rated, it would not be $T-e(\mathbf{E}\cdot\mathbf{u})$ which would be conserved. We should, in fact, have

$$(1/J)(dT/dt)=e(\mathbf{E}\cdot\mathbf{u}).$$

It is true that the neutrino manifests itself in connection with particle energies far below those concerned in cosmic-rays, energies comparable with a million electron volts. It is to be observed, however, that there is nothing to require that J should change monotonically with increase of the velocity of the particle.

It must further be pointed out that there is little to *necessitate* regarding the ordinary expression (3) as having anything to do with the quantity which we speak of in energy transitions in atomic structure problems. The assignment of energy levels in atoms, and the subsequent determination of frequencies by their differences, for example, are things which do not involve T as given by (3) having any relation to that which should be conserved in the processes involved. The energy magnitudes concerned in atomic structure problems come, for the most part, from a consideration of magnitudes of constants which determine the characteristic solutions of ψ equations. It is quite true that experiments on critical potentials and the like form a bridge between kinetic energy as born of the force equation and energy as it occurs in problems of atomic structure; but, this bridge can hardly be considered to have been established for energies as high even as a million electron volts. However, it is not our purpose here to stress to the realm of the neutrino the considerations here presented. The main purpose of the paper concerns the cosmic-ray particles.

SEPTEMBER 1, 1937 PHYSICAL REVIEW VOLUME 52

The Disintegration of Lithium by Deuterons

JOHN H. WILLIAMS, WILLIAM G. SHEPHERD AND ROBERT O. HAXBY
University of Minnesota, Minneapolis, Minnesota

(Received June 21, 1937)

The following disintegrations have been studied in the range of deuteron energy from 100 to 250 kv:

$$_3Li^7+{}_1H^2\rightarrow{}_2He^4+{}_2He^4+{}_0n^1+Q_1 \quad (1)$$
$$_3Li^6+{}_1H^2\rightarrow{}_2He^4+{}_2He^4+Q_2 \quad (2)$$
$$_3Li^6+{}_1H^2\rightarrow{}_3Li^7+{}_1H^1+Q_{3a} \quad (3a)$$
$$_3Li^6+{}_1H^2\rightarrow{}_3Li^{7*}+{}_1H^1+Q_{3b} \quad (3b)$$
$$_3Li^{7*}\rightarrow{}_3Li^7+h\nu$$
$$_3Li^7+{}_1H^2\rightarrow{}_2He^5+{}_2He^4+Q_4 \quad (4)$$

Efficiency curves for (1), (2) and (3a) are regular. It is concluded that the Oppenheimer-Phillips process is not applicable to (3a). The relative yield of (3b) to (3a) increases with increasing deuteron energy. The return of the excited Li nucleus in (3b) to its normal state is shown by the emission of a gamma-ray of 400 kv energy as determined by absorption measurements. The existence of a homogeneous group of particles from (4) is interpreted as evidence for the instability of He^5, which has a mean life of approximately 6×10^{-20} sec. and is unstable by 0.93 Mev, disintegrating into an alpha-particle and a neutron. Absolute yields for the five disintegrations studied are given for a deuteron energy of 212 kv.

INTRODUCTION

STUDIES of the disintegration of lithium by deuterons over a wide range of energies have been made by various workers.[1-3] These researches, particularly with targets of separated isotopes, have established the identity of the disintegration processes and the reaction products.

The present paper reports a systematic study of the disintegration efficiency and the energy distribution of products of the following reactions in the deuteron energy range 100 to 250 kv.

$$_3Li^7+{}_1H^2\rightarrow{}_2He^4+{}_2He^4+{}_0n^1+Q_1, \quad (1)$$

$$_3Li^6+{}_1H^2\rightarrow{}_2He^4+{}_2He^4+Q_2, \quad (2)$$

[1] Cockcroft and Walton, Proc. Roy. Soc. **A144**, 704 (1934); Oliphant, Shire and Crowther, Proc. Roy. Soc. **A146**, 922 (1934); Oliphant, Kempton and Rutherford, Proc. Roy. Soc. **A149**, 406 (1935); Kempton, Browne and Maasdorp, Proc. Roy. Soc. **A157**, 372 (1936).
[2] Rumbaugh and Hafstad, Phys. Rev. **50**, 681 (1936).
[3] Alexopoulos, Helv. Phys. Acta **87**, 60 (1935).

$$_3Li^6+{}_1H^2\rightarrow{}_3Li^7+{}_1H^1+Q_{3a}, \quad (3a)$$

$$_3Li^6+{}_1H^2\rightarrow{}_3Li^{7*}+{}_1H^1+Q_{3b}, \quad (3b)$$
$$_3Li^{7*}\rightarrow{}_3Li^7+h\nu,$$

$$_3Li^7+{}_1H^2\rightarrow{}_2He^5+{}_2He^4. \quad (4)$$

The discovery of the existence of the postulated[2] gamma-ray following (3b) and the He^5 reaction (4) are also described.

Since Oliphant, Shire and Crowther[1] and Rumbaugh and Hafstad,[2] working with the separated isotopes of lithium, have already established the correct assignment of all the reactions except (4), these experiments were made using ordinary *thick* targets containing both lithium isotopes. To establish the nature of (4), targets of the separated isotopes Li^6 and Li^7 were used.

Apparatus

The transformer kenetron set, ion source, and accelerating tube described by Williams, Wells, Tate and Hill[4] were used. A new voltmeter consisting of 250 10 meg resistors similar to the one described by Hafstad, Heydenberg, and Tuve[5] served to measure voltages which were manually controlled and held to fluctuations in the output of less than 1 percent.

Charged particles were collected by means of a parallel plate ionization chamber connected to a Dunning type[6] amplifier. The output of this was fed into a thyratron scale of 8 counter[7] and a mechanical counter through a potentiometer. By adjusting this potentiometer and the depth of the ionization chamber, the counter could be made to respond only to particles whose specific ionization in the ionization chamber was above any desired amount. The amplifier power was supplied from a commercial voltage stabilizer and the gain was constant from day to day.

Due to the fact that the ion current is not steady and it is tedious and inaccurate to read a meter and average readings, a current integrator was constructed as shown in Fig. 1. The current from the Faraday cage charges a condenser

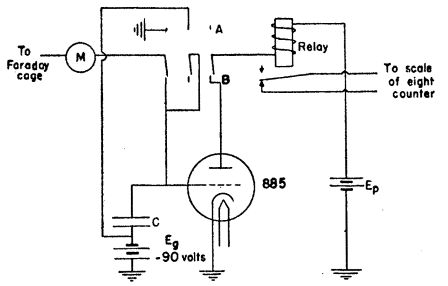

FIG. 1. Circuit diagram of current integrator. $C=22$ μf; A, B are positions of triple-pole double-throw switch; M is a microammeter, $E_p\sim150$ volts.

until the potential on the grid is sufficient to trip an 885 tube. When the tube fires the plate current of the 885 passes through a relay opening the input circuit of the scale of 8 counter. When the triple-pole double-throw switch is thrown to A it resets the circuit and when it is thrown to B the condenser charges from the collected ion beam. Thus, by taking readings of the counter before throwing the switch and again after the relay has opened, one obtains the number of counts for a definite amount of charge. As it is very essential to avoid leakage current W. E. 21L 2 μf paper condensers were used, since they were found to have inappreciable leakage conductance and bound charge. When the switch is first thrown to B the potential of the Faraday cage is about -90 volts. As the condensers charge this increase to about -12 volts when the thyratron fires. Because ions formed in the residual gas could produce a spurious current to the Faraday cage, a guard ring at a potential of about 45 volts was placed between the Faraday cage and the grounded part of the accelerating tube. With this precaution the spurious current collected was very small and in both directions so that the errors in a set of readings are less than one percent. The circuit was operated from a power pack connected to the stabilizer in order to eliminate errors due to voltage fluctuations.

Efficiency Curves

Since the concentration of deuterium in the mass two spot of the accelerating apparatus may change with time, measurements of the efficiency of a disintegration process as a function of deuteron energy are most readily made by comparing the yield to that at some standard

[4] Williams, Wells, Tate and Hill, Phys. Rev. **51**, 434 (1937).
[5] Hafstad, Heydenberg and Tuve, Phys. Rev. **50**, 504 (1936).
[6] Dunning, Rev. Sci. Inst. **5**, 387 (1934).
[7] Shepherd and Haxby, Rev. Sci. Inst. **7**, 425 (1936).

voltage. Our procedure was to take alternate readings of yield at a predetermined standard voltage, 212 kv. A further source of error arises from the deposition of hydrocarbons on the target under bombardment. To minimize this effect the LiCl thick targets were mounted on a disk holder which could be rotated to present a fresh target after each exposure of approximately three minutes duration.

The method employed in determining the efficiency curve for (1) is as follows. The amplifier detector system was made sufficiently differential to reject the α-particles of 8.4 cm range arising from molecular hydrogen in the mass two spot [the number of such α-particles was always less than 1 percent of those from (1)], as well as the α-particles from (2). With absorbing material of 2.8 cm air equivalent between the target and the ionization chamber the yield from (1) was determined as a function of voltage. In order to determine the numerical yield from this disintegration the area under a numbers *vs.* range curve at the standard voltage was compared to the yield from (2) under identical experimental conditions. As the minimum range was 2.8 cm a linear extrapolation of the numbers to zero absorber may introduce an error of 25 percent or less in the numerical yield determination.

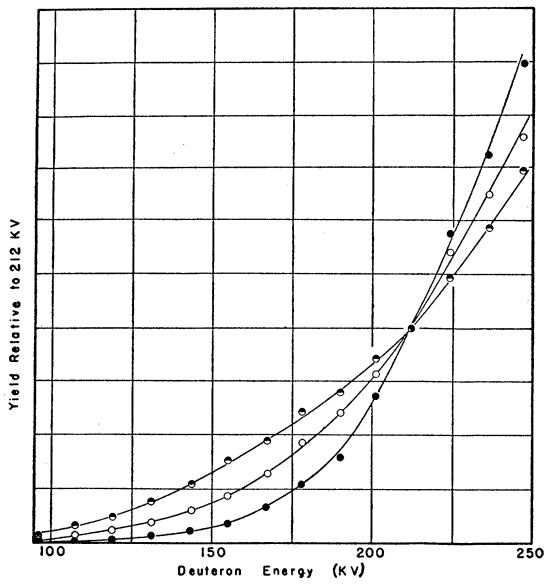

FIG. 2. Efficiency curves as a function of deuteron energy. Full circles, (1); half-full circles, (2); open circles, (3a). These curves are arbitrarily fitted at 212 kv.

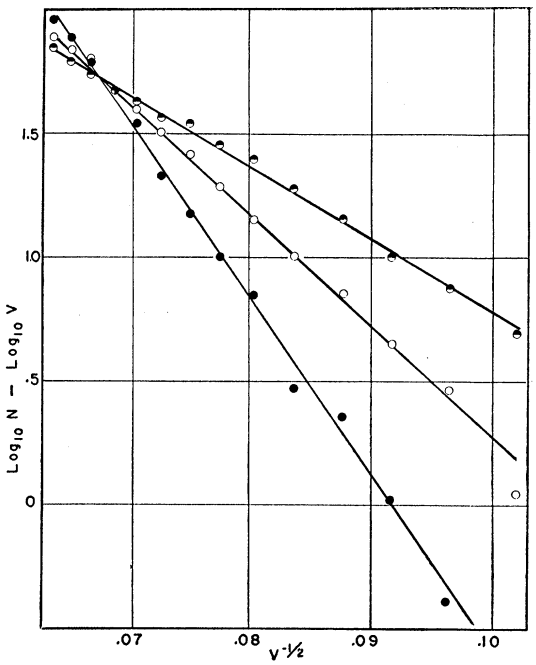

FIG. 3. Gamow plots of reactions (1), (2) and (3a) with same symbols as Fig. 2 from thick target data assuming $R \sim V^{\frac{1}{2}}$.

The α-particles from (2) were distinguished from the contamination deuterium-deuterium protons and other products by interposing an equivalent air path of 10 cm and by adjusting the potentiometer of the recording apparatus to count only α-particles.

In the case of the protons from (3a) sufficient absorbing material was introduced to remove the short range group from (3b). The counting mechanism was made sufficiently integral to record the protons without confusion due to increasing range with increasing bombarding deuteron energy.

In calculating the absolute yields from these disintegrations we have made reasonable assumptions as to the solid angle employed and have assumed an isotropic angular distribution which Neuert[8] has found to apply to (3a). The uncertainty in the concentration of deuterium in the mass two spot could be minimized by counting the number of α-particles of 8.4 cm range arising from molecular hydrogen bombardment and combining these numbers with the well-known yields from this proton reaction. We

[8] Neuert, Physik. Zeits. **38**, 122 (1937).

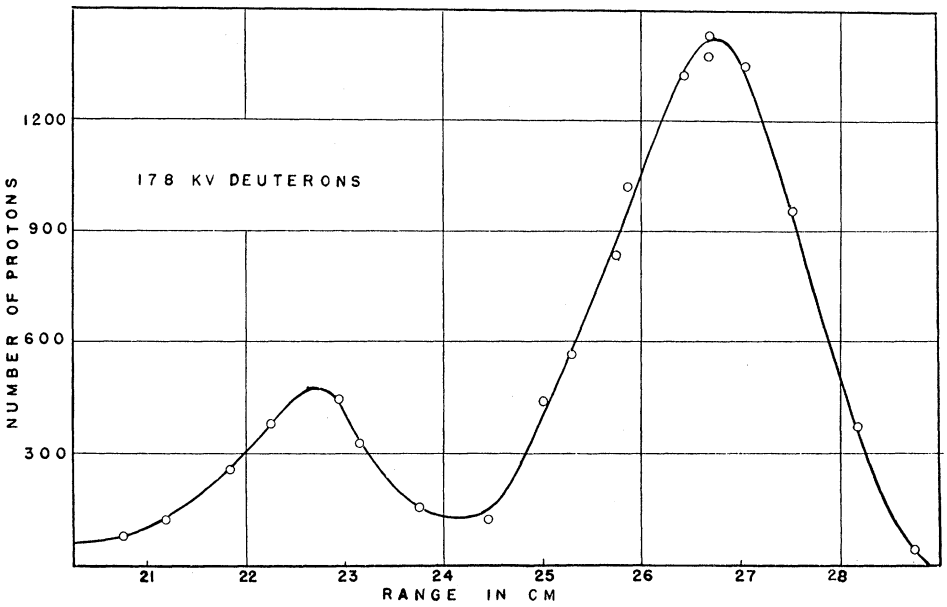

FIG. 4. Numbers *vs.* range curve for the protons from (3b) and (3a). The absolute range scale is not accurately determined.

estimate that our measured current is at least 90 percent deuterium. We have calculated our results on the basis of a thick target of lithium by multiplying the observations on LiCl by 20/3. Yields in disintegrations per deuteron of 212 kv energy are: (1) 4×10^{-7}, (2) 2×10^{-9}, (3a) 7×10^{-9}, (3b) 2×10^{-9}, (4) 3×10^{-9}. The estimated accuracy is ±50 percent.

The yields for (3b) and (4) were calculated from comparison measurements with the (3a) and (2), respectively, using the data described in later sections of this paper.

The efficiency curves for reactions (1), (2) and (3a) are shown in Fig. 2 where the curves are fitted at the standard voltage of 212 kv. It is seen that the yields increase smoothly with increasing deuteron energy with no evidence for resonance effects or other peculiarities. Increasing deuteron energy causes a more rapid increase in yield for (1) than for (2) while that for reaction (3a) falls intermediately.

Gamow plots, constructed from the thick target data following Oppenheimer's[9] integration which assumes range proportional to $V^{\frac{3}{2}}$, are shown in Fig. 3. It is evident that the data can be well fitted by three straight lines, as might well be expected for (1) and (2) since these processes are of the simple capture type discussed by Gamow. Conversely, reaction (3) is of the Oppenheimer-Phillips[10] type envisioned as a dissociation of the deuteron with the rejection of the proton. Since the data do fit Gamow plots assuming $R\sim V^{\frac{3}{2}}$, or $R\sim V^{1.2}$ as indicated by Mano's[11] data (the assumption is apparently not critical), one would conclude that the Oppenheimer-Phillips process is not important for this case.

A qualitative explanation for this conclusion follows. From the experimental evaluation of the exponent in the Gamow formula (assuming $R\sim V^{1.2}$) one can calculate a reasonable nuclear radius for (3a) of 4.5×10^{-13} cm. From the Oppenheimer-Phillips theory one concludes that if the deuteron is to be dissociated by the field of the nucleus the most probable distance to which the center of mass of the deuteron penetrates from the center of the nucleus should be roughly given by $X=Ze^2/2I$, where I is the binding energy of the deuteron ($\geqq2\times10^6$ ev). This gives $X\geqq1\times10^{-13}$ cm. Consequently one sees that for the lithium nucleus the deuteron would have already penetrated the potential barrier before dissociation would be probable. The Oppen-

[9] Henderson, Phys. Rev. **43**, 98 (1933).

[10] Oppenheimer and Phillips, Phys. Rev. **48**, 500 (1935).

[11] Mano, Ann. de physique **11**, 407 (1934).

heimer-Phillips process therefore does not occur for light nuclei where the potential barrier is less than the dissociation energy of the deuteron and the Gamow penetration theory should apply to these cases.

Protons from Li^6 and the Associated Gamma-Rays

Rumbaugh and Hafstad[2] have established the existence of two proton groups (3a) and (3b) of range approximately 26 cm and 30 cm by examining the disintegration products from targets of the separated isotope Li^6. The relative probability of these disintegrations has been examined throughout our voltage range. To measure the separate groups the ionization chamber and amplifier were set sufficiently differentially to almost completely resolve the two groups on an exploratory numbers *vs.* range plot as shown in Fig. 4. Several readings of the relative heights of the peaks were obtained by taking consecutive readings of numbers on the peaks. At each different deuteron energy the range position of the peaks was redetermined and relative peak readings taken at the appropriate amounts of absorbing material. The results are shown in Fig. 5, where the ratio of the yield of (3b) to (3a) is plotted as a function of deuteron energy.

The increase in relative yield is not linear and agrees in absolute value with the determinations of Rumbaugh, Roberts and Hafstad[12] at higher voltages. This increase might be expected on the general grounds that at higher bombarding energies (e.g., alpha-particle bombardment) the disintegration in which the nucleus is left in an excited state becomes relatively more probable.

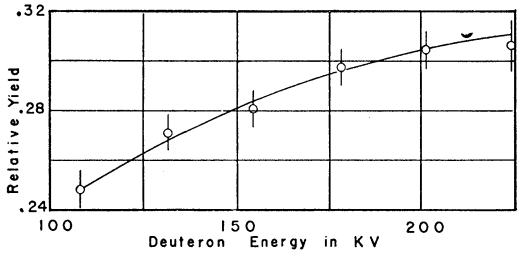

FIG. 5. Relative yield of protons from (3b) to protons from (3a) as a function of bombarding deuteron energy.

[12] Rumbaugh, Roberts and Hafstad (private communication). (We are indebted to these authors for the privilege of discussing their results prior to publication.)

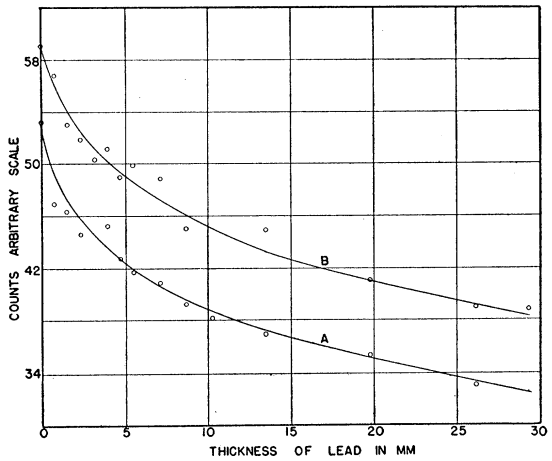

FIG. 6. Number of Geiger counter counts to an arbitrary scale as a function of thickness of lead absorber.

The interpretation of the two groups as due to the product nucleus being left in an excited state for (3b) leads to the prediction[2] of a gamma-ray of approximately 400 ± 40 kv energy being emitted as a secondary process.

To make absorption measurements of this radiation we have used a Geiger counter mounted in a tubular lead shield of 3 cm wall thickness. A port cut in the side of this shield allowed the counter to view the LiOH target without being exposed to any x-rays that were not scattered. Lead absorber sheets could be placed between the port and the target. The absorption measurements were complicated not only by the soft x-rays (primary rays less than 200 kv, scattered at least once) but by the copious neutrons emitted from the Li and contamination deuterium in the target under deuteron bombardment.

Two typical absorption curves are shown in Fig. 6. It is seen that the first millimeter of lead removes most of the x-rays and the absorption curve at large thicknesses of absorber allows an extrapolation to subtract the background effect of the neutrons present at lesser thicknesses of absorber. After the subtraction of the neutron background the logarithm of the remaining counts is a linear function of the thickness of lead as is shown in Fig. 7.

The absorption coefficient of this radiation in lead is calculated from our data to be 2.42 ± 0.20 cm^{-1}. This absorption coefficient indicates the presence of a gamma-ray of energy 400 to within

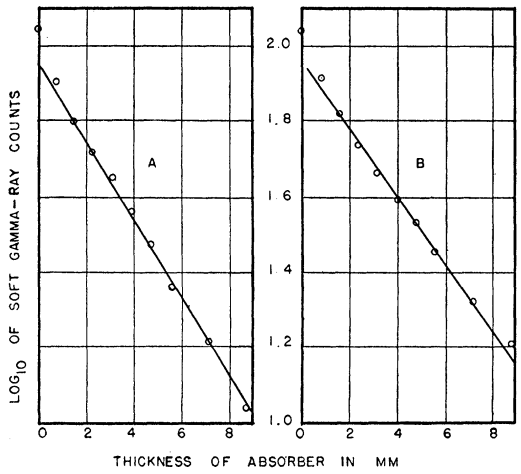

FIG. 7. Logarithm of counts not attributed to extraneous sources as a function of thickness of lead absorber.

an accuracy of 25 kv. It is only because the absorption coefficient is such a rapidly varying function of the energy of the radiation in this region that one can set such narrow limits on the energy. The evidence is thus in good agreement with the interpretation of the two proton groups. The failure of Alexopoulos[3] to observe the gamma-ray may be attributed to lack of intensity after absorption by 2 cm of lead.

THE INSTABILITY OF He^5

We have reported in a previous publication[13] evidence for the instability of He^5 from a study of the reaction

$$_3Li^7+{}_1H^2\rightarrow{}_2He^5+{}_2He^4+Q_4. \qquad (4)$$

Our measurements established the presence of a homogeneous group of alpha-particles of mean range 7.10 cm from Li^7 as shown in Fig. 8. This group was interpreted as the He^4 from reaction (4). The absence of a comparable homogeneous group of He^5 particles at 4.35 cm is to be expected since the substitution of mass-energy data in Eq. (4) gives He^5 a mass of 5.0140 which is unstable by 0.93 Mev.

We interpret the disintegration process as He^5 existing for a sufficient time to give the He^4 a somewhat definite energy in the disintegration. The He^5 then disintegrates into a neutron and an alpha-particle which share the initial energy of the He^5 and its negative energy of binding. One would then expect to observe these secondary alpha-particles with a calculable energy distribution. The energy of the alpha-particles may be written

$$E=4/5\epsilon+1/5Q+4(\epsilon Q)^{\frac{1}{2}}\cos\theta_r/5, \qquad (5)$$

where ϵ is the energy of the He^5 nucleus in the initial disintegration, Q is the disintegration energy of the He^5 into an alpha-particle and a neutron, and θ_r is the angle between the resultant He^4 and the initial He^5 in a coordinate system referred to the center of mass. Substituting the experimentally determined values, $\epsilon=6.25$ Mev and $Q=0.93$ Mev, one obtains values of E from 3.26 Mev to 7.12 Mev. The continuum of alpha-particle ranges would then extend from 1.90 cm to 6.06 cm.

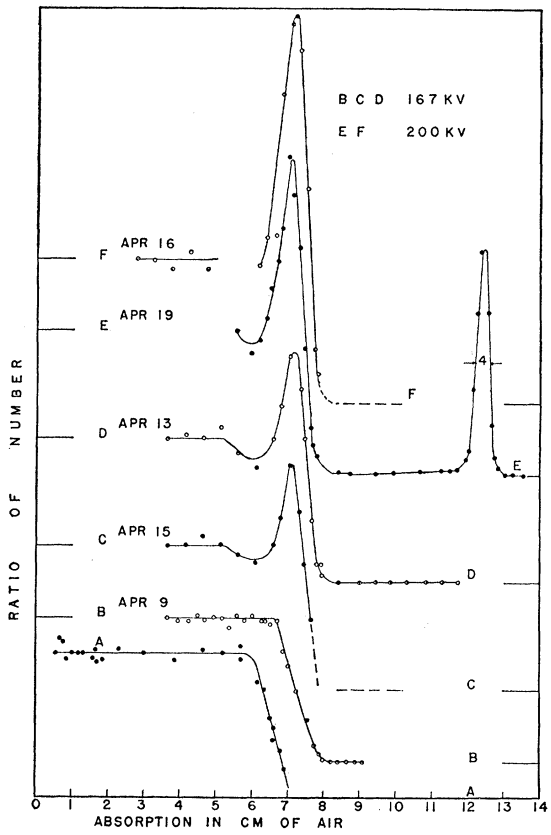

FIG. 8. Ratio of number of particles detected at a given absorption to the number at minimum absorption. The lettered scale marks on the left are unity and the corresponding marks on the right are zero. Curve A is from Oliphant, Kempton and Rutherford, reference 1. Increasing peak height at a given voltage is evidence of increasing differentiality of detecting apparatus.

[13] Williams, Shepherd, and Haxby, Phys. Rev. **51**, 888 (1937).

Assuming isotropic angular distribution of the secondary disintegration products with respect to the He^5 at rest, this continuum would present a plateau on the numbers *vs.* range curve between these limits. Our observations serve to indicate such a plateau by the dip in the numbers curve at 6 cm range. The experimentally allowable minimum range is not sufficiently small to enable a search for the corresponding decrease at small range. The evidence for the existence of this continuum is partially vitiated by uncertainty as to the exact distribution of particles in the background from (1).

Further evidence for the validity of our hypothesis arises from the extended width of the "homogeneous" alpha-particle group of 7.10 cm range as compared to the homogeneous alpha-particle group of 12.4 cm range from reaction (2). If we assume the shape of the underlying continuum due to (1) as extending horizontally to intercept the vertical portion of the total curve and attribute the residue to reaction (4), we find the width at half-maximum of the resultant peak is 6 mm. The half-width at half-maximum is thus 1 mm greater than is observed in the simple reaction (2).

This additional width corresponds to a variation in energy of 0.07 Mev and applying the uncertainty principle one calculates the mean life of He^5 to be approximately 6×10^{-20} sec.

ACKNOWLEDGMENTS

We wish to express our indebtedness to Dr. L. H. Rumbaugh of the Bartol Research Foundation who kindly supplied the separated isotopes of Li. We also wish to express our appreciation to Professor E. L. Hill for his stimulating and elucidating discussions and to Professor John T. Tate for his continued interest and encouragement.

This research was supported in part by a grant from the Graduate School.

SEPTEMBER 1, 1937 PHYSICAL REVIEW VOLUME 52

On the Comparison of Proton-Proton and Proton-Neutron Interactions

G. BREIT AND J. R. STEHN
University of Wisconsin, Madison, Wisconsin

(Received June 30, 1937)

Based on the data of Tuve, Heydenburg and Hafstad for the scattering of protons by protons and that of Amaldi and Fermi for the scattering of neutrons by protons a comparison of the two interactions is made. The present comparison is made more accurately than previously and allows for the uncertainty in the chemical factor C which is used in the interpretation of the neutron-proton experiments. The results are substantially in agreement with those of Breit, Condon and Present, the two interactions being very nearly equal. A slight excess of neutron-proton attraction over that between protons is indicated by the present calculation. Fermi's conclusion that the singlet S level of deuterium is virtual is reexamined by taking into account the effect of the range of force and of the chemical factor on the mean life of neutrons in an atmosphere of protons. Experiment agrees better with a virtual than with a real level. Nevertheless the evidence for its virtual character is not so good as to exclude completely the possibility that it is real. Tests by means of which a real level could be found if present are discussed.

A COMPARISON of the proton-proton and proton-neutron singlet S interactions using the experiments of Tuve, Heydenburg, Hafstad[1] on protons and of Amaldi, Fermi[2] on neutrons has already been made.[3] This comparison was not as complete as is desirable because: (a) Only Fermi's conclusion[4] that the lowest proton-

[1] M. A. Tuve, N. P. Heydenburg and L. R. Hafstad, Phys. Rev. **50**, 806 (1936).

[2] E. Amaldi and E. Fermi, Ricerca Scient. **7** *I*, 310 (1936); E. Amaldi and E. Fermi, Phys. Rev. **50**, 899 (1936).

[3] G. Breit, E. U. Condon and R. D. Present, Phys. Rev. **50**, 825 (1936).

[4] E. Fermi, Ricerca Scient. **7** *II*, 13 (1936). The extension of Fermi's formula used here is obtained by calculating without approximations, the transition probability due to