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Radioactivity of Li^8

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The continuous distribution of alpha-particles observed in conjunction with the beta-decay of Li^8 is examined theoretically from the Fermi theory of beta-decay. It has previously been noted that the Konopinski-Uhlenbeck theory does not give the distribution correctly. An approximate form of the Fermi theory suffices to account for the general form of the distribution. Calculations are presented for $L=0$ and $L=2$, with several values of the nuclear radius. An abnormally small value of Fermi's constant g is found for the beta-decay process, which classes the process as improbable. The consequences of a stable ground state for Be^8 are discussed.

THE bombardment of Li^7 by deuterons produces Li^8,[1, 2] a radioactive nucleus which emits beta-rays and has a half-life of 0.88 ± 0.1 sec.[3] This emission of β-particles is accompanied by an alpha-particle activity which decays with the same period. The reactions are:

$$Li^7+D^2=Li^8+H^1$$
$$Li^8=(Be^8)^*+e^-+\nu+Q_1,$$
$$(Be^8)^*=He^4+He^4+Q_2.$$

Breit and Wigner[4] have suggested that the α-particles are emitted from a broad excited virtual state of the intermediate Be^8 nucleus. There is evidence for the existence of such a state, in the neighborhood of 3-Mev excitation energy and with a breadth of about 1 Mev, from the disintegration of B^{11} by protons. Dee and Gilbert[5] showed that the distribution of the three emitted α-particles in the boron reaction could be explained by assuming that one α-particle was first ejected, leaving an excited $(Be^8)^*$ nucleus which then decomposed into two more α-particles. All efforts to detect γ-rays from Li^7 bombarded by deuterons have been unsuccessful;[6, 7] it may therefore be concluded that the disintegration into two α-particles is a more probable process than the transition to the ground state of Be^8 with the emission of γ-radiation.

The disintegration sequence is supposed to be: (1) A Li^8 nucleus is formed in a well-defined state; the nucleus subsequently decays with a half-life of 0.88 sec. by beta-neutrino emission. The lower state of this transition does not have a well-defined energy, but corresponds in general to an excited state in the continuum of $(Be^8)^*$. (2) The $(Be^8)^*$ then disintegrates, in a time less than 10^{-20} sec., into two α-particles.

* Wisconsin Alumni Research Foundation Fellow.

[1] H. R. Crane, L. A. Delsasso, W. A. Fowler and C. C. Lauritsen, Phys. Rev. **47**, 971 (1935).

[2] L. H. Rumbaugh and L. R. Hafstad, Phys. Rev. **50**, 681 (1936).

[3] W. B. Lewis, W. E. Burcham and W. Y. Chang, Nature **139**, 24 (1937).

[4] E. Wigner and G. Breit, Phys. Rev. **50**, 1191 (1936); G. Breit and E. Wigner, Phys. Rev. **51**, 593 (1937).

[5] P. I. Dee and C. W. Gilbert, Proc. Roy. Soc. **A154**, 279 (1936).

[6] L. H. Rumbaugh, R. B. Roberts and L. R. Hafstad, Phys. Rev. **54**, 657 (1938).

[7] D.S. Bayley and H. R. Crane, Phys. Rev. **52**, 604 (1937).

The energy distribution of the α-particles has been investigated by several groups of workers.[6, 8, 9] Gamow and Teller[10] have suggested that the observed distributions furnish strong evidence for the Fermi theory of beta-neutrino decay, as opposed to the Konopinski-Uhlenbeck theory, which here leads to predictions in marked disagreement with observation. The main purpose of the present report is to show what general features of the α-particle distribution can be accounted for by the Fermi theory.

The total disintegration energy $Q=Q_1+Q_2=15.9$ Mev is divided between the energy of the light particles $Q_1=E_e+E_\nu$, where E_e is the energy of the electron and E_ν that of the neutrino, and the energy of the two α-particles which is $Q_2=2E_\alpha$ since the two α-particles must receive nearly equal energies if momentum is to be conserved. The probability $N(Q_1)$ of a β-decay process with energy Q_1 in the Fermi theory is roughly proportional to Q_1^5, and therefore to $(Q-2E_\alpha)^5$. For each beta-neutrino process with end point energy Q_1, two α-particles are observed, each with energy E_α. Therefore the number-energy distribution for the α-particles is given by $N(E_\alpha)dE_\alpha \propto (Q-2E_\alpha)^5 dE_\alpha$. This fifth power dependence of the distribution on energy is represented by the straight line A in Fig. 1, and is seen to agree roughly with the experimental points except in the extreme regions of high and low α-energies. The K-U theory predicts a seventh power dependence of distribution on energy, which clearly cannot account for the facts. A log-log plot of number *vs.* energy is equivalent in this problem to a Sargent diagram.

The Fermi theory leads to

$$p(Q_1)=\frac{64\pi^4 g^2}{h^7 c^6}\left|\int u^* v d\tau\right|^2 \frac{(mc^2)^5}{30}(\sinh^5\theta)\mathfrak{F} \quad (1)$$

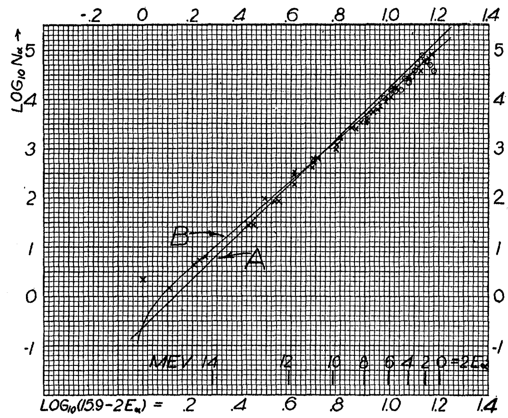

FIG. 1. Number-energy distribution for α-particles. Crosses: R.R.H. counter. Circles: R.R.H. cloud chamber. A. Plot of fifth power approximation. B. Plot of $(\log_{10}\mathfrak{F}\mathrm{sh}^5)-2.35$.

for the probability per nucleus per unit time that a β-process with energy Q_1 will take place. g = Fermi's constant, u and v are the wave functions of the initial and final states, respectively, and $\cosh\theta=Q_1/(mc^2)$. $\mathfrak{F}$ is given by

$$\mathfrak{F}=\left[1-\frac{5}{2}\frac{1}{\sinh^2\theta}-\frac{15}{2}\frac{1}{\sinh^4\theta}+\frac{15}{2}\frac{\theta\cosh\theta}{\sinh^5\theta}\right].$$

It is a very slowly varying function of the energy, and is effectively equal to one except for low values of Q_1.

For a complete treatment of the problem one would have to evaluate the matrix elements $\int u^* v d\tau$ using solutions of the many-body problem for Li^8 as well as for the continuum of Be^8. It is very difficult at this stage to obtain sufficiently good approximations to these solutions. In the present note, therefore, the effect of the energy of $\int u^* v d\tau$ is taken into account only in a rather rough approximation. It is supposed that, in the region of configuration space which overlaps Li^8, the variation with energy of the amplitude of the many-body wave function of the continuum of Be^8 is proportional to the variation with energy of the two-body function for two alpha-particles having the empirical value of the phase shift. For distances between α-particles greater than the α-particle diameter this procedure can be expected to be fairly accurate, but it is of course very imperfect for smaller distances. Most of the calculations made followed a method in which the interaction

[8] W. A. Fowler and C. C. Lauritsen, Phys. Rev. **51**, 1103 (1937).

[9] C. Smith and W. Y. Chang, Proc. Roy. Soc. **A166**, 415 (1938).

[10] Considerations of G. Gamow and E. Teller quoted by L. H. Rumbaugh, R. B. Roberts and L. R. Hafstad, Phys. Rev. **51**, 1106 (1937). Although the original β-ray theories are being remodeled at present along mesotron lines, the Fermi and K-U theories practically reappear in a new guise. It is of interest that here also the experimental evidence indicates a preference for the Fermi-like type of theory.

potential between the α-particles was adjusted to give the experimental phase shift, and the two-body function corresponding to this potential was used within the nuclear distance. In order to see to what extent the results are dependent on the above-mentioned approximation, a second method was tried in which the two-body functions were continued to $r=0$ as though there were no interaction potential. Several estimates were also made in which the integral of the wave function through the potential well was replaced by the maximum amplitude of the function within the well; the results in these cases were generally similar to those obtained from the first method.

After normalizing the α-wave functions for the continuum in a large sphere, one obtains the approximate form suitable for the present problem:

$$N_\alpha(Q_2)dQ_2 = \frac{256\pi^4 g^2 m^5 c^4}{h^8} \times \left(\frac{1}{V_\alpha}\int_0^{r_0} \bar{F}^2 dr\right)\frac{\sinh^5\theta}{30}\mathfrak{F}dQ_2,$$

where $N_\alpha(Q_2)dQ_2$ is the probability of an α-process with energy in dQ_2 at Q_2 per nucleus per second, V_α is the relative velocity of the two α-particles, $\bar{F}$ is the α-particle radial wave function, and r_0 is the radius of the nuclear barrier.

There is evidence from the work of Rumbaugh, Roberts and Hafstad, and Fowler and Lauritsen for a maximum in the alpha-particle distribution at $2E_\alpha \sim 2.5$ Mev, with a falling off below the fifth power expression on the low energy side of the maximum. The maximum has appeared only when the distribution is obtained with an expansion chamber; counters do not reveal the maximum, but counter results are known to be uncertain at these low energies. Rather rough calculations have been made of the behavior to be expected theoretically in this region, on the two-body simplification. The term $(V_\alpha^{-1}\int\bar{F}^2dr)$ was calculated for both s waves and d waves with a Coulomb barrier.

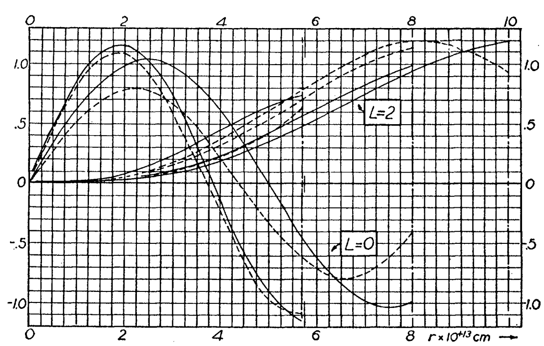

FIG. 2. Internal wave functions for $L=0$ and $L=2$. Solid lines: $Q_2=1.80$ Mev. Broken lines: $Q_2=3.18$ Mev. ($L=0$ functions have been multiplied by -1 for the sake of clarity.)

The internal nuclear wave functions were joined to wave functions for a Coulomb field at the boundary. The internal functions were taken for a flat bottom cylindrical well. No preassigned depth was taken for the well; instead the wave-lengths of the internal functions were adjusted to join smoothly the preassigned external functions at the boundary. The external functions for large arguments can be written as $A(r)\sin[\Phi(r)+K]$ where the amplitude $A(r)$ and phase $\Phi(r)$ have been computed by Wheeler;[11] K is the usual phase shift. The values of the phase shifts which were used are those calculated by J. A. Wheeler[12] from experimental data of the scattering of α-particles in helium. Calculations were made for $L=0$: $r_0=5.00$, 5.68, 6.20, 8.00×10^{-13} cm; and $L=2$: $r_0=5.68$, 8.00, 10.00×10^{-13} cm. The radius is strictly the distance between the centers of the α-particles when confined within the volume of the unstable Li^8 nucleus; the radius is to be compared with the diameter of the Li^8 nucleus, which may be rather large. In Fig. 2 several of the internal radial wave functions $\bar{F}_L$ are shown for $L=0$ and $L=2$. An internal function is determined only by its logarithmic derivative at r_0. If the wave function possesses a node in the neighborhood of r_0, the value of the integral is very sensitive to the interaction around r_0. Since the assumption of a constant interaction inside the well is crude, the results are probably only reliable when the amplitude of the wave function at the boundary is near its maximum.

The calculated curves are joined smoothly to the $\mathfrak{F}sh^5$ curve at $Q_2=2E_\alpha=3.18$ Mev. The main features of the experimental data can be reproduced for either the $L=0$ interaction with a small radius, or the $L=2$ interaction with a

[11] J. A. Wheeler, Phys. Rev. **52**, 1123 (1937).
[12] J. A. Wheeler, private communication.

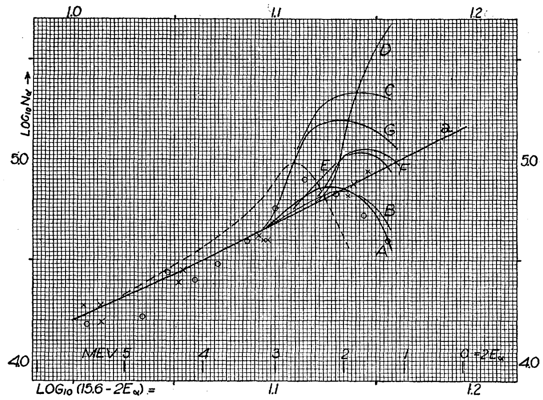

FIG. 3. Number-energy distribution for α-particles. Circles: R.R.H. cloud chamber. Crosses: R.R.H. counter. Dashes: Fowler-Lauritsen cloud chamber (smoothed). a. $(\log_{10} \mathfrak{F}sh^5)-2.35$. A. $L=2$, $r_0=8\times 10^{-13}$ cm, B. $L=2$, $r_0=10\times 10^{-13}$ cm, C. $L=2$, $r_0=5.68\times 10^{-13}$ cm, D. $L=0$, $r_0=8\times 10^{-13}$ cm, E. $L=0$, $r_0=5.0\times 10^{-13}$ cm, F. $L=0$, $r_0=5.68\times 10^{-13}$ cm, G. $L=0$, $r_0=6.2\times 10^{-13}$ cm; extended Coulomb function.

larger radius. It is not at present possible to make a definite decision as to the angular momentum of the excited state of $(Be^8)^*$. The best fit seems to be for $L=2$, $r_0=8.00\times 10^{-13}$ cm. $L=1$ is ruled out because the wave functions for two α-particles must be symmetrical in the two particles. The general form of the calculated distributions is maintained for the several values of r_0; this is some justification for the use of "one-body" phase shifts in the calculation. The assumption is made that no appreciable resonance effects occur for energies above 3.18 Mev; on the one-body model this is a reasonable assumption.

A further calculation was made in which the Coulomb functions for $L=0$ with the phase shifts as before were extended into $r_0=0$; the radius for the integral was taken as $r_0=6.20\times 10^{-13}$ cm. Wheeler's tables for the wave functions may be used as far as about 3.60×10^{-13} cm; from 0 to about 2×10^{-13} cm. The tables of Yost, Wheeler and Breit[13] can be used. Wheeler's $A(r)\sin[\Phi(r)+K]=F\cos K+G\sin K$ in the notation of Y. W. B. The curve in the intermediate region was traced in by eye. The distribution expected for this case is represented by curve G in Fig. 3.

The agreement with experiment in the region of $Q_2>10$ Mev is very sensitive to the value of $Q=Q_1+Q_2$ used. Figs. 1 and 4 are plots of $\mathfrak{F}sh^5$ for $Q=15.9$ and 15.6 Mev, respectively. The former value appears to give improved agreement with the observed distribution in the region of high α-particle energies. Rumbaugh, Roberts and Hafstad[6] give $Q=15.9$ (± 0.1) Mev from observed masses.

Fermi's constant g was evaluated for the process by equating the integral $\int_0^Q N_\alpha(Q_2)dQ_2$ to the observed disintegration probability. The integral was evaluated graphically with the theoretical distribution for $L=0$, $r_0=5.68\times 10^{-13}$ cm and also for $L=2$, $r_0=8\times 10^{-13}$ cm. The disintegration probability is given by $(ln2)/\tau$, where the half-life $\tau=0.88\pm 0.1$ sec. For $L=0$ one obtains $g=1.7\pm 0.2\times 10^{-50}$ erg cm^3; for $L=2$, $g=2.0\pm 0.2\times 10^{-50}$ erg cm^3. For heavy nuclei Fermi found $g=4.00\times 10^{-50}$. Breit and Knipp,[14] however, found with $g=4.00\times 10^{-50}$ that He^6, Be^7 and C^{11} have anomalously high values of the matrix elements, and have suggested that there may be a decrease in the intrinsic β-emitting powers of nuclear particles in heavy nuclei. They give $|M|^2=120$ for He^6, 30 for Be^7, and 9 for C^{11}. The value of g for Li^8 would correspond to $|M|^2=0.25\pm 0.03$ for $L=2$, or $|M|^2=0.18\pm 0.02$ for $L=0$. This value is so much smaller than the value for neighboring processes that the β-decay of Li^8 must be classed as an improbable process. The ratio

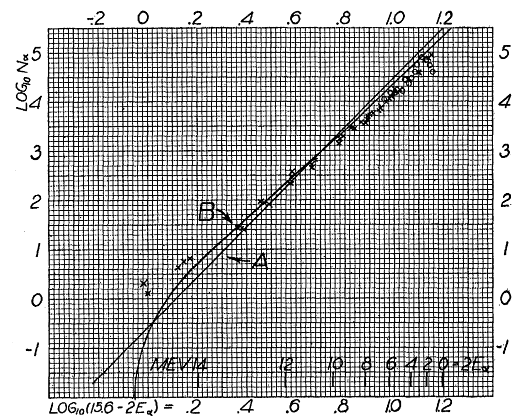

FIG. 4. Shows effect of change of energy scale. Compare with Fig. 1. A. Plot of fifth power approximation. B. Plot of $(\log_{10} \mathfrak{F}sh^5)-2.20$.

$$\frac{|M|^2(Be^7)}{|M|^2(Li^8, L=2)} \sim 125\pm 15.$$

[13] F. L. Yost, J. A. Wheeler and G. Breit, Terr. Mag. **40**, 443 (1935).

[14] G. Breit and J. K. Knipp, Phys. Rev. **54**, 652 (1938).

The ratio between two adjacent Sargent curves is about 100. It is not immediately possible to decide whether the improbability in the case of Li^8 is caused by spin changes, geometrical factors, or a combination of both.

The existence of a stable ground state for Be^8 would admit the possibility of β-transitions to the ground state without the emission of α-particles. Allison and co-workers[15] have recently reported that Be^8 is stable with respect to two α-particles by 0.31 ± 0.06 Mev. Rumbaugh, Roberts and Hafstad[6] found that the number of delayed α-particles from the Li^8 reaction is 1.1 times greater than the total number of β-particles observed. They suggest that various corrections would tend to increase the ratio of α to β. The ratio 1.1 : 1 may be regarded as setting a limiting value to the relative probabilities of β-decay to the continuum and to the stable state of Be^8. Beta-decay to the continuum will have to compete with decay to the ground state; this competition will decrease the values of the matrix elements as calculated above, which represent transitions to the continuum only, by a factor of 0.55. One obtains $|M_c|^2=0.10(L=0)$; $=0.14(L=2)$.

The matrix element for transitions to the stable state can be estimated in a similar way. The direct estimate must be corrected for the spreading of the wave function of the ground state beyond the boundaries of the potential well. The ground state is assumed to consist of two α-particles with $L=0$. One gets finally $|M_s|^2\leqq 0.04$. On the basis of this low value one might tentatively suggest that the excited state has $L=2$, and β-transitions to the ground state are forbidden by a strong selection rule.

It is a pleasure to thank Professor G. Breit for suggesting this problem, and for his constant advice. I am very indebted to Professor J. A. Wheeler for permission to use his calculations of phase shifts before publication. The Wisconsin Alumni Research Foundation has granted financial support.

[15] S. K. Allison, E. R. Graves, L. S. Skaggs and N. M. Smith, Jr., Phys. Rev. 55, 107 (1939).

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Total Secondary Electron Emission from Tungsten and Thorium-Coated Tungsten

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The secondary electron emission from polycrystalline tungsten covered with monomolecular films of thorium evaporated onto it from a thoriated tungsten filament, has been investigated over an energy range for primary electrons of 100 to 1000 volts. The state of the target surface was ascertained from thermionic emission measurements. For clean thorium on clean tungsten apparently the secondary emission coefficient did not change with thoriation for primary energies below 200 volts, but decreased at higher voltages with increasing amounts of thorium on the target. No observed increase in secondary emission takes place with a reduction in the work function of tungsten by a monomolecular layer of pure thorium; apparently there is a decrease in secondary emission in this case. When the thorium-coated tungsten was treated with oxygen released from the thoriated tungsten filament the work function increased, but there obtained also an increase in the secondary emission coefficient; further change in work function by evaporation of thorium caused a variation of the secondary emission coefficient that other experimenters also have observed.

Introduction

Systematic studies of the secondary electron emission from composite surfaces bombarded with low energy primary electrons have been carried out by several investigators,[1–3] but conclusions reached are at variance. Data[2] are available which check a theory stating that

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[1] Paul L. Copeland, Phys. Rev. 46, 435 (1933).
[2] L. R. G. Treloar, Proc. Phys. Soc. 49, 392 (1937).
[3] H. Bruining and J. H. de Boer, Physica 5, 17 (1938).