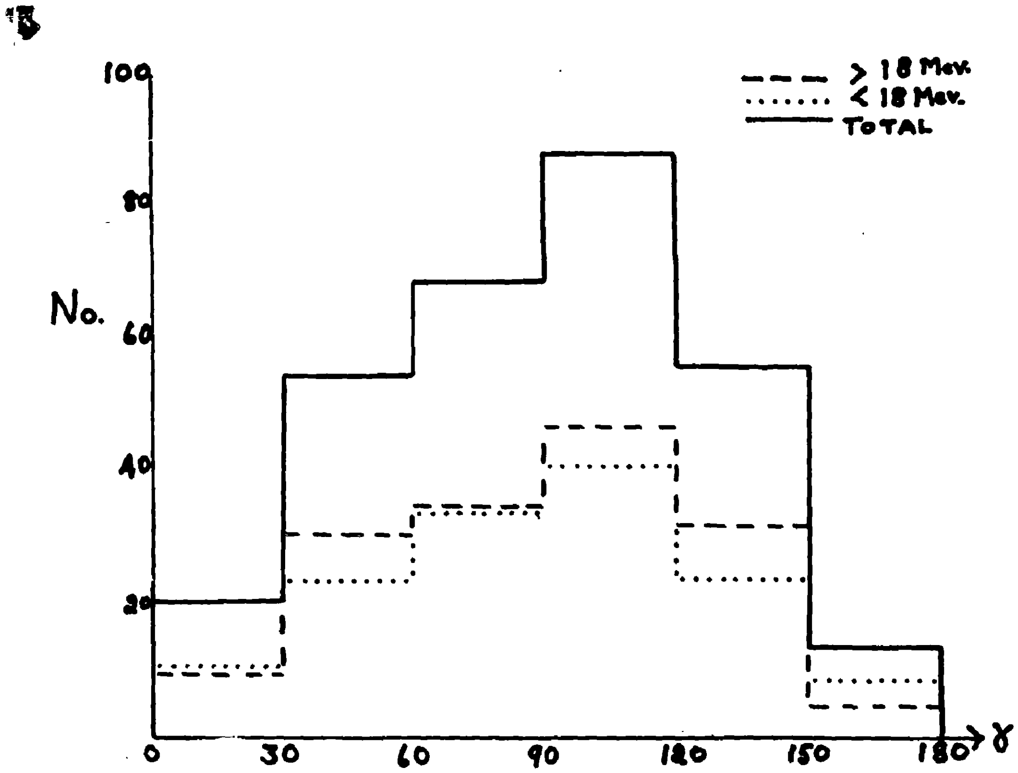


Figure 9. More Reliable Angular Distribution.

to a facsimile of the grid which was placed on the reprojection table. The error in position so introduced was not greater than 5 cm. (the half diagonal of the grid squares) and the corresponding angular error was unlikely to exceed ten degrees. The angular distribution so obtained is shown in figure 8, in which the dotted line corresponds to an isotropic distribution, with which the experimental results are obviously consistent.

Figure 9 shows the results obtained by plotting the values of the angles between the photoprotons and the gamma-ray beam obtained when the full analysis technique was used. Once again the results are consistent with an isotropic distribution. When the method of 'least squares' was used to fit the observed distribution to the form $a + b\sin^2\theta$ the ratio a/b was found to be $8/1$. A division of the results into "high" and "low" energy events revealed no significant difference between the distributions for those events with photon energy above, and below 17 MeV.

III.4 Discussion of Experimental Results.

(a) The (γ,α) Reaction.

The isotopic spin selection rules, which were discussed in chapter I.4, require that the compound nucleus state, which is formed by electric dipole photon absorption in Ne^{20}, have T = 1; for magnetic dipole or electric quadrupole absorption either T = 1 or T = 0 is possible. Since alpha-particle emission is accompanied by no change of isotopic spin, the (γ,α) reaction in neon is allowed, following electric dipole absorption, only if the residual nucleus (O^{16}) is left in a state with T = 1. Hence (γ,α) events which leave the oxygen nucleus in states with T = 0 correspond either to that part of the total magnetic dipole and electric quadrupole absorption for which $\Delta T = 0$, or to a relaxation of the selection rules. The first T = 1 state in O^{16} is believed to lie at about 13 MeV (Wilkinson 1953), which is above the threshold for both proton and alpha-particle emission from that nucleus. It may reasonably be expected, therefore, that if a (γ,α) transition in Ne^{20} leaves the O^{16} residual nucleus in a T = 1 state further particle emission will occur, and the event will be observed as a "star" i.e. as an event corresponding to one of the reactions $Ne^{20}(\gamma,\alpha\alpha)C^{12}$ or $Ne^{20}(\gamma,\alpha p)N^{15}$.

It has been reported (Erdman and Barnes 1953) that, at a photon energy of 17.6 MeV, transitions which leave the O^{16} nucleus in one of several excited states at 6 - 7 MeV are very much more frequent than ground state transitions. If this were true of the (γ,α) events which were observed in the present experiment then, in the previous notation, the values of E_γ for the photons causing the events would be equal to $(E^1 + 6)$ or $(E^1 + 7)$ MeV. Thus almost all of the events would correspond to photon energies of 15 MeV and above. That this should be so seems unlikely, since the only photonuclear reactions in Ne^{20} in which particles are emitted, which can take place at energies below 15 MeV, are the (γ,α) and (γ,p) reactions, and the (γ,p) yield is believed to be low at such energies (see next section). However, the absence of any significant correlation between the observed values of E^1 and the excitation energies of the known levels in Ne^{20} (Ajzenberg and Lauritsen 1955) suggests that the proportion of events in which the O^{16} residual nucleus was formed in one of the excited states at 6 - 7 MeV may well be large.

The yield of events of this reaction for bremsstrahlung of 23 MeV peak energy is 7.5×10^3 events per mole per roentgen, which is an order of magnitude greater than the yield (500/mole/roentgen) which has been reported for the reaction $O^{16}(\gamma,\alpha)C^{12}$ (Greenberg et al. 1954).

(b) <u>The (γ,p) Reaction</u>.

The close similarity between the results for the (γ,n) reaction (Ferguson et al. 1954) and the second histogram shown in figure suggests that the estimate which was made of the proportion of events in which the residual nucleus was left in the three groups of states, was reasonable. It cannot, however, be claimed on that basis that the assumed ratios are definitely established, for the method of "correction" was rather crude and, in fact, the difference in the cross-section which would be introduced if slightly different ratios were assumed (e.g. $\frac{1}{2}$, $\frac{1}{4}$,$\frac{1}{4}$ instead of $\frac{1}{3}$,$\frac{1}{3}$,$\frac{1}{3}$) is not great. However, with that reservation, the assumptions do provide a reasonable explanation of the observed energy distribution.

There is another possible explanation for the apparent absence of a "giant resonance". If it is assumed that, in all the stars in which both an alpha-particle and a proton were emitted, the proton was the first fragment, then these forty events can be regarded as (γ,p) events. However, the addition of these events, all of which had values of E_γ which were greater than 20 MeV, to the number of "ordinary" (γ,p) events is not, in itself, sufficient to produce the desired change in the energy distribution. For, although the cross-section in the region 20 - 23 MeV would have a value close to that which would be expected from the (γ,n) results, the number of events corresponding to photon energies of 17 - 18 MeV would still be unusually large.

That many of the photoproton events should leave the F^{19} nucleus in excited states is to be expected since s-wave proton emission is a more favoured process than p-wave emission. Since the ground state of F^{19} is $(\frac{1}{2}+)$ and the compound nucleus state formed in Ne^{20} following electric dipole photon absorption is $(1-)$, transitions in which the residual state is the ground state correspond to p-wave proton emission. S-wave proton emission will leave the F^{19} nucleus in a state which is $(\frac{1}{2}-)$ or $(\frac{3}{2}-)$. It seems reasonable to expect that a sufficient number of the many states of F^{19} in the energy range 0 - 4 MeV have one, or other, of these combinations of spin and parity to justify the assumptions which have been made about the nature of the (γ, p) reaction.

The earlier determination of the angular distribution of the photoprotons was, of course, rendered obselete by the later measurements. However, it is, perhaps, of some interest that the earlier results were in accord with the more carefully obtained distribution. The isotropic distribution which was observed suggests that s-wave proton emission did, in fact, predominate. It must be conceded however, that the observed distribution could be obtained by the appropriate admixture of p-wave protons of varying channel spin.

The probability of ground state transitions in (γ, p) reactions in a number of light nuclei (not, unfortunately including Ne^{20}) has recently been calculated (Gol'danskii 1956), on the basis of results for the inverse (p, γ) reactions. The cross-section for the formation of the residual nucleus in its ground state following photon absorption in the 'giant resonance' region is found to reach about 10 per cent of the integrated dipole cross-section.

Only three photoproton tracks stopped in the illuminated part of the chamber, which is a surprisingly small number. The probability that the track of a proton of 2 MeV energy, with a range of approximately 8 cm., would stop in the chamber is 0.2. Hence the number of (γ, p) events with photon energies below 15 MeV is not more than 25, which figure makes reasonable allowance for the statistical uncertainty of the evidence. This estimate is certainly an upper limit since some, or all, of the three events may well have been transitions in which the residual nucleus was left in an excited state. It may be concluded, therefore, that not more than one-twelfth of the total photoproton yield corresponds to the absorption of photons with energies below 15 MeV. This is markedly different from the results which have been reported for the photo-disintegration of nitrogen (Wright et al. 1956) and oxygen (Spicer 1955; Stephens et al. 1955, 1956; Johansson and Forkman 1955, 1956) in which large yields of photoprotons in this energy range were found. The conclusion is, however, in accord with the results of workers who studied the inverse reaction, $F^{19}(p,\gamma)Ne^{20}$, (Clegg, Jones, Wilkinson 1955; Sinclair 1954) but were unable to detect any gamma-rays corresponding to ground state transitions. No explanation has been suggested for the preferential decay by the emission of two photons in cascade, via the level at 1.63 MeV, of the states at 13.5 - 14.2 MeV which were excited. It is interesting, however, that a similar situation exists in magnesium. In a study of the reaction $Na^{23}(p,\gamma)Mg^{24}$ it was found (Rutherglen 1955) that the excited states of Mg^{24} which were formed decayed by the emission of two gamma-rays in cascade, via a level at 1.38 MeV. In the decay of these states, in neon and magnesium, each of the gamma-rays in the cascade is magnetic dipole in character, as would have been the ground state transition, had it existed.

(c) <u>The (γ,$\alpha\alpha$) Reaction</u>.

There is some conflict between the results, which have been summarised in a review article (Titterton 1955), of experiments on photonuclear reactions in which several alpha-particles are emitted. It is generally agreed that the reaction $C^{12}(\gamma,3\alpha)$ corresponds to the excitation and subsequent decay of compound nucleus states in C^{12} and Be^{8}. Although there is less unanimity about the reaction $O^{16}(\gamma,4\alpha)$, there are reasonable grounds for the belief that this also is a cascade process. The results for these two reactions provide the main justification for the assumptions which have been made about the nature of the reaction $Ne^{20}(\gamma,\alpha\alpha)C^{12}$.

Since each event which was attributed to this reaction has been treated as a (γ,α) event in which the residual oxygen nucleus was formed in an excited state which lay above the threshold for the emission of an alpha-particle, the isotopic spin selection rules apply to this reaction as they do to the (γ,α) reaction, with the further restriction that isotopic spin must be conserved in the second alpha-particle transition. Thus the reaction is, in principle, forbidden following electric dipole photon absorption, unless the C^{12} nucleus be formed in a state with $T = 1$. Since the lowest such state lies at about 15 MeV an initial photon energy of at least 27 MeV would be required, but it not available in the present experiment, in which the maximum energy of the gamma-rays was 23 MeV. As mentioned in chapter I.4, it has been suggested that alpha-particle cascades may occur in violation of the selection rules and that, in such events, it would be the second transition which would violate the rules. Therefore it might be expected that, since almost all of the $(\gamma,\alpha\alpha)$ events occur in the "giant resonance" region of photon absorption where electric dipole transitions certainly predominate, the states in the intermediate nucleus (O^{16}) which were excited in this reaction would be predominantly T = 1.

Since it is impossible to decide which of the alpha-particles was first to be emitted, it is difficult to make definite deductions from the results which were obtained. However, the interpretation which was adopted of the reaction is supported by the fact that, for almost all of the events, at least one of the two values of excitation energy is consistent with the energy of a known level in O^{16}. These values have been shaded in figure 3. The first T = 1 state in O^{16} is believed to be one of those at 12.51 MeV and 12.95 MeV, and is probably the latter (Wilkinson, 1956). In ten of the eighteen events corresponding to this reaction which were analysed, both values of the excitation energy were below 12.5 MeV. In three of these ten events the residual nucleus (C^{12}) could have been formed in the first excited state, at 4.43 MeV, and, in four more, this possibility cannot be neglected, since the peak synchrotron energy was not known exactly. However, since it is unlikely that the error in peak energy (which was, nominally, 23 MeV) is as great as 1 MeV, these events probably correspond to ground state transitions. Hence at least three and, probably, seven of these events correspond to transitions in which the intermediate state was, nominally, T = 0.

It may be concluded, therefore, that these events either correspond to that part of the magnetic dipole and electric quadrupole photon absorption which occurs without change of isotopic spin, or represent a relaxation of the selection rules. Since all but three of the events had photon energies above 18 MeV, the first of these explanations seems unlikely. It seems probable, therefore, that this reaction occurs because of the known impurity of the isotopic spin states (Wilkinson 1956) which, it is suggested, are approximately equally impure at about 13 and 20 MeV in O^{16}. If the states in Ne^{20} at excitation energies of about 20 MeV are equally impure, then this provides the possibility of a second apparent breakdown in the selection rules and a second channel through which the reaction $Ne^{20}(\gamma,\alpha\alpha)C^{12}$ may proceed.

(d) The $(\gamma,\alpha p)$ Reaction.

As was mentioned earlier, there is no way of telling which fragment, in events belonging to this reaction, was first to be emitted. It will be assumed initially that the alpha-particle was the first fragment and that, in consequence, all such events may be considered as (γ,α) events in which the residual nucleus (O^{16}) was left in an excited state above the threshold (12.11 MeV) for proton emission and that, in fact, a proton was emitted.

Since the photon energy for such events was invariably greater than 20 MeV, it may be concluded that the photon absorption was electric dipole in character and that the compound nucleus state in Ne^{20} was (1-), T = 1. Hence the selection rules require that the intermediate state in O^{16} have T = 1. The lowest T = 1 state in O^{16} is (2-) and is, in consequence, unlikely to be excited in this reaction, since an alpha-particle transition from a (1-) state which leaves the residual nucleus in a (2-) state is unfavoured. Hence, it may be expected that the state in O^{16} of lowest energy which would be excited would be that at 13.06 MeV, which is (1-) and T = 1. In fact, the lowest value of excitation energy which was obtained in the present experiment was 12.97 MeV, which would suggest that the 12.96 MeV level is, in fact T = 1. However, since the resolution of the experiment is approximately 0.1 MeV, this event cannot definitely be assigned to either level.

The values of excitation energy in O^{16}, which are shown in figure suggest that many levels in the region 12.8 - 14 MeV contribute to the reaction. The properties of the energy levels in O^{16} which have been reported (Ajzenberg and Lauritsen 1955) are shown in Table 1.

Excitation Energy (in MeV)	12.95	13.09	13.24	13.65
Spin, Parity	2-	1-	4+	1+ or 2-
Isotopic Spin (where known)	1	1		

Table 1.

Since these levels were identified as a result of bombarding N^{15} with protons, it is reasonable to expect them to de-excite by proton emission. However, relatively improbable transitions are required if all of these states are to take part in the $Ne^{20}(\gamma,\alpha p)$ reaction. Electric dipole absorption, s-wave alpha-particle emission followed by s-wave proton emission is, surely, a more probable transition than magnetic dipole absorption, p-wave alpha-particle and p-wave proton emission. The intermediate state in O^{16} would be (1-) on the first of these schemes, which would suggest that transitions in which the 1306 MeV level was excited should predominate. There is no evidence for this in the experimental results. It is unfortunate that less than half of the events of this reaction could be analysed but, since the number of alpha-particle tracks which failed to stop was small, and the probability of a proton, which was emitted from the 13.06 level, stopping in the chamber is high (0.8), it seems unlikely that a significant number of events corresponding to this excitation energy were unmeasurable.

The experimental results suggest that all of the states which were mentioned above were excited in this experiment, and that there is at least one further state, at about 13.9 MeV. It would appear also that either the information given in Table 1 is incomplete (or incorrect) or the majority of the events belong to the $(\gamma, p\alpha)$ reaction. The second of these possibilities is improbable, since several $(\gamma, \alpha\alpha)$ events corresponding to this excitation energy were observed, and there should be many more $(\gamma, \alpha p)$ events. (Even if a pessimistic view is taken of the isotopic spin impurities of the states, the favoured transition - $(\gamma, \alpha p)$ - should be at least three to ten times as probable as that which is inhibited). It is suggested, therefore that the information of

Table 1 is unsatisfactory in that either the spins and parities of the states have been incorrectly assigned, or there are several more states in that energy range with spins and parities which are more appropriate to the $Ne^{20}(\gamma,\alpha p)$ reaction.

This suggestion is supported by evidence which had been published since the completion of the present experiment. These results are discussed in the next chapter, which describes an experiment which was performed largely in an attempt to gain more information about the mode of decay of those states of O^{16} which have excitation energies in the range 13 - 14 MeV.

If it is accepted that an appreciable number of the (γ,p) events which were observed corresponded to transitions in which the F^{19} nucleis were formed in excited states at about 4 MeV, then at least a few $(\gamma,p\alpha)$ events must be expected, since the threshold for alpha-particle emission from F^{19} is 3.986 MeV. There is no reason to expect 4 MeV to be an upper limit to the excitation energy of the states which were formed and states of higher energy than this would surely de-excite by the emission of an alpha-particle, rather than by photon emission. Further, the reaction is allowed by the isotopic spin selection rules, since the states of F^{19} and N^{15} which would be formed are of half-integral isotopic spin. (Only the ground state of N^{15} is energetically accessible, since the first excited state of that nucleus lies at 5.28 MeV and the lowest photon energy which was observed was within 3 MeV of the peak energy of the synchrotron.

Unfortunately little is known about the level structure of F^{19} in the energy range appropriate to the $Ne^{20}(\gamma, p\alpha)$ reaction and, hence, there is nothing with which to compare the values of excitation energy which were calculated. However, the absence of any striking signs of grouping in the values of E^x, as shown in figure 4, suggests that this mode of decay of the excited neon nucleus is less prevalent than that in which proton emission follows primary alpha-particle emission.

III.5 Conclusions.

The results obtained from this experiment are consistent with a model of photonuclear processes based on the concept of the compound nucleus. The cross-section for any reaction, on this model, is the product of the cross-section for the absorption of photons and the probability of emission of the particle (or particles) in question. It is postulated that photon absorption into individual levels occurs and that the emission probability is determined by such factors as the spins, parities and isotopic spins of the particles and excited states. It is convenient, in this summary of the results, to consider separately several ranges of photon-energy (E_γ).

(a) E_γ below 13 MeV.

There are only two possible reactions - (γ,α) and (γ,γ') - below the (γ,p) threshold, which is 12.87 MeV. Since the probability of particle emission is much greater than that of photon emission, the total photon absorption cross-section in this energy range can be only slightly greater than the cross-section for the (γ,α) reaction, which has been found, in the present experiment, to be small. Thus the total photon absorption was small.

(b) E_γ between 13 MeV and 15 MeV.

In this energy region, the excited neon nucleus can de-excite by the emission of quanta, alpha-particles or protons (which latter will be of low energy). Since only three proton tracks from (γ, p) events were observed to stop in the chamber - and since it is possible that even these could have been produced in a reaction of higher photon energy - it is concluded that the cross-section for the (γ, p) reaction is small below 15 MeV. As has been mentioned, this is in accord with the results of the inverse reaction $F^{19}(p,\gamma)Ne^{20}$, in which no gamma-rays corresponding to ground state transitions were observed.

Very few (γ,α) events could be ascribed to photons of this energy range. Hence, it is concluded that the total photon absorption is small below 15 MeV.

(c) Higher values of E_γ

The yield of protons and alpha-particles from reactions caused by gamma-rays of energy greater than 15 MeV was large - corresponding to the 'giant resonance' of the photon absorption cross-section. The number of events in which the various particles were the first (or only) fragment to be emitted are shown in Table 2. The events in which both an alpha-particle and a proton were emitted have been, rather arbitrarily, assigned equally to the $(\gamma,\alpha p)$ and $(\gamma, p\alpha)$ reactions. It is not possible to determine the correct sub-division but, since there are reasons for believing that both reactions contribute, it is unlikely that the chosen ratio is grossly in error. Only those events of the (γ, p) and (γ, α) reactions in which the photon energy was above 15 MeV have been included. The figures for the (γ, n) reaction have been deduced from a published graph of cross-section against photon energy (Ferguson et al. 1954).

Table 2.

Primary Particle	Reaction	Number of Events	Total.
Proton	(γ, p)	275	
	(γ, $p\alpha$)	20	295
Neutron	(γ, n)	300	300
Alpha-particle	(γ, α)	5	
	(γ, $\alpha\alpha$)	20	
	(γ, αp)	20	45

The yields of protons and neutrons were very similar. It is believed that, basically, proton and neutron emission are equally probable but that Coulomb barrier considerations, and the availability of energy levels affect the actual yields from any particular nucleus. It is presumed that, in Ne^{20}, such factors affect the reactions equally.

An important feature of the results is the large number of events in which an alpha-particle is the first fragment to be emitted. As can be seen from Table 2, the yield of primary alpha-particles amounts to about one-seventh of that of protons or neutrons, which proportion is unusually high.

The influence of the isotopic spin selection rules.

One of the aims of this experiment was to test the applicability of the isotopic spin selection rules. It was expected that, if these rules, were absolute, the character of the multi-fragment - $(\gamma,\alpha\alpha)$ and $(\gamma,\alpha p)$ - reactions observed would have a definite form viz. there would be a relatively large yield of $(\gamma,\alpha p)$ events with protons of low energy, corresponding to excitation energies of about 13 MeV in O^{16}, and a much smaller yield of $(\gamma,\alpha\alpha)$ events, none of which had values of excitation energy which were greater than about 12.5 MeV.

In fact, a large number of $(\gamma,\alpha p)$ events were observed and, from the calculated values of the excitation energy of the O^{16} nucleus, it may tentatively be inferred that the first T = 1 state, which was known to lie at either 12.51 MeV or 12.95 MeV, is the latter. There would appear also to be several T = 1 states between 13 and 14 MeV, not all of which have been reported, which could not, however, be precisely determined. The yield of $(\gamma,\alpha\alpha)$ events was surprisingly large and, in some events, both values of the excitation energy of the intermediate nucleus lay above 13 MeV, which indicates that 'inhibited' alpha-particle emission can compete with 'allowed' proton emission. It must be concluded, therefore, that the selection rules, although they do appear to influence reaction probabilities, are not absolute.

CHAPTER FOUR

THE PHOTODISINTEGRATION OF OXYGEN

IV.1 Introduction

In previous experiments which have been carried out at the University of Glasgow, photonuclear reactions in helium, nitrogen and neon have been studied. Since oxygen is the only other gaseous element with atomic weight below 40 which is suitable for use in a cloud chamber, it had been decided before the completion of the neon experiment, which is described in chapter III, that oxygen would be the next element to be studied. The importance of this experiment became obvious when the results of the neon experiment were discussed, since states in O^{16} with excitation energies of 13 - 14 MeV appear to play an important part in the decay of the neon compound nucleus. The results suggested that several levels between that at 12.95 MeV (which was tentatively identified as the lowest T = 1 state) and 14 MeV decayed by proton emission, and that the information which was then available (Ajzenberg and Lauritsen 1955), about the levels in that region, was far from complete. It was hoped that the increased number of events, and the improved energy resolution which would be available in a study of the reaction $O^{16}(\gamma,p)N^{15}$ (as opposed to $Ne^{20}(\gamma,\alpha p)N^{15}$) might enable levels in this region to be identified. The emission of alpha-particles from level in this range is also of interest, because of the possibility of a comparison with the results obtained for the reaction

$Ne^{20}(\gamma,\alpha\alpha)C^{12}$.

The results of experiments on the reactions $O^{16}(\gamma,p)N^{15}$, $O^{16}(\gamma,\alpha)C^{12}$, $O^{16}(\gamma,n)O^{15}$ and $O^{16}(\gamma,4\alpha)$were available before the decision to study the photodisintegration of oxygen was made. Several more comprehensive papers on the reaction $O^{16}(\gamma,p)N^{15}$ were published during the period between selecting the experiment and actually commencing the irradiations. However, the discrepancies which were noted between the results of the three experiments whose results were published encouraged rather than discouraged, the continuation of the planned programme. The results which have been published on these reactions are summarised, and discussed, in the following paragraphs.

(a) The reaction $O^{16}(\gamma,4\alpha)$

This reaction has been studied by many workers (e.g. Goward and Wilkins 1950, 1952; Hsaio and Telegdi 1953; Livesey and Smith 1952, 1953; Millar and Cameron 1953). Since the cross-section was found to be small below 22.5 MeV, it was not anticipated that any significant number of events would be observed in the present experiment. The published results are of interest principally because of the evidence they provide in favour of a compound nucleus interpretation of photonuclear processes. In all these studies photographic emulsions were used.

(b) The Reaction $O^{16}(\gamma,\alpha)C^{12}$

This reaction has been extensively studied, using photographic emulsions exposed to the gamma-rays from the $Li^7(p,\gamma)$ reaction, by Waffler and his co-workers (e.g. Waffler and Younis 1949; Nabholz, Stoll and Waffler 1952). A more thorough investigation using 31 MeV bremsstrahlung has also been carried out (Erdos, Schmouker and Stoll 1953). It is reported that the cross-section is small at about 24 MeV - the energy of the giant resonance which was observed in the (γ,n) reaction - and continues to be small above this energy although the isotopic spin selection rules, which inhibit alpha-particle emission following electric dipole photon absorption unless the product nucleus is formed in a T = 1 state, can now be satisfied. (The lowest T = 1 state in C^{12} is believed to lie at about 15 MeV; the threshold for the reaction $O^{16}(\gamma,\alpha)C^{12}$ is 7.15 MeV). It is concluded that the preferred mode of decay of such highly excited states of C^{12}, is by the emission of a second alpha-particle, leaving a Be^8 nucleus which disintegrates into two alpha-particles.

The reaction has also been studied by exposing photographic emulsions to 25 MeV bremsstrahlung (Millar and Cameron 1953). The appropriate events were identified by comparing the values of recoil energy obtained from the recoil range and the fragment range. These should obviously agree within the resolution of the measurements. (Such an identification technique was required to separate events from the reaction $O^{16}(\gamma,\alpha)C^{12}$ from (γ,α) events from the other nuclei which were present in the emulsion). A broad resonance at a photon energy of about 17.5 MeV is reported with a peak value of 0.05 mb.

The experiment of Millar and Cameron has been repeated by other workers (Greenberg et al. 1954) who are in substantial agreement with their results. Some considerable doubt is however cast upon the ability of the technique to detect alpha-particles of relatively low energy, because the recoils corresponding to such fragments would be almost invisibly short. It is suggested that many (γ,α) events corresponding to excitation energies of about 13 MeV in O^{16} may have escaped detection and further that many transitions corresponding to higher photon energies would leave the C^{12} nuclei, in excited states, with the result that they also might be overlooked. It is significant that the cross-section at 17.6 MeV reported by workers using the $Li^{7}(p,\gamma)$ radiation (Nabholz et al. 1952) is more than three times as large as that reported by Millar and Cameron. Since the photon energies in this experiment were known, it was possible to predict the energies of the alpha-particles from the $O^{16}(\gamma,\alpha)C^{12}$ reaction, and to use the observed alpha-particle ranges as the criterion for identifying an event.

(c) The Reaction $O^{16}(\gamma,n)O^{15}$

The excitation curve of this reaction has been measured by two groups (Katz et al. 1954; Penfold and Spicer 1955), both of whom report several "breaks", which are interpreted as being narrow resonances in the reaction cross-section. Although the second group found rather more breaks than did the first, the agreement is reasonably good. Further, the positions of the breaks agree well with the energies of resonances which have, more recently, been observed in the (γ, p) reaction.

(d) <u>The Reaction $O^{16}(\gamma, p)N^{15}$</u>

The cross-section for this reaction at 17.6 MeV was measured by exposing photographic plates, which had been soaked in water, to the gamma-rays from the $Li^7(p, \gamma)$ reaction (Waffler and Younis 1949). More recent investigations have used bremsstrahlung of varying peak energies:-

18.7 MeV (Spicer 1955)

20.5 MeV (Johansson and Forkman 1955)

23 MeV, 26 MeV (Johansson and Forkman 1956)

25 MeV (Stephens et al. 1955, 1956)

The technique used was essentially similar in each case. A well-collimated bremsstrahlung beam passed axially through a cylindrical 'camera' filled with oxygen at a pressure equivalent to about 1.5 atmospheres. Photographic emulsions were mounted in the camera so that their near edge was a few centimetres from the beam. As a result of energy loss in the gas, protons of energies below 1.5 MeV could not be detected in these experiments.

Spicer chose a peak energy of 18.7 MeV to ensure that all the proton tracks which were observed corresponded to transitions in which the N^{15} nucleus was formed in its ground state. (The first excited state of N^{15} is at 5.3 MeV, and the maximum proton energy from transitions to this level is about 1.2 MeV. Such protons would not be recorded in the emulsions). He reports a broad resonance at a proton energy of approximately 2.4 MeV, with small, subsidiary, peaks at 3.1 MeV and 3.7 MeV. The angular distribution of the photoprotons is said to be a $(1 + \cos^2 \theta)$, from which it is deduced that the resonance at 2.4 MeV - which corresponds to a photon energy of 14.7 MeV - corresponds to either electric quadrupole or magnetic dipole photon absorption. Wilkinson (1955) has discussed these results and suggests that "reasonable considerations about radiative widths" favour the former interpretation. The peak cross-section is found to be approximately 5 mb. and the yield 4×10^4 protons per mole per roentgen, at 18.7 MeV peak energy.

The majority of the photoprotons observed by Johansson and Forkman in their 20.5 MeV experiment must correspond to ground state transitions. However, protons of up to about 3 MeV in energy could correspond to transitions leaving the N^{15} nucleus in the first two excited states, which lie close to 5.3 MeV. These workers report a group of protons, of energy about 2.2 MeV, which could be identified with the resonance at 2.4 MeV which was reported by Spicer, since the slight difference in energy may be caused by differences in the corrections which were applied for energy loss before the proton entered the emulsion. (No details of these corrections were given). The maximum value of the cross-section of this resonance which was reported by Johansson must be regarded as an upper limit, in view of the possibility (which has been mentioned above) that the observed photoprotons may include a number corresponding to transitions to excited states of the residual nucleus, as well as to ground state transitions. It is all the more surprising, therefore, that a value equal to no more than one third of that reported by Spicer was found.

Stephens et al. also reports a peak at between 2 MeV and 2.5 MeV which, because of the photon energy used, may well correspond to high energy photon absorption following which the N^{15} nucleus was formed in any of the excited states at 5.3, 6.3 or 7.3 MeV. In fact, the low energy region of the photoproton spectrum can be explained only if assumptions are made about the photon absorption. By accepting Spicer's result - that there was only one main resonance below 18 MeV, it was possible to assign all of the proton groups which were observed to specific photon energies. It was assumed that all of the protons in the low energy group corresponded to ground state transitions. Even so, the value of integrated cross-section for the resonance at 14.7 MeV which was found was rather lower than that reported by Spicer.

The energy distribution of the photoprotons which is reported by Stephens et al. is similar to the distributions found by Johansson and Forkman in their high energy experiments. The chief differences in the high energy region can be explained by the unusual procedure which was adopted by Stephens et al. in dealing with those tracks which passed through the emulsion. Such tracks were assumed to correspond to protons whose energy was equal to the mean energy of all the protons of greater range whose tracks stopped in the plates. The present author can find no justification for this. One further disturbing feature of the results is the magnitude of the 'background' which was reported by Johansson and Forkman. Such tracks are believed to correspond to (n,p) reactions, either in the gas or in the emulsion itself. These workers measured the 'background' in two ways:

(a) by scanning the plates used in the normal irradiations for tracks coming from directions which were inconsistent with an origin in the synchrotron beam. (This is the method used by other workers).

(b) Emulsions were exposed in the normal way, except that a lead plug was placed in the collimator, so that few, if any, photons reached the camera. Hence all the tracks which were found corresponded to (n,p) events.

This latter method, on the basis of which a background of 20% of the total number of tracks was subtracted from the photoproton results, would appear to suffer from the disadvantage that although the photon flux through the camera is reduced, the neutron flux is, inevitably, increased because of the photoneutrons formed in the plug.

The principle disagreement between the results of Stephens et al. and Johansson and Forkman lies in the angular distributions for the photoprotons which were measured. The latter report that equal number of tracks were observed to go in a forward and in a backward direction; the former group found a definite preponderance of the tracks going forward. (The angle between the track and the forward direction of the photon beam is measured. If this angle is acute the track is said to "go forward"). This disagreement is particularly surprising in view of the good agreement between the reported energy spectra.

Both of these groups of workers report an isotropic angular distribution for the photoprotons in the resonance at 2.5 MeV. This is very different from the angular distribution ($1 + \cos^2\theta$) which was reported by Spicer for protons of this energy. Once again the discrepancy is difficult to understand.

It was not anticipated that the experiment presently to be described would resolve all of these discrepancies. On the other hand the improved sensitivity of the cloud chamber technique was expected to enable the protons of energy less than 1.5 MeV - which surely were emitted - to be detected. Further, although the maximum working pressure of the cloud chamber which was used was insufficient to provide a large probability of stopping the protons from the 2.5 MeV resonance, it was hoped that the results might support one or other of the measured values of cross-section at this energy.

IV.2 Experimental Procedure

The technique was largely similar to that used in the neon experiment. The expansion chamber was filled with commercial oxygen to an expanded pressure of 1.3 atmospheres and saturated with water vapour. The peak energy of the synchrotron was 18 MeV during the irradiations.

This was chosen as the highest energy which could safely be used without the possibility of protons from transitions in which the residual nucleus N^{15} was formed in the excited states at 5.3 MeV obscuring the energy spectrum of the protons from transitions in which the photon energy was 13 - 14 MeV. Unfortunately the energy scale of the Glasgow synchrotron was not very reliably established but, since one of the calibration points was the threshold for the reaction $C^{12}(\gamma,n)C^{11}$, which is 18.711 MeV, the peak energy during the irradiations should certainly have been within 0.5 MeV of the nominal value. Unfortunately, a series of faults in the synchrotron and the associated apparatus, prevented the completion of the calibration of the output monitoring system and, hence, the radiation dose during the irradiations was unknown. Thus the absolute values of the reaction cross-sections could not be determined.

In order to obtain the largest possible number of events from the limited supply of film which was available, only two cameras were used. Several of the advantages of the analysis technique were sacrificed by so doing, particularly the protection against human errors, which was discussed in chapter II. In principle, however, only two cameras are required and, in practice, no loss of reliability was sustained, since each event was remeasured, independently, before it finally was accepted. Naturally, for some of the events, the lens distortion was larger than before but, with the small apertures which were used, this was still negligibly small, even for events in the region of the chamber which was furthest from the cameras.

IV.3 Classification and Analysis of the Events.

The scanning of the films was carried out in a different fashion from previous experiments. The films were replaced, after processing, in the cameras, which were placed above the reprojection table with lamps arranged to shine downwards through the lenses. No attempt was made to align the films nor to make measurements of the images, but the number of events and their positions and appearances were noted. A total of 677 events were observed, and were classified as follows:-

473 'flags' (events in which both a recoil track and a fragment track were visible).
198 'singles' (events in which only one track could be distinguished).
6 'stars' (in all of which four tracks were visible).

No attempt was made to analyse the 'stars', which were presumed to belong to the reaction $O^{16}(\gamma, 4\alpha)$, because a much greater number of events would be required before any significant conclusions could be drawn. However, the detection of these events was of interest, for in each case all of the tracks were so short that it seemed improbable that corresponding events would be visible in nuclear emulsions.

The events which were classified as 'singles' could belong to several reactions, not all of which took place in the chamber gas. Fifty-four, for instance, originated either in the front or the rear wall of the chamber. Others may well be photon or neutron-induced events in the top or bottom plates of the chamber or in the gas outwith the illuminated region which, as was stated in chapter II, was deliberately made to be smaller than the chamber itself. The third possibility is that these were normal (γ, p) (or (n, p)) events in which the recoil could not be distinguished. It is possible that some may have been the tracks of alpha-particles which originated outwith the illuminated part of the chamber, but it is very unlikely that any were (γ, α) or (n, α) events, lying within the illuminated region, whose recoil was not visible.

The 'flags' were subdivided into several categories depending on the nature of the fragment, whether or not the fragment track stopped in the chamber and whether or not the event was collinear. (A "collinear flag" is one in which the angle between the recoil track and that of the fragment lies between 170^{o} and 190^{o}).

IV.4 Experimental Results.

There are four reactions which would produce 'flag' events:-

(a)	$O^{16}(\gamma, p)N^{15}$	Threshold	12.11 MeV
(b)	$O^{16}(\gamma, \alpha)C^{12}$		7.149 MeV
(c)	$O^{16}(n, p)N^{16}$		9.62 MeV
(d)	$O^{16}(n, \alpha)C^{13}$		2.2 MeV.

(Both the (γ, d) and (γ, pn) reactions have thresholds above 20 MeV, which is much greater than the maximum photon energy). Events corresponding to reactions (c) and (d) above would be observed as non-

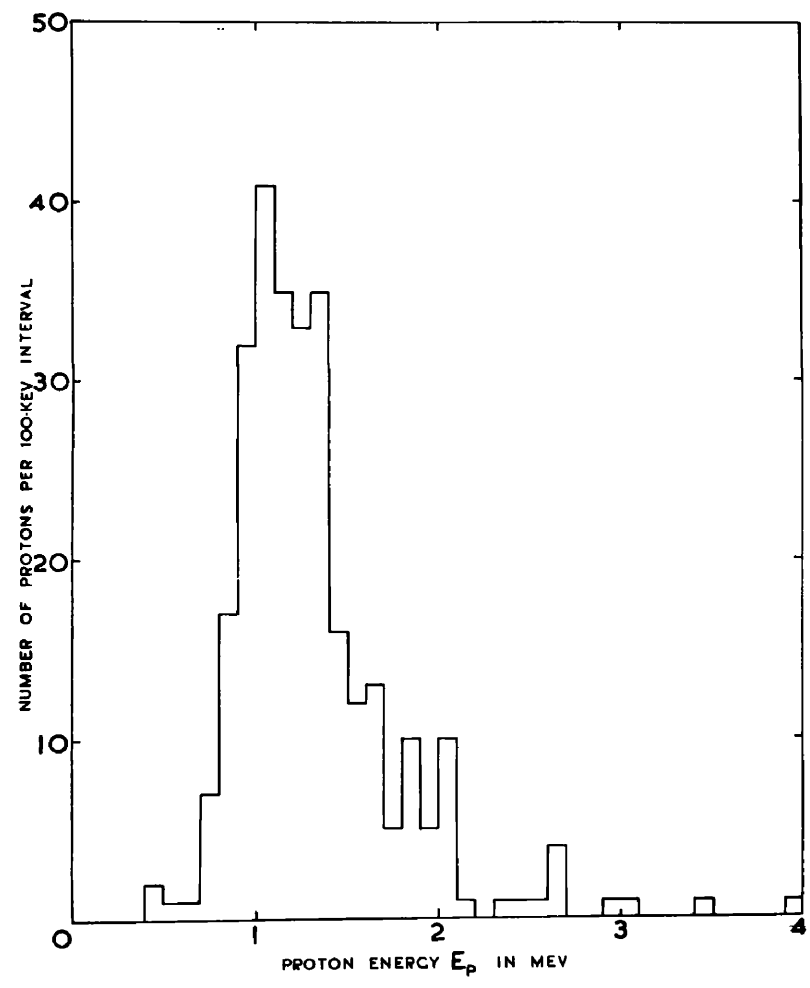


Figure 10. Proton Energy for (γ, p) Events in O^{16}.

collinear flags, since only thus could momentum be conserved. (The momentum introduced into the system by neutrons of sufficient energy to cause the reactions would be 100 to 150 $\frac{\text{MeV}}{c}$). Hence, since no non-collinear flags were observed, it is concluded that only reactions (a) and (b) took place. Events from these two reactions can be identified by a visual examination, since the stringent requirement of momentum balancing can be replaced, for an experienced observer, by a comparison of the ranges of the recoil and fragment tracks.

(a) The (γ, p) Reaction.

The total number of events which were attributed to this reaction was 447. In 323 of these events the proton track stopped in the illuminated region of the chamber. For these latter events the co-ordinates of the origin of the event and the length and angles of the proton track were measured. It is disturbing that approximately 10% of the tracks appeared to originate outwith the photon beam. The 36 events in this category were excluded from this section, and will be discussed, separately, later. For the other events in which the proton tracks stopped in the chamber, the energy of the proton was obtained from its measured range. As a result a histogram of number of events against proton energy was drawn, as in figure 10. Since it is certain that, except possibly for the events of lowest energy, the residual (N^{15}) nucleus was formed in its ground state, the energy (E_γ) of the incident photon is given by:

$$E_\gamma = Ep + E_N{}^{15} - Q \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(A)$$

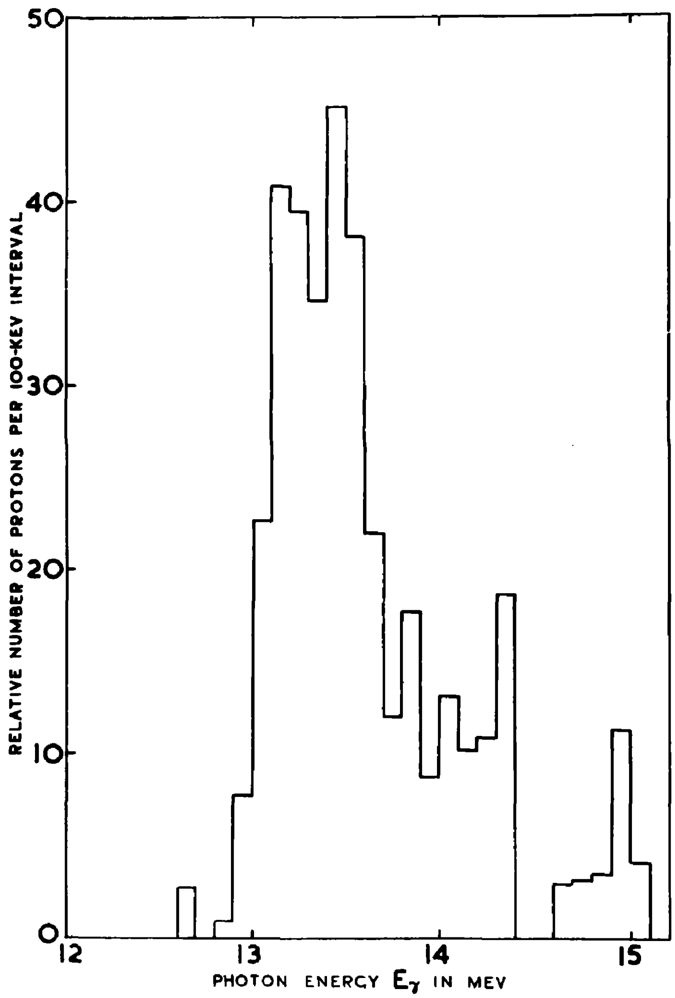


Figure 11. Photon Energy for (γ, p) Events in O^{16}.

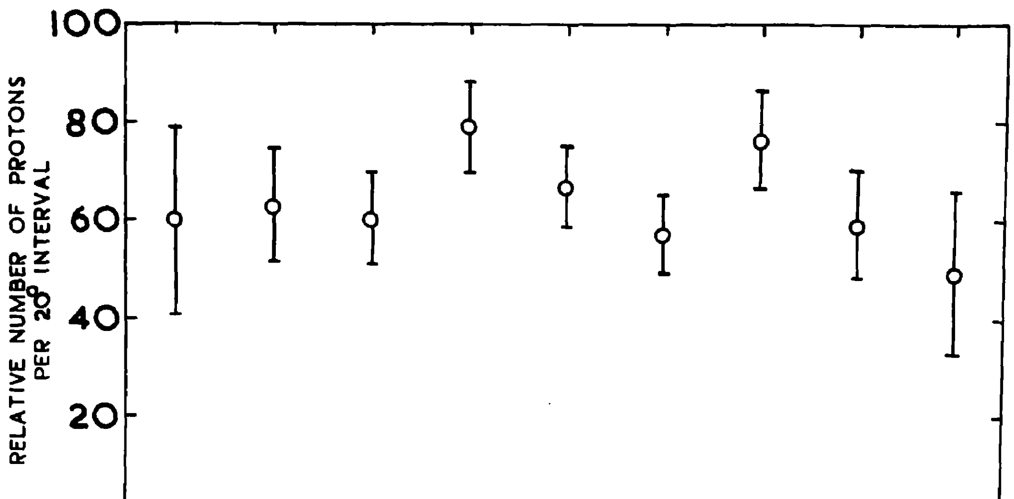


Figure 12. Angular Distribution of Photoprotons from O^{16}.

To a very good approximation, this can be reduced to

$$E_\gamma = \frac{16}{15} Ep - Q \quad \text{.....................(B)}$$

Relation (B) was used to calculate the photon energy for each event. A correction was now made for the varying probability of tracks of different lengths stopping in the chamber. The formula on which this correction was based was essentially similar to, though derived independently of, one used in nuclear emulsion work (Green and Livesey 1948). If a further correction, for the output spectrum of the synchrotron (Katz and Cameron 1951), is applied a histogram of relative cross-section against photon energy may be drawn, as in figure 11.

In drawing the angular distribution of the photoprotons all the (γ, p) events were included, whether or not the proton track stopped in the chamber. The distribution which was obtained for the angle (γ) between the proton tracks and the photon beam is shown in figure 12. The errors shown in this diagram are purely statistical; the accuracy with which each angle was determined is much greater than would be suggested by the width of the groups into which the values have been divided. In this diagram, a correction has been made for the varying solid angle which is subtended by the angular intervals. This correction consists of multiplying the number of events in each group by the mean value of the cosecant of the angle γ in that angular interval. No significant difference was found between the distribution for the events in which the proton stopped in the chamber and for those in which it did

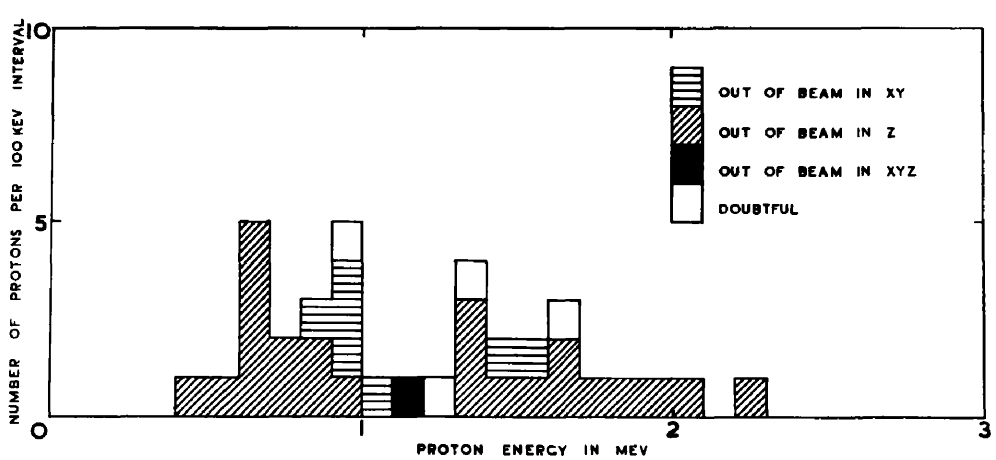


Figure 13. Proton Energy for events which were 'out of the beam'

not. Consequently these individual distributions are not reproduced here.

(b) The (γ,α) Reaction.

Twenty-six of the 'flag' events were attributed to this reaction. None of these were analysed, partly because the number of events was small, and partly because the track quality was such that the origins of such events were difficult to distinguish. This was because the operating conditions of the chamber had been so chosen as to provide fairly dense proton tracks. In consequence there was little difference in density between the tracks of alpha-particles and recoiling nuclei.

(c) Events which occurred out of the beam.

As was noted above 36 events were observed which appeared to be (γ,p) events in which the proton track stopped in the chamber, but whose origins lay outwith the predicted volume of the beam. The energies of such tracks were obtained from measurements of the proton range, and are displayed in figure 13. The degree of shading in this diagram indicates which of the co-ordinates of the track lay outside the prescribed limits.

The fact that all of these events were "collinear flags" implies that they must either be (γ,p) events, or (n,p) events in some gas other than oxygen. It may be assumed that some nitrogen (in which the (n,p) cross-section is high at thermal energies) diffused into the chamber during the five week period during which the irradiations took place, but it seems extremely improbable that a sufficient volume did so to account for all of these events. Further the (n,p) reaction in nitrogen, at thermal energies, produce protons of energy 0.58 MeV (Wright et al. 1956) and only a small proportion of the observed events correspond to this proton energy. It is concluded therefore that at least the majority of these events do, in fact, belong to the reaction $O^{16}(\gamma,p)N^{15}$.

It must be assumed, therefore, that the limits which were imposed in deciding whether or not an event originated within the beam were too narrow. The most reasonable explanation for this is that scattering of photons is a more frequent occurrence than was assumed when the dimensions of the beam were calculated. Since few of the origins of the events were far from the calculated limits of the beam the angular spread which would be required is small.

It was discovered after the completion of the irradiations that the synchrotron target had been moved between the setting up of the cloud chamber and the first of the irradiations. Hence the beam passed below the centre of the chamber. If the angular divergence of the beam is rather greater than was estimated - as has been suggested above - then it is probable that an appreciable number of protons struck the bottom of the chamber. This would provide an explanation for the large number of single proton tracks which were observed.

IV.5 Discussion of Results.

The photon energy distribution, shown in figure 11, appears to consist of several resonances which, although reasonably narrow, are so closely spaced that not all are well resolved in that histogram. In Table 3 the energies of these resonances are shown, together with the excitation energies of the levels of O^{16} in the relevant energy interval. The energy of the resonances has, in each case, been evaluated from the mean range of the corresponding proton group, rather than from the histogram of photon energies.

Table 3.

Proton Energy	0.8	0.95	1.05	1.15	1.3	1.45	1.62
Photon Energy	12.96	13.12	13.23	13.35	13.50	13.66	13.84
Levels in O^{16}	12.95	13.09	13.24	(13.39)		13.65	

Proton Energy	1.8	2.05	(2.7)
Photon Energy	14.03	14.30	(15.0)
Levels in O^{16}	13.98	(14.2)	14.92

References to the reported levels in O^{16} are as follows:-

12.95, 13.09, 13.24 and 13.65 MeV (Ajzenberg and Lauritsen 1955)

13.98, 14.92 MeV (Carlson and Bashkin 1955)

(13.39) (Hornyak and Sherr 1955)

(14.2) (Stoll 1954)

The existance of the latter two states was not considered to be well established. Similarly, in the present experiment, the resonance at 15 MeV is not certain, since only a very small number of events were observed at this energy.

The correlation between the observed resonances and the known energy levels is excellent, and their number and energies provide the desired confirmation of the results for the reaction $Ne^{20}(\gamma,\alpha h)N^{15}$, which were discussed in the previous chapter. These results suggested that all of the states in O^{16} in this range of excitation energy which were then known (those in the first reference above) were excited in the reaction, and that at least one further state between 13.5 and 14 MeV existed.

As was noted in the discussion of that reaction, the spins and parities which have been assigned to some of these states seem rather unlikely, in view of the relative frequency with which protons are emitted. In the present experiment the number of protons from the resonances at 13.12, 13.23, 13.35 and 13.50 MeV are approximately equal. The first of these resonances corresponds to the state in O^{16} at 13.09, which is known to be (1-), and the photon absorption must therefore have been electric dipole in character; the emitted protons were s-wave. That a state which is (4+) should be excited with equal frequency seems very improbable.

The observed angular distributions of the photoprotons, which are isotropic, suggest that s-wave proton emission was the dominant process. It would seem not unreasonable, therefore, to suggest that all four strong resonances correspond to states which are (1-). This suggestion receives some confirmation from a recently reported determination of the spins and parities of the first three excited states of N^{16} (Zimmerman, 1956). Since N^{16}, O^{16} and F^{16} form an isobaric triplet, the ground state of N^{16} corresponds to the first T = 1 state of O^{16}, at 12.95 MeV. Hence the three excited states would appear to correspond to the states of O^{16} shown in Table 4, in which the spins and parities are also indicated.

Table 4.

Excitation Energy in N^{16}	0.113	0.300	0.391
Excitation Energy in O^{16}	13.09	13.24	13.39
Spin, Parity			
(a) Zimmerman	0-,1-	1-,2-,3-	0-,1-
(b) Previously reported	1-	4+	

There is no sign of the strong resonance reported by Spicer at 14.7 MeV. Since the radiation dose of the present experiment could not be determined it is not possible to place an exact upper limit on the cross-section at this energy. However, if the maximum cross-section in the region 13 - 13.5 MeV is presumed to be about 5 mb. (which seems a reasonably probable value and is, in fact, the value obtained by calculation from the results of the inverse reaction $N^{15}(p,\gamma)O^{16}$ for the resonance at

13.09 MeV) then the cross-section at 14.7 MeV would appear to be about one tenth of the value reported by Spicer. This compares with the upper limit of one third suggested by Johansson and Forkman, and one thirtieth obtained by detailed balancing (Atkinson 1956).

It is unfortunate that the (γ,α) events which were observed were insufficient for analysis purposes. It is interesting, however, to note that the yield of alpha-particles is approximately one seventeenth of the yield of protons. This value is rather less than one half of the ratio observed in the photodisintegration of neon.

REFERENCES

Ajzenberg, F. and Lauritsen, T.	1955	Rev. Mod. Phys. 27 1.
Arthur, J.S., Allen, A.J., Bender, R.S. Hausman, H.J., and McDole, C.J.	1952	Phys. Rev. 88 1291.
Atkinson, J.R.	1956	Private Communication.
Baldwin, G.C., and Klaiber G.S.	1946 1948	Phys. Rev. 70 289. Phys. Rev. 73 1156.
Baldwin, G.C., and Koch H.W.	1943	Phys. Rev. 63 462A.
Balfour, D.	1956	Private Communication.
Blatt, J.M., and Weisskopf, V.F.	1952	"Theoretical Nuclear Physics" (New York - John Wiley and Sons)
Bohr, N.	1938	NATURE 141 326.
Bothe, W. and Gentner, W.	1937	Z. Physik 106 236.
Butler, W.A., and Almy, G.M.	1953	Phys. Rev. 91 58.
Carlson, R.R., and Bashkin, S.	1955	Phys. Rev. 100 1254A.
Clegg, A.B., Jones, G.A., and Wilkinson, D.H.	1955	Proc. Phys. Soc. A, 68 538
Courant, E.D.	1951	Phys. Rev. 82 703.
Diven, B .C., and Almy, G.M.	1950	Phys. Rev. 80 407.

Erdman, K.L., and Barnes, C.A.	1953	Proc. Roy. Soc. (Can) 47 131.
Erdös, P., Schmouker, J., and Stoll, P.	1954	Helv. Phys. Acta 27 186.
Ferguson, G.A., Halpern, J., Nathans, R. and Yergin, P.F.	1954	Phys. Rev. 95. 776.
Feshbach, H., Porter, C.E. and Weisskopf, V.F.	1954	Phys. Rev. 96 448.
Gell-Mann, M., Goldberger, M.C., and Thirring, W.E.	1954	Phys. Rev. 95 1612.
Gell-Mann, M., and Telegdi, V.L.	1953	Phys. Rev. 91 169.
Gol'danskii, V.I.	1956	Zh. eksper. teor. Fig. 30 969.
Goldemberg, J., and Katz, L.	1953	Bull. Amer. Phys. Soc. 28 16.
Goward, F.K., and Wilkins, J.J.	1950	Proc. Phys. Soc. A. 63 1171
	1952	Proc. Phys. Soc. A. 65 671
	1953	Proc. Roy. Soc. A. 217 357.
Green, W.M., and Livesey, D.L.	1948	Phil. Trans. Roy. Soc., 241 323.
Greenberg, L.H., Taylor, J.G.V., and Haslam, R.N.H.	1954	Phys. Rev. 95 1540.
Haslam, R.N.H., Johns, H.E., and Horsley, R.J.	1951	Phys. Rev. 82. 270.

Heisenberg	1932	Z. Phys. 77 1.
Hirzel, O., and Wäffler, H.	1947	Helv. Phys. Acta. 20 373.
Hornyak, W.F., and Sherr, R.	1955	Phys. Rev. 100 1409.
Hsiao, C.A., and Telegdi, V.L.	1953	Phys. Rev. 90 494.
Huber, O., Lienhard, O., Scherrer, P., and Waffler, H.	1943 1944	Helv. Phys. Acta. 16 431. Helv. Phys. Acta 17 139.
Johansson and Forkman	1955 1956	Phys. Rev. 99 1031. Private Communication.
Johns, H.E., Horsley, R.J., Haslam, R.N.H., and Quinton.	1951	Phys. Rev. 84. 856.
Johns, H.E., Katz, L., Douglas, R.A., and Haslam, R.N.H.	1950	Phys. Rev. 80 1062.
Katz, L., and Cameron, A.G.W.	1951	Can. J. Phys. 29 518.
Katz, L., Haslam, R.N.H., Horsley R.J. Cameron, A.G.W., and Montalbetti, R.	1954	Phys. Rev. 95 464.
Kerst. D.W.	1941	Phys. Rev. 60 47.
Koch, H.W., McElhinney, J., and Cunningham, J.A.	1951	Phys. Rev. 81 318(A)
Kroll, M.N., and Foldy, L.L.	1952	Phys. Rev. 88 1177.

Lane, A.M., and Radicati, L.A. 1954 Proc. Phys. Soc.A. 67 167

Levinger, J.S. 1954 Annual Rev. Nuc. Sc. 4 13.

Levinger, J.S. and Bethe, H.A. 1950 Phys. Rev. 78 115.

Levinthal, C., and Silverman, A. 1951 Phys. Rev. 82 822.

Livesey, D.L., and Smith, C.L. 1952 Proc. Phys. Soc. A. 65 758
1953 Proc. Phys. Soc. A. 66 689.

Mac Donald, W.M. 1954 Phys. Rev. 98 60
1955 Phys. Rev. 100 51.

Mann, A.K. and Halpern, J. 1950 Phys. Rev. 80 470

Mann, A.K., Halpern, J., and Rothman, M. 1952 Phys. Rev. 87 164.

Mann, A.K. Stephens, W.E., and Wilkinson, D.H. 1955 Phys. Rev. 97 1184

Marshall, L. 1951 Phys. Rev. 83 345.

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

Millar, C.H., and Cameron, A.G.W. 1953 Can. J. Phys. 31 723.

Morrison, D.R.O. 1954 Private Communication.

Nabholz, H., Stoll, P., and Wäffler, H. 1952 Phys. Rev. 86 1043.

Peaslee, D.C., and Telegdi, V.L. 1953 Phys. Rev. 92 126.

Penfold, A.S., and Spicer, B.M. 1955. Phys. Rev. 100 1377.

Radicati, L.A.	1952	Phys. Rev. 87 521.
	1953	Proc. Phys. Soc.A. 66 139
Rutherglen, J.G.	1955	Proc. Glasgow Conf. 102.
Sinclair, R.M.	1954	Phys. Rev. 93 1082.
Spicer, B.M.	1955	Phys. Rev. 99 33.
Stephens, W.E., Mann, A.K., Patton, B.J. and Winhold, E.J.	1955	Phys. Rev. 98 839
	1956	Private Communication.
Stoll, P.	1954	Helv. Phys. Acta, 27 395
Strauch, K.	1953	Annual Rev. Nuc. Sc. 2 105.
Szilard, L., and Chalmers, T.A.	1934	Nature 134 494.
Titterton, E.W.	1955	Prog. Nuc. Phys. 4 1.
Titterton, E.W., and Brinkley, T.A.	1953	Proc. Phys. Soc. A, 66 579
Toms, M.E., and Stephens, W.E.	1951	Phys. Rev. 82 709
	1953	Phys. Rev. 92 362.
Trainor, L.E.H.	1952	Phys. Rev. 85 962.
Walker, R.L., and McDaniel, B.D.	1948	Phys. Rev. 74 322.
Weinstock, E.V., and Halpern, J.	1954	Phys. Rev. 94 1651

Wilkinson, D.H.	1953	Nature 172 576.
	1953 - 6	Phil. Mag. 44 542.
		Phil. Mag. 44 1019
		Phil. Mag. 44 1269
		Phil. Mag. 44 1322.
		Phil. Mag. 45 703
		Phil. Mag(8) 1 291.
	1954	Proc. Glasgow Conf. 161
	1955	Phys. Rev. 99 1347
	1956	Phil. Mag. 1 384.
Wilkinson, D.H., Toppel, B.J., and Alburger, D.E.	1956	Phys. Rev. 101 673.
Wright, I.F., Morrison, D.R.O., Reid, J.M., and Atkinson, J.R.	1956	Proc. Phys. Soc.A, 69 77.
Zimmerman, W.	1956	Phys. Rev. 104 387.