Particle Groups from the Bombardment of Aluminum by Deuterons

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Targets of aluminum leaf 30 kev thick have been bombarded by deuterons and found to emit protons in 14 groups and alpha-particles in four groups. These correspond to levels in Al^{28} and Mg^{25}. The level spacing in Al^{28} appears to become somewhat less at excitation energies of 5 Mev, and the population of the highly excited states is greater. There appear to be five major groupings, each having a finer structure. Observation at 90° and 0° with respect to the incident deuterons shows a considerable variation in relative yield. In comparison with neutron scattering levels for the same nucleus, the spacing here observed is greater. This may be due to the adverse selection of groups of high angular momentum on account of the Coulomb barrier. The level spacing in Mg^{25} is approximately 0.8 Mev. From the maximum energy of the protons and alpha-particles the mass difference between Al^{28} and Al^{27} is found to be 1.00073 ± 0.00008, and between Mg^{25} and Al^{27} is 1.99619 ± 0.00006 mass units.

INTRODUCTION

A STUDY of particle groups produced in the bombardment of elements between Ne and A[1] shows that they possess group structure corresponding to deep energy levels in the product nucleus. In the case of Al^{27} it was observed by Schultz, Davidson, and Ott[2] that the proton groups correspond to a level separation which is small so that no actual values for the nuclear energy changes could be given. More recent work by Allan and Wilkinson[3] using deuterons of much lower energy shows the presence of four well marked groups with a total excitation energy of a little over 2 Mev.

For the emission of protons the product nucleus is Al^{28}. Evidence regarding the level structure of this nucleus has been gained by Allen, Burcham, and Wilkinson[4] and Seagondollar and Barschall[5] by observing the variation in the total neutron cross section of aluminum as a function of neutron energy. These experiments show the presence of levels at excitation energies above 7 Mev. It would be interesting to try to observe proton groups of short range and at high bombarding energies to attempt to observe the same levels as found in the neutron scattering work. Our experiments do not permit this direct comparison to be made but show a trend which enables energy spacings to be estimated roughly.

EXPERIMENTAL METHOD AND RESULTS

The beam of the cyclotron is brought out through a deflecting magnet into a bombardment chamber as described by Martin.[6] Since the proton spectrum is known to be complicated, it is essential to remove any possible source of contamination by high yield elements. To aid this, the target of aluminum was suspended across a large C-shaped support so that no protons could emerge through the proton port unless they originate in the leaf. In this way any backing material is eliminated from the target. Observation was made at 90° to the deuteron beam by this method. For 0° observation the target was placed in the end of the bombardment chamber and backed by sufficient gold to stop the beam. The end of the bombardment chamber was made vacuum tight by an aluminum foil.

At these bombarding energies the cross section of aluminum is comparable with, or greater than, that of lighter elements. Therefore, there is no reason to expect larger yields from contaminants than from aluminum. A possible exception is oxygen, which has a high cross section and which is present as a thin oxide layer on the surface of the leaf. Groups having Q values close to those of oxygen were accordingly suspected, and a special

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[1] Elder, Motz, and Davison, Phys. Rev. **71**, 917 (1947); P. W. Davison, in course of publication; E. Pollard and P. W. Davison, Phys. Rev. **73**, 1241 (1948).
[2] Schultz, Davidson, and Ott, Phys. Rev. **58**, 1043 (1940).
[3] H. R. Allan and Mrs. C. A. Wilkinson, Proc. Roy. Soc. (in course of publication).
[4] Allen, Burcham, and Wilkinson, Proc. Roy. Soc. **A192**, 114 (1947).
[5] L. W. Seagondollar and H. H. Barschall, Phys. Rev. **72**, 439 (1947).
[6] Albert B. Martin, Phys. Rev. **71**, 127 (1947).

TABLE I. Beam energy determination.

Scattered deuterons	Direct beam range	Proton range variation
3.74±0.05	3.79±0.05	3.80±0.07

series of bombardments was undertaken to investigate the possibility of oxygen contamination.

The energy and homogeneity of the beam were measured by three methods. The first was by scattering the deuterons from a gold leaf and observing their range using a proportional counter for detection. The results are shown in Fig. 1 as the full curve. A second series of measurements were made on the direct beam using a galvanometer to detect the deuterons and a small gas cell to introduce variable absorption into the beam. A third check on the beam energy was obtained from reduced energy bombardment of the target. A foil of 9.50-cm air equivalent was placed in the path of the beam. The maximum energy of the protons in the reaction $Al^{27}(dp)Al^{28}$ then fell from 89.0 cm to 54.0 cm. Table I shows the beam energy as derived in the three ways. The direct beam measurement is to be preferred. The individual measurements by this method are considerably better than indicated by the errors

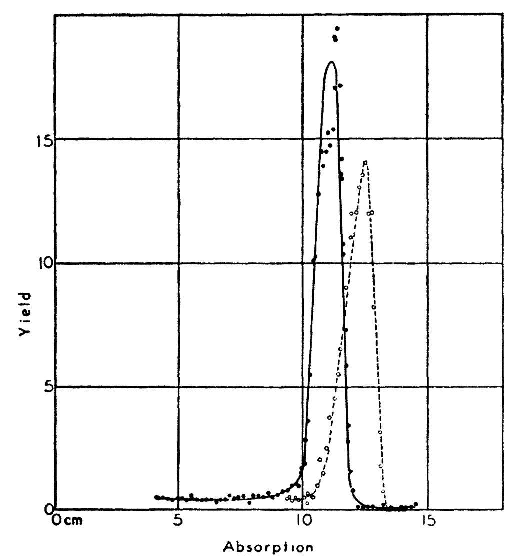

FIG. 1. Scattered deuterons and differential curve of beam. The full curve shows the variation of yield of deuterons scattered from a thin gold leaf as the thickness of absorber is increased. The dashed curve is derived from range measurements made on the direct beam using a galvanometer for detection.

given, but because the beam energy is not completely homogeneous across the target, a larger estimate of error has been taken. A value of 3.79 Mev has been used in our calculations.

The beam homogeneity can be inferred from Fig. 1. There is a certain amount of low energy beam, which will account for very small yields between proton groups. This is probably due to scattering as the beam emerges from the cyclotron. The half-width of the great majority of the beam is 1.20 cm, the theoretical half-width caused by straggling in the absorption cell is 0.4 cm, so that the spread of energy of the beam is ±0.083 Mev.

In the measurement of ranges aluminum foils were used. These were corrected by the calibration curve of Livingston and Bethe to air equivalent. A correction was applied for the effective depth of the proportional counter; however, it is not too precise a correction as the value depends on the bias of the counters. For scattering measurements and alpha-particle range determination a helium-filled counter was used, which greatly reduces this correction. The equivalent counter depth was taken to consist of two parts, the first the drift space before the discharge region is reached, and the second the depth of gas required to give the detected pulse. The drift space corresponded closely with the distance from the front of the counter to the axial wire.

The ranges were read as extrapolated numbers range. There is a small error involved in so doing as the target is not infinitely thin. However, the same procedure was applied to the measurement of the beam range and repeated comparisons have shown that the error introduced is smaller than other experimental errors. The Cornell 1937 range energy relations were used.

Proton Group Observation

The results of a typical run, of which ten were taken, at 90° to the incident beam are shown in Fig. 2. The bias level of the counting circuit was set so that only particles very close to the end of their path would record. It can be seen that five broad sets of particle groups are present. Careful observation led us to consider that the group of maximum energy is single or, if a doublet, cannot be resolved with our equipment.

The second pair of groups appear to be single. This is then followed by a set of three groups of decreasing yield as excitation increases and a set of two and perhaps three groups follows it. The highest yield set consists of five imperfectly resolved groups again falling off in yield as the excitation increases. The Q values for all these groups are given in Table II. Of these groups Q_7 and Q_{10} are possibly due to oxygen contamination. This is further discussed later.

Since the region of greatest interest is that of high excitation, a series of runs was taken in which the particles of ranges between 13 cm (the elastically scattered deuterons) and 30 cm were carefully examined. For this a low solid angle arrangement with a thinner target and an air absorption cell was used. The results are shown in Fig. 3. Five groups are believed to be present. Four can definitely be seen, and the presence of the fifth is deduced from the excessive width of the group at 24 cm.

Independent information on group structure can be obtained by varying both the angle of observation and the beam energy. A run taken at 0° with respect to the beam is shown in Fig. 4. Six groups are clearly seen, of which two, those ending at 58 cm and 42 cm, are abnormally wide. The angular resolution in this run was not so good as the 90° case which accounts for the poorer resolution. It can be seen that the relative yield of the groups is greatly different, a fact that has been observed in other reactions.[7] In this set of runs it was necessary to stop the beam in gold foil. This gold foil has a varying air equivalent for different energies. This variation is discussed in Bethe and Livingston's review article but the precision they claim is not very high. In order to enable the calculation of Q values from these data, we made a calibration of the gold foil by inserting it in the 90° absorption path and making a direct comparison with aluminum absorbers. The results we obtained

TABLE II. Q values.

	Al^{28} (90°)	0°	Mg^{25} (90°)
Q_0	5.45±0.05 Mev	5.38 Mev	6.52±0.06 Mev
Q_1	4.42±0.05	4.36	5.71±0.08
Q_2	3.88±0.10	3.74	4.94±0.08
Q_3	3.29±0.07	3.28	3.98±0.08
Q_4	2.84±0.08	2.72	
Q_5	2.48±0.10		
Q_6	2.04±0.08	1.98	
Q_7	1.55±0.10		
Q_8	0.98±0.12	0.96	
Q_9	0.73±0.05		
Q_{10}	0.57±0.10		
Q_{11}	0.29±0.08		
Q_{12}	0.01±0.08		
Q_{13}	−0.31±0.08		

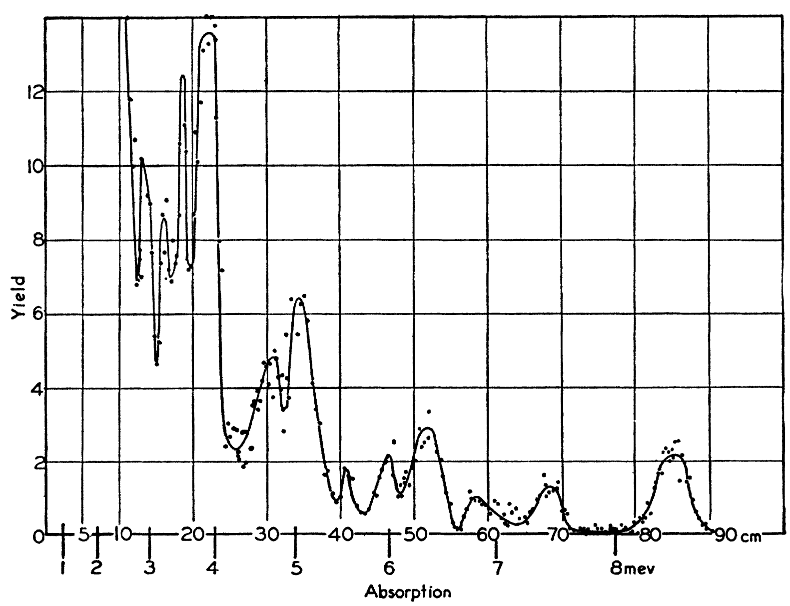

FIG. 2. Typical run at 90°. Absorption curve for the protons emitted at 90° to the deuteron beam. Five sets of groups can be seen, and 13 total groups at least are present. The yield is higher for high excitation.

[7] Powell and co-workers, unpublished; N. P. Heydenburg and D. R. Inglis, Phys. Rev. **73**, 230 (1948); P. W. Davison (in course of publication).

TABLE III.

Av. proton energy in 12.5 cm of gold	Measured range correction needed using 3.77 mg/cm² per cm of air	Range correction using Bethe and Livingston data
8.23 Mev	3.5 cm	3.26 cm
7.22	3.0	3.09
6.72	3.3	2.92
6.07	3.10	2.81
4.90	2.3	2.48

are given in Table III. Such a procedure is not highly precise unless extreme care is taken; however, our results are in good agreement with Bethe and Livingston.

Using this calibration the Q values given in Table II, second column, were calculated. Agreement with the 90° data is reasonable when allowance is made for the poorer geometrical conditions.

Some groups appear to be missing at 0°. Thus Q_5 and Q_6 appear definitely in the 90° run, but only Q_6 is apparent at 0°. This is surprising because the vanishing of $\cos\theta$ at 90° would be expected to modify the yield at that angle and reduce the intensity of some groups. It is surprising to find the 90° spectrum apparently richer.

The results of bombardment at different beam energies are shown in Fig. 5. The general appearance of the spectrum does not change very much, though the yield does diminish gradually for all groups. The fact that the cross section in the $O^{16}(dp)O^{17}$ reaction should be higher at this energy enables some estimate of the proportion of oxygen contaminant present. At a 1.5-Mev bombarding energy the actual yield of a suspected oxygen group is one-half that at full energy. Therefore, it is unlikely that more than half this suspected group is due to oxygen. We feel that Q_7 represents a mixture of yield from aluminum and oxygen but is not purely due to either.

Apart from the question of oxygen contamination, this curve shows that no considerable resonances occur except in the Q_6-Q_8 region.

An integral curve, in which all protons were counted, was plotted. From this approximate values for the cross sections of each group were estimated. These are shown on the energy level diagram, Fig. 7.

Alpha-Particle Group Observation

An attempt was made to observe proton groups of range less than that of the scattered deuterons. It was found that groups of highly ionizing particles existed, of greatest range somewhat less than the maximum range of the deuterons. By increasing the counter bias it was found possible to avoid counting deuterons entirely and detect only these groups of particles. Their ionization density checked with that of ThC′ alpha-particles, and we conclude that they are due to the reaction $Al^{27}(d\alpha)Mg^{25}$.

The results of a measurement of yield *versus*

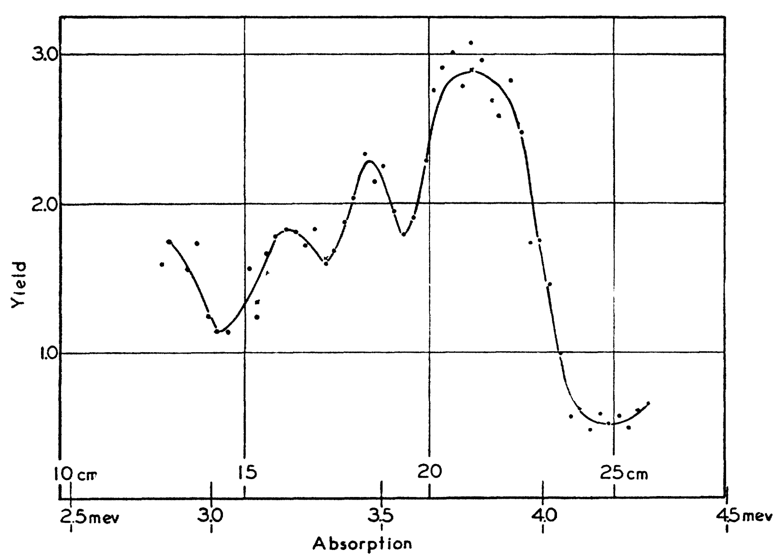

FIG. 3. Detail of proton groups at high excitation. Absorption curve in the high energy region showing the multiplicity of proton groups at low energy.

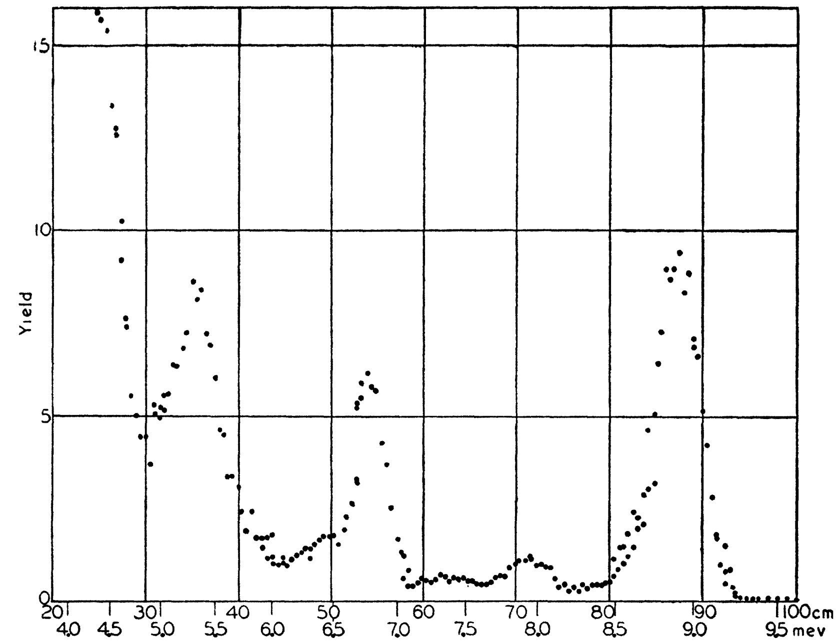

FIG. 4. Protons at 0°. Absorption curve for the protons emitted at 0° to the deuteron beam. Six groups can be seen, of which two are multiple. The relative yields are different from the 90° case.

absorption are shown in Fig. 6. Four groups of alpha-particles are observed. The Q values are given in Table II, and the cross sections are shown in Fig. 7.

The fact that the use of biasing methods was successful is due to the high resolution attained by the counters and amplifiers. We wish to give full credit for this design to Dr. H. L. Schultz of this laboratory.

DISCUSSION

Energy level diagrams for Al^{28} and Mg^{25} are given in Fig. 7 with the cross sections of each group based on observations at 90°. For comparison the levels found by Allen, Burcham, and Wilkinson, and by Seagondollar and Barschall are shown. The degree of excitation in the neutron scattering work can be accurately inferred from our data. Thus the maximum Q value sets the energy difference due to mass between the sum of a deuteron and Al^{27} and of a proton and Al^{28} as 5.45 Mev. The energy difference due to mass between the sum of Al^{27} and a neutron and Al^{28} can then be found to be 7.62 Mev. This makes use of the accepted values for the mass of deuteron, neutron, and proton. Accordingly, the minimum excitation energy in the neutron scattering experiments is 7.62 Mev. Our data do not quite overlap this work, but approach it so nearly that the trend can be inferred. It appears definitely that the level spacing we observe is

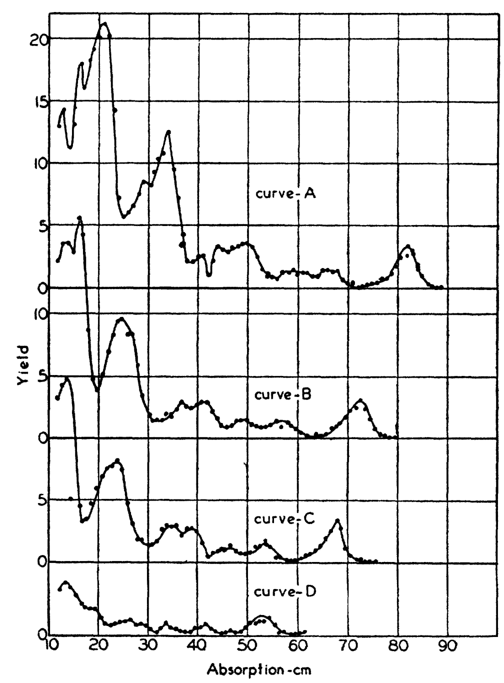

FIG. 5. Protons at different bombarding energies. Absorption curve for protons emitted at 90° to the beam for four bombarding energies. No great change in relative yield is observed except for the region Q_6-Q_8.

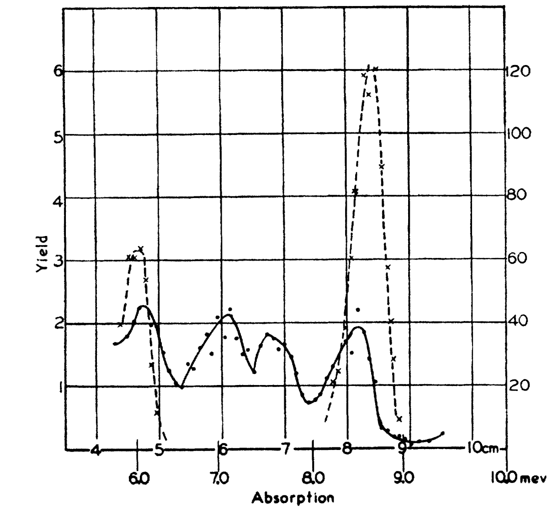

FIG. 6. Alpha-particle groups. Absorption curve for alpha-particles emitted at 90° to the deuteron beam with a superposed curve for the two groups of alpha-particles from ThC′.

larger than that found by Seagondollar and Barschall.

A possible explanation for this can be found in the condition affecting the emergence of protons. The region of high excitation, say from Q_4 up to Q_{13}, is one in which the protons are near the energy of the potential barrier. Penetration through the barrier is possible but will diminish the cross section for any groups for which it is necessary. This factor is increased for groups having high angular momentum, and we suggest, therefore, that our experiments fail to detect groups having a value of l in excess of 2. This will increase the apparent level spacing for higher excitation.

A consideration of energy level spacings and of the relative yield of particles has been given by Weisskopf,[8] who points out the influence of the potential barrier as given above. If we take the relation he suggests, namely,

$$D = A\exp[-BE^{\frac{1}{2}}],$$

where D is the level spacing at excitation energy E and A and B are constants for any one nuclear species, we find from our data $A = 1.48$ Mev and $B = 0.77$ (Mev)$^{-\frac{1}{2}}$. These values predict a level spacing in Seagondollar and Barschall's work of 0.16 Mev, whereas the observed spacing is more nearly 0.06 Mev.

On the other hand, if our level spacing at 1.9 Mev is taken together with the value 0.06 just quoted, the resulting values for A and B are 4.0 Mev and 1.48 (Mev)$^{-\frac{1}{2}}$, respectively. This requires a spacing at 5.15 Mev of 0.14 Mev which is about 50 percent of our observed value. However, if it is supposed that these values of A and B are right and that in our experiments only levels of low angular momentum are observed, the agreement is not so bad. If this supposition is right then for bombarding energies of 7 Mev and up, with good resolution in detection, there should be found several more levels between our Q_6 and Q_{13}.

This same line of reasoning makes it likely that the levels Q_0 to Q_5 are the actual deep energy levels of Al^{28}. This is made the more likely because of the close agreement between our experiments and those of Allan and Wilkinson for the values Q_0 to Q_3. If actually there are several levels not found due to selection rules, it is to be expected that at higher bombarding energies at least one would show up. Our experiments were at four times their bombarding energy.

The most striking features of the proton ab-

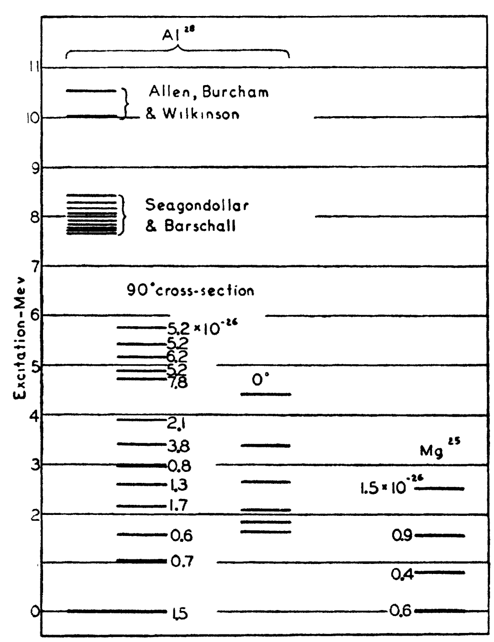

FIG. 7. Level schemes and cross sections. Energy level diagrams for Al^{28} and Mg^{25} as derived from our work. For comparison the levels derived from scattering are shown.

[8] Victor F. Weisskopf, Phys. Rev. 52, 295 (1937).

sorption curve are the two "sawtooth" sets of groups. It may be that this is due to the effect of the barrier on groups of increasing angular momentum, in which case the highest local peaks would be S levels.

The three excited states of Mg^{25} are shown in Fig. 7. These should agree with levels found from other reactions, such as $Mg^{24}(dp)Mg^{25}$. The fact that three isotopes of Mg exist renders the correct assignment of Q values difficult, so no comparison can be made at present with our values.

The mass differences $Al^{28}-Al^{27}$ and $Al^{27}-Mg^{25}$ are 1.000735 and 1.99619, respectively.

We wish to thank Professor R. F. Humphreys for much valuable discussion and Professor Howard L. Schultz for design of and assistance with the counting circuits.

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The Emission of Radiation in the Disintegration of Mesons*

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The probability has been calculated that a meson of integral spin disintegrates into an electron, a neutrino, and a photon. This is essentially a classical process, the radiation being regarded as caused by the acceleration of charge in the disintegration. Because of the classical nature of the problem, the result is independent of the quantum mechanical properties (spin, coupling) of the meson field. For definiteness, the non-radiative decay is taken as being a two-body process in accordance with the original Yukawa theory, but several different types of couplings are used. The quantum mechanical probability for emission of one photon diverges at the low frequency end of the spectrum; this difficulty is avoided by using as a measure of the process the ratio of mean energy emitted to mean energy available for the process per unit time. This is of order $e^2/\hbar c$; the energy spectrum also is in agreement with the classical result.

I. INTRODUCTION

THE nature of the products of decay of the ordinary cosmic-ray mesons (μ-mesons) is still unsettled. Recent experiments[1] however, have established that the decay does not result in the emission of a 50-Mev photon, as would be expected if the process involves simply the emission of two bodies, and the μ-meson has a spin of one-half. From the theoretical point of view, there is another possibility for the emission of electromagnetic radiation in the decay, which is of interest since it can occur regardless of the nature of the other particles emitted and is one of the few processes involving mesons which is essentially classical in nature. If the meson is at rest before disintegrating, and the decay electron has a high velocity, the sudden acceleration of charge should produce radiation. Quantum mechanically, this corresponds to a higher order process, in which a photon is emitted as well as the ordinary decay products. Similar calculations for radiative beta-decay of nuclei have been performed by Bloch and by Knipp and Uhlenbeck.[2]

Because of the classical nature of the problem, the quantum mechanical details of meson spin, and type of interaction between the meson and electron fields, which are not known from experimental evidence, should not affect the results. Some calculations for different types of interactions will be indicated, however, since they afford an interesting example of the way in

* Summary of a thesis presented in partial fulfillment of the requirements for the degree of Doctor of Philosophy at Harvard University.

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[2] F. Bloch, Phys. Rev. **50**, 272 (1936); J. Knipp and G. Uhlenbeck, Physica **3**, 425 (1936).