neutron 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 non-existing, 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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Radiative $\pi-\mu$ Decay

TETSUO EGUCHI*
Institute for Atomic Research and Department of Physics, Iowa State College, Ames, Iowa
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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.

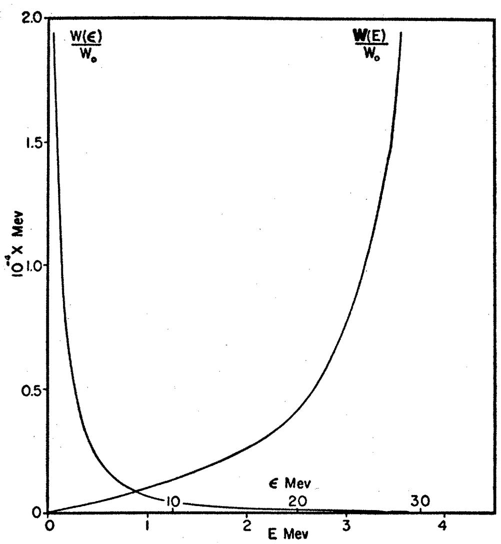

FIG. 1. The probability distributions of the μ-meson and the photon in the radiative $\pi-\mu$ decay (per normal decay). The curve rising to the right gives the probability per Mev interval of a μ-meson of kinetic energy E. The curve rising to the left gives the probability per Mev interval of a photon 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 a photon with energy more than 1 Mev is 3×10^{-4} per ordinary decay. The average photon energy per decay is 12 kev. It would be of interest to have an experimental determination of these quantities.

In the interaction (1) we have assumed that a π-meson interacts directly with a μ-meson. Of the alternative assumptions concerning the mechanism of the decay, that in which the mesons interact only through nucleons[12] might be of special interest and is under consideration.

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* On leave from Kyushu University, Fukuoka, Japan.

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Internal Conversion in the L-Shell*

H. Gellman, B. A. Griffith, and J. P. Stanley
Computation Centre McLennan Laboratory, University of Toronto, Toronto, Ontario, Canada
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In a previous paper,[1] the authors have given the results of calculations for the internal conversion of γ-radiation in the L_{I}-shell. The present communication contains a summary of these results together with the corresponding results for the L_{II}- and L_{III}-shells. The calculations reported here complete a program undertaken with the object of providing a table of internal conversion coefficients for the L-shell covering the range of γ-ray energies and atomic numbers employed by Reitz.[2]

All values given for the internal conversion coefficient are based on formulas derived from those obtained by Goertzel and Rose.[3] The method of derivation of those formulas has been reported earlier, together with a summary of the actual formulas for: the L_{I}-shell—electric dipole, electric quadrupole, and magnetic dipole; the L_{II}-shell—electric dipole; and the L_{III}-shell—electric dipole.

The additional modified formulas required for the present calculations are quite similar and we hope to publish them at a later date. It should be noted that these formulas take account of relativistic terms but not the effects of screening. It is expected that numerical values for internal conversion coefficients for the L-shell will be computed by a method which, like that of Reitz, allows for screening effects; at that time the present results should furnish a good estimate of the importance of screening effects for internal conversion in the L-shell.

Tables I, II, and III give values for the internal conversion coefficient in the electric dipole, the electric quadrupole, and the magnetic dipole cases, respectively. Values are shown for each of three atomic numbers and for three γ-ray energies. Except for the use of IBM machines in the calculation of the hypergeometric functions, all numerical work was done on Marchant and Friden desk calculating machines.

Table I. Internal conversion coefficients for electric dipole radiation (observed L_N-electrons/observed photons of energy k).

Atomic number Z	Gamma-ray energy k (mc^2 units)	L_{I} shell	L_{II} shell	L_{III} shell	L shell
92	0.09273	0.2372	0.2567	0.2856	0.7795
	0.2927	0.02097	0.009763	0.007779	0.03851
	0.6427	0.003916	0.001076	0.0006813	0.005673
84	0.0833	0.2910	0.2606	0.3544	0.9060
	0.2333	0.03011	0.01241	0.01185	0.05437
	0.5333	0.004569	0.001080	0.0008520	0.006501
49	0.0283	2.202	1.347	2.531	6.080
	0.2083	0.01520	0.001819	0.002605	0.01962
	0.4083	0.002440	0.0001763	0.0002468	0.002863

Table II. Internal conversion coefficients for electric quadrupole radiation (observed L_N-electrons/observed photons of energy k).

Atomic number Z	Gamma-ray energy k (mc^2 units)	L_{I} shell	L_{II} shell	L_{III} shell	L shell
92	0.09273	9.199	235.2	202.9	447.3
	0.2927	0.1548	1.239	0.7025	2.096
	0.6427	0.01694	0.04557	0.01660	0.07911
84	0.0833	5.300	195.4	195.9	396.6
	0.2333	0.1103	1.617	1.184	2.911
	0.5333	0.01546	0.04494	0.02219	0.08259
49	0.0283	5.787	1792.	3260.	5058.
	0.2083	0.1026	0.1059	0.1188	0.3273
	0.4083	0.01176	0.004734	0.005271	0.02176

Table III. Internal conversion coefficients for magnetic dipole radiation (observed L_N-electrons/observed photons of energy k).

Atomic number Z	Gamma-ray energy k (mc^2 units)	L_{I} shell	L_{II} shell	L_{III} shell	L shell
92	0.09273	43.98	4.244	0.06309	48.29
	0.2927	1.896	0.1758	0.002150	2.074
	0.6427	0.2079	0.02046	0.0003458	0.2287
84	0.0833	27.85	2.397	0.02979	30.28
	0.2333	1.381	0.1123	0.002503	1.496
	0.5333	0.1313	0.01071	0.0003588	0.1424
49	0.0283	19.22	1.299	0.05643	20.58
	0.2083	0.05396	0.001244	0.0004160	0.05562
	0.4083	0.007751	0.0001476	0.00007558	0.007974

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Fine Structure and Angular Correlation in Po^{210}*

S. De Benedetti and G. H. Minton
Carnegie Institute of Technology, Pittsburgh, Pennsylvania
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Polonium[210] is usually considered as a pure α-emitter, although the presence of a weak γ-radiation (energy 803 kev, intensity about 10^{-5} per α) is definitely established.[1,2] The low energy α-particles preceding these γ-rays have escaped observation despite repeated attempts to study the fine structure of Po.

By using a coincidence method we were able to detect the low energy α-group and to study its angular correlation relative to the γ-rays following it.

For the first part of our experiments a source of Po was immersed in a scintillating solution (terphenyl phenylcyclohexane) and the height of the scintillation pulses was studied with a differential pulse-height selector (Fig. 1, curve I). Then, a thick piece of stilbene was located near the α-source and used to detect the γ-rays in coincidence with the α-particles. A fast coincidence circuit[3] (3×10^{-9} sec resolving time) was used in order to minimize the random counting rate. The pulse-height distribution produced by α-particles in coincidence with γ-rays is shown in Fig. 1, curve II. The shift between the two curves of Fig. 1 is, within experimental error, in agreement with an energy difference of 0.8 Mev.