The Half-Life of the 1.3-Mev Excited State in K^{41}

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THE ground state of K^{41} is classified as a $d_{3/2}$ level,[1] while the first excited state of the 19th proton would be expected to be an $f_{7/2}$ level. A gamma-ray transition between these levels would then be magnetic quadrupole ($M2$).

About 99.3 percent of A^{41} beta-disintegrations lead to a 1.3-Mev excited state in K^{41}, and 0.7 perent lead to the ground state.[2] An assignment of $f_{7/2}$ to this excited state is consistent with these observed beta-transition probabilities. The theoretical half-life given by Weisskopf's formula[3] for such a 1.3-Mev $M2$ transition is 0.45×10^{-9} second.

The half-life of this 1.3-Mev excited state in K^{41} has been measured by the following delayed coincidence experiment. A source of the 109-minute A^{41} activity was prepared by thermal neutron irradiation of a sample of 99.6 percent tank argon sealed in a thin quartz bulb. After a 20-minute neutron irradiation, the source was placed between two *trans*-stilbene scintillation counters using $IP21$ photomultipliers. One counter was sensitive to beta-rays, while the other was covered with sufficient absorber to stop the beta-radiation and leave the counter sensitive to gamma-radiation. The counter pulses were led to a coincidence apparatus consisting of four coincidence mixers arranged with beta-pulse delays of 4×10^{-9} second inserted between successive mixers. The individual mixers are similar in principle to that described by Bell and Petch[4] and were adjusted to have a resolving time of about $2\tau_0=4\times 10^{-9}$ second. Coincidence counts were then recorded in the four mixing channels for a series of delays in either the beta- or the gamma-counter lines leading to the coincidence apparatus. In this way four independent sets of data were obtained in each run. The set of data obtained in one of the mixing channels during one run and corrected for A^{41} decay is shown in Fig. 1. Prompt coincidence curves were obtained by replacing the source of A^{41} by a source of Au^{198}. One such curve is also shown in Fig. 1 for comparison.

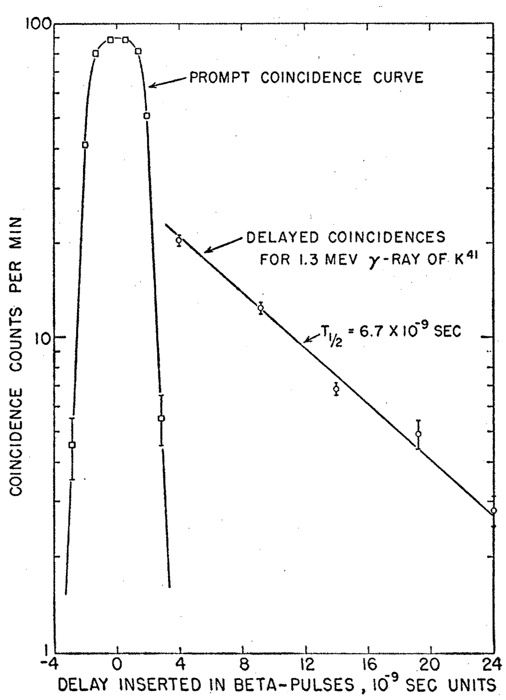

FIG. 1. The delayed coincidence curve taken in one mixing channel and showing the half-life of the 1.3-Mev gamma-transition in K^{41} with a prompt coincidence curve for comparison. The measured background of random coincidences was small and has been subtracted at each point.

The mean value of the half-life of the 1.3-Mev excited state in K^{41} obtained from two runs using different sources is $(6.7\pm 0.5)\times 10^{-9}$ second. This is seen to be appreciably longer than the theoretical half-life given by Weisskopf's formula.

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[1] M. G. Mayer, Phys. Rev. **78**, 18 (1950).
[2] Bleuler, Boltmann, and Zünti, Helv. Phys. Acta **19**, 419 (1946).
[3] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951).
[4] R. E. Bell and H. E. Petch, Phys. Rev. **76**, 1409 (1949).

The Tetraneutron*

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IT is known that a system of two protons and two neutrons has an unusually high binding energy. If one considers that the filling of neutrons and protons in a nucleus is, in general, independent of each other, one might infer that a certain amount of binding energy may be obtained if two neutrons are substituted for the two protons in the above case; thus forming a tetraneutron.

Assuming the tetraneutron is unstable with respect to a helium nucleus but stable with respect to free neutrons, one could set up an upper limit for the binding energy of the tetraneutron as follows:

$$4n\rightarrow n^4 + Q_1 \tag{1}$$

$$n^4\xrightarrow{\beta^-}H^4 + Q_2 \tag{2}$$

$$H^4\xrightarrow{\beta^-}He^4 + Q_3. \tag{3}$$

Combining these equations and using Breit and McIntosh's limiting values for Q_3,[1] one obtains

$$Q_1=[(9.4\text{ to }13.8)-Q_2]\text{ Mev}. \tag{4}$$

If reaction (2) occurs, Q_2 is positive; then the maximum value of Q_1, the binding energy of the tetraneutron, will be about 14 Mev.

If one considers the following two exothermic reactions and combines them with reaction (1)

$$X^A+n\rightarrow Y^{A-3}+4n-|Q_5| \tag{5}$$

$$X^A+n\rightarrow Y^{A-3}+n^4-|Q_6| \tag{6}$$

one obtains

$$|Q_5|-|Q_6|=Q_1 \tag{7}$$

It is obvious that if reaction (6) can be carried out before reaction (5) by using energies of impinging neutrons lower than that of the threshold for reaction (5), it should indicate the existence of the tetraneutron. This method of detection is particularly convenient if the binding energy of the tetraneutron is larger than, say, 3 Mev.

The maximum energy of neutrons produced by the 16-Mev deuterons from the University of Pittsburgh cyclotron on Be is about 18 Mev at a convenient angle where high intensity fast neutrons are available. These neutrons were used to bombard Rh^{103} and Bi^{209}. The thresholds for the reactions $Rh^{103}(n, 4n)Rh^{100}$ and $Bi^{209}(n, 4n)Bi^{206}$ are, respectively, 27.8 and 20.8 Mev (from the calculated mass data by Metropolis and Reitwiesner[2]). Many experiments were tried to search for the Rh^{100} and Bi^{206} activities; none were found. Some 20-hr activities were noted in the bombarded Rh-samples, but were attributed to the Pt impurities present in the Rh-samples. This indicates either that the tetraneutron does not exist, or that if it exists, its binding energy is below 3 Mev or the yield is extremely small. The upper limit of yield may be set as a few microbarns from the present experiment with bismuth.

Another method to detect the existence of a tetraneutron, which is applicable especially if its binding energy is less than 3 Mev, is to look for a monoenergetic recoil group from a reaction of the type,

$$Bi^{209}+H^1\rightarrow Po^{206}+n^4+Q_8 \quad (8)$$

where Q_8 is about -21.5 Mev if the binding energy of n^4 is taken near zero. Using a 32-Mev proton beam, such as the one from the linear accelerator of the University of California, the Po^{206} recoils from a very thin target may assume an energy in the neighborhood of 540 kev at a 30° angle from the proton beam. Because of the high momentum of the recoils, they may be separated from other particles by a magnetic field. The presence of monoenergetic Po^{206} group will be a direct proof of the existence of the tetraneutron.

If the tetraneutron or other polyneutrons are shown to be nonexisting, then the simultaneous presence of both proton(s) and neutron(s) must be a necessary condition in the formation of any nucleus with mass number greater than one.

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[1] G. Breit and J. S. McIntosh, Phys. Rev. **83**, 1245 (1951).
[2] N. Metropolis and G. Reitwiesner, *Table of Atomic Masses* (Argonne National Laboratories, Chicago, 1950).

Radiative $\pi-\mu$ Decay

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SINCE the discovery by Lattes, Occhialini, and Powell[1] of the decay of a π-meson into a μ-meson, it has been believed that the μ-meson produced by the decay had a definite kinetic energy 4.1 Mev, the decay energy 33 Mev being shared by the μ-meson and a neutral particle of small mass. However, recently a number of decays of positive π-mesons into μ-mesons having anomalously short range have been found by Fry[2] and others.[3] According to the observations by Fry, 8 tracks of μ-mesons with energy less than 3.5 Mev have been found among about 6000 ordinary $\pi-\mu$ decays. Of these, four events might possibly be interpreted as decays in flight. Furthermore, μ-mesons of ordinary range have a higher probability of getting out of the emulsion than the short-range particles. Considering these effects, the probability of the anomalous $\pi-\mu$ decay is estimated to be about 3×10^{-4} that of the ordinary decay.[2]

Because a charged μ-meson is accelerated to a high velocity by the decay, we can expect the decay process to be accompanied by a continuous γ-ray spectrum. This effect has been considered in the case of nuclear β-decay by Knipp and Uhlenbeck,[4] Bloch,[5] and Chang and Falkoff;[6] nuclear K-capture by Møller[7] and Morrison and Schiff;[8] meson production by Schiff;[9] and mesonic β-decay by Feer.[10] The problem of radiative $\pi-\mu$ decay has been considered nonrelativistically by Primakoff,[11] using the Bloch and Nordsieck method. The present calculation, which was initiated independently, is a relativistic second-order perturbation analysis. As will be seen, the two calculations give roughly the same probability for the anomalous decay.

We assume that the π-meson is described by a scalar or a pseudoscalar field Ψ, which satisfies the Klein-Gordon equation, and that the μ-meson and neutral particle are described by spinor fields ψ and φ, respectively, both of which satisfy Dirac equations. The Hamiltonian density of the interaction of these three fields is assumed to be proportional to

$$(\psi^*\eta\varphi)\Psi, \quad (1)$$

where η is given either by $\eta=\beta$ if Ψ is scalar, or by $\eta=\beta\alpha_1\alpha_2\alpha_3$ if Ψ is pseudoscalar, β and α's being conventional Dirac operators.

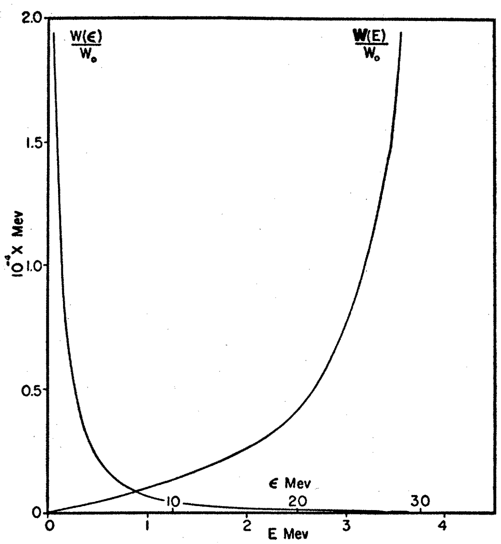

FIG. 1. The probability distributions of the μ-meson and the photon in the radiative $\pi-\mu$ decay (per normal decay). The curve rising to the right gives the probability per Mev interval of a μ-meson of kinetic energy E. The curve rising to the left gives the probability per Mev interval of a photon of energy ϵ.

The probabilities of radiationless and radiative $\pi-\mu$ decay are calculated relativistically by ordinary perturbation methods, assuming the π-meson to be at rest before the decay and neglecting the mass of the neutral particle. The probability per unit time for the decay of the π-meson into a μ-meson of kinetic energy between E and $E+dE$, a photon of energy between ϵ and $\epsilon+d\epsilon$, and a neutral particle with the remaining energy, is given by

$$W(E,\epsilon)dEd\epsilon=\frac{4}{\pi}\cdot\frac{e^2}{\hbar c}\cdot W_0\cdot\left(\frac{1+E_0}{2E_0+E_0^2}\right)^2 \cdot\frac{(E_0-E-\epsilon)(1+E)}{[2(1+E_0)(E+\epsilon)-E_0^2]^2}\cdot\left[(2+2E_0+E_0^2)-(2E_0+E_0^2) \cdot\frac{(2E+E^2)\cos^2\theta+\epsilon(2E+E^2)^{\frac{1}{2}}\cos\theta}{(E_0-E-\epsilon)(1+E)}-\frac{2(1+E_0)}{1+E}\right]dEd\epsilon, \quad (2)$$

for both scalar and pseudoscalar assumptions. In the expression (2), W_0 is the probability per unit time of the radiationless decay; $E_0=0.33$ is the decay energy, all energy quantities being measured in the unit of mass energy of the μ-meson (about 100 Mev); and θ is the angle between the emitted μ-meson and the photon, which is given by

$$\cos\theta=\frac{(E_0-E-\epsilon)^2-(2E+E^2)-\epsilon^2}{2\epsilon(2E+E^2)^{\frac{1}{2}}} \quad (3)$$

from the conservation of energy and momentum.

By integrating (2) over ϵ for a given value of E or over E for a given value of ϵ, we get the energy distribution of the μ-meson $\mathbf{W}(E)dE$ or the photon $W(\epsilon)d\epsilon$, respectively. The ranges of these integrations are given by $-1\leq\cos\theta\leq1$ with (3). The energy distributions thus obtained are shown in Fig. 1; they have an "infrared catastrophe" at 4.1 and 0 Mev, respectively. Although Primakoff[11] gives 17 Mev as the upper limit of the photon energy, our formula gives 28.9 Mev for this value. In the former case the decay energy is shared by the neutral particle and the photon, but in the latter it is shared by the μ-meson and the photon, the third particle being at rest in both cases. On integrating the distribution of the μ-meson graphically from 0 to 3.5 Mev, we get the value 1.3×10^{-4} for the probability of radiative decay relative to the radiationless decay. The corresponding value obtained by Primakoff[11] is 2×10^{-4}. These values are not inconsistent with the value found by Fry,[2] if one considers the small number of events which have actually been observed. The probability for getting