Letters to the Editor

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Production of μ-Mesons by Gamma-Rays

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IN a recent paper Wentzel[1] has proposed a theory in which the μ-meson field is strongly coupled to the nucleon field by a pair type interaction similar to that used to explain beta-decay. This interaction provides forces between a $\mu-\mu^0$ pair, and the resulting bound state is identified with the π-meson. However, besides coupling π-mesons and nucleons, the pair theory also predicts processes in which the μ-mesons appear in unbound states, one example of such a process being photo-production, for which Wentzel estimates a ratio of $\mu-\mu^0$ production cross section to π-production cross section of $0.1-0.01$ at photon energies of 350 Mev. This is about the energy available on the Berkeley synchrotron, and since experiments of Peterson[2] have already placed an upper limit on the number of μ-mesons produced from this machine, it seemed worthwhile to recalculate this ratio more precisely.

The calculations were carried out to the lowest order in the coupling constant using the Feynman-Dyson methods, and, since the theory is not covariant, all matrix elements were evaluated in the rest system of the π-meson and then assumed to transform covariantly on returning to the center-of-mass system. Furthermore, in this problem, the usual plane wave solutions for a pair of μ-mesons in the field are no longer correct, because of the presence of binding forces, so two approximate sets of wave functions were adopted. The first consisted of all plane waves plus the single bound level; the second was the same except that each plane wave was corrected by addition of some of the bound solution, the amount being so chosen that the corrected waves were orthogonal to the bound state. Finally, because of the noncovariance, it was necessary to neglect binding effects in the intermediate states and to treat all intermediate particles as being free.

With these approximations the cross section for the production of a π^+ meson by a γ-ray incident on a proton is

$$\sigma_\pi=\frac{e^2}{2\hbar c}\frac{|U|^2}{Mc^2(Mc^2+\hbar\omega)}\left(\frac{p_\pi}{mc}\right)\left(\frac{mc}{\hbar}\right),$$

where $|U|^2$ is the parameter used by Wentzel, p_π is the momentum of the outgoing meson in the center-of-mass system, and m and M are the masses of the π-meson and nucleon, respectively. For the pair cross section, using the first set of wave functions mentioned above, the following expression was obtained:

$$\sigma_{\mu\mu^0}=\frac{\pi^2e^2}{\hbar c}\left[\frac{2Mc^2+\hbar\omega}{Mc^2+2\hbar\omega}\right]\left(\frac{\Delta}{Mc^2}\right)^2\frac{\eta^2(\mu c)^3}{\hbar\omega\hbar c(2\pi\hbar)^3},$$

where μ is the mass of the pair meson, η the coupling constant, and Δ the total kinetic energy in the center-of-mass system of the three outgoing particles. A similar calculation using the second set of wave functions yields a formula with the same form, but the numerical coefficient of which is approximately half as great. It should be noted that these expressions were derived under the assumption that outgoing particles were nonrelativistic, and they are, therefore, incorrect for energies far from threshold.

From the cross sections the relative yield of $\mu-\mu^0$ pairs to π's is calculated by integrating over a bremsstrahlen (dE/E) spectrum. For a maximum photon energy of 322 Mev and using the value $|U|^2/\eta^2=2.4\pi(\mu c)^3/(2\pi\hbar)^3$ (the numerical factor arises from evaluating the integral called "c" by Wentzel), the relative yield turns out to be 0.11 or 0.06 depending upon which set of wave functions was used. These figures are to be compared with the upper limit 0.04($\pm$0.04) given by Peterson from experiments on the synchrotron. Finally, it is interesting to note that the ratio calculated above is virtually independent of nucleon cutoff, depending only on $|U|^2/\eta^2$, which is insensitive to the upper limit placed on the nucleon momenta.

In conclusion, I would like to express my thanks to Professor Robert Serber who has given me much helpful advice and encouragement on this problem.

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[2] J. Peterson (to be published).

Disintegrations of Nd^{147} and Pm^{149}

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SLOW neutron bombardment of neodymium yields, among other short half-lives, two activities known to have half-lives of 11 days and of 2 hr. The 11-day period has been assigned to Nd^{147} and the 2-hr activity to Nd^{149} which decays by negatron emission to Pm^{149}.[1] Pm^{149} further decays with a half-life of about 2 days.[1]

"Specpure" Nd_2O_3 was irradiated by slow neutrons in the Harwell pile for 4 weeks, and the resulting activities were studied at this Institute using a β-ray spectrometer.[2] Finely powdered Nd_2O_3 was spread with an average thickness of about 2 mg/cm² over an aluminum backing of 2 mg/cm². The half-life graph showed two components, one having a value 48±3 hr and another 11.6±0.3 days.

The β-spectrum was taken at several periods of decay. Two electron lines, one at 730 gauss-cm and another at 1007.4 gauss-cm, corresponding to the electron energies 44.9 and 82.6 kev, were found. From their energies and intensities they were identified as the K and L lines of a 90-kev γ-ray. These lines were found to decay with the 11-day period. The 11-day period β-spectrum yielded two components on Fermi analysis. The energies of these two components were found to be 350±8 kev and 780±8 kev.

After taking into account the 11-day β-spectrum, Fermi analysis of the 2-day β-spectrum showed that it consists of a single component having maximum energy 1.05±0.01 Mev.

The γ-spectrum, taken in the same spectrograph using a thick copper capsule and a lead-foil about 20 mg/cm² thick, showed 5 photo-electron peaks of different intensities. The first one at 963.6 gauss-cm, corresponding to 76-kev energy, was identified as the L photo-line of a 91.8-kev γ-ray. A small peak at 1752 gauss-cm, corresponding to 221 kev, was taken to be the K line of a 309-kev γ-ray. Another small peak at 2117 gauss-cm, corresponding to 304 kev, was taken to be the K line of a 391-kev γ-ray. The last two lines at 2657 and 2920 gauss-cm, corresponding to 435 kev and 502 kev, respectively, were found to be the K and L photo-lines of a 520-kev γ-ray. All these photo-lines seem to decay with the 11-day period. The first photo-spectrum was taken after about a 3-day decay of the sample, and no γ-ray having the half-life of 2 days was observed. The energies of the γ-rays from the γ-spectrum were found to be 91±1, 309±5, 391±5, and 520±3 kev.

The intensities of the two β-components of the 11-day period were estimated to be about 32 and 65 percent, the harder component being the more intense. Using these estimates and the photo-spectrum, the intensities of the γ-rays were estimated as: 91 kev, 66 percent; 309 kev, 1 percent; 391 kev, 2 percent; 520 kev, 32 percent. The K to L ratio for the 91-kev γ-ray was found to be 6.5±1.5 from the β-spectrum. The conversion coefficient for the 91-kev γ-ray is approximately 0.9. Comparison with Hebb and Nelson's formulas[3] and Rose's tables,[4] makes it appear that the 91-kev γ-ray is probably a mixture of magnetic dipole and electric quadrupole radiations.

Using Feenberg's curves[5] the comparative half-lives for the β-components were found to be 350 kev (11-day) log $(ft)=6.6$, 780 kev (11-day) $\log(ft)=7.4$, 1.05 Mev (2-day) $\log(ft)=6.96$. Applying the considerations of Nordheim[6] all these three can be placed in the first forbidden group with a change in parity and a change in spin of 0 or 1.

A probable disintegration scheme for Nd^{147} is suggested in Fig. 1.

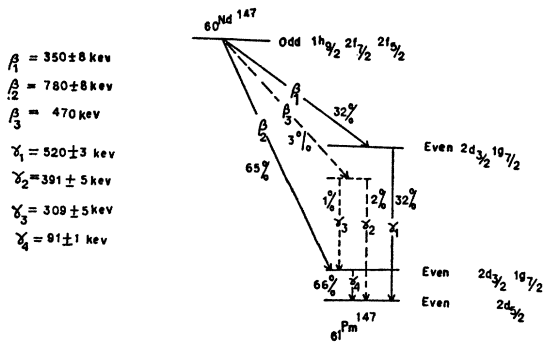

FIG. 1. Probable disintegration scheme for Nd^{147}.

The energies of the γ-rays add up well within the experimental errors mentioned. The β_3-component, having maximum energy of about 470 kev, was not obtained from the Fermi analysis of the 11-day β-spectrum. This is probably due to its low intensity ($\sim$3 percent). However, the possibility that the 391- and 309-kev γ-rays may arise from some impurity of a nearby half-life cannot be entirely ruled out, so these two γ-rays and the corresponding β-ray are shown by broken lines.

Pm^{149} appears to decay by a single β-ray of maximum energy 1.05 Mev. No γ-rays having this period (2 days) were observed.

The term scheme given in Fig. 1 was arrived at from the spin-orbit coupling model of the nucleus.[7,8] A detailed paper describing the experimental details will be published in the *Arkiv för Fysik*.

I wish to convey my sincere thanks to Professor Manne Siegbahn, the director of this institute. My thanks are also due Dr. Kai Siegbahn for kindly supervising this work.

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K^{40} and the Age of the Atmosphere

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NOW that the decay scheme of K^{40} seems to be rather well established,[1] it is of interest to attempt a calculation of the age of the atmosphere from the amount of this isotope in the earth and the A^{40} content of the atmosphere. Calculations of a similar nature have been made by Poole[2] and Suess[3] using incorrect data.[4] The main difficulties lie in the estimation of (a) the relevant figures for the K^{40} abundance, and (b) the time elapsed since the crust became so well solidified that further additions to the atmosphere have been inappreciable.

With regard to (a) we can take the abundance of ordinary K in the upper crust layers as[5] 2.60 percent, the K^{40} isotopic abundance as[6] 0.0119 percent, the density of the crust as[5] 2.8, and the depth of the K-bearing crust as 4×10^6 cm. This latter figure is admittedly something of a guess.[5] With respect to (b) let us suppose the argon to have been generated from a time t_0 until a time $t=2\times10^9$ yr ago when the crust first began to solidify. Undoubtedly, some argon would have escaped since then, so that we shall derive an upper limit for t_0. Alternatively, if we allow an interval from t_0 to only $t=1\times19^9$ yr ago, we shall obtain a value for t_0 which is perhaps nearer to a lower limit. We then easily derive the relation

$$\frac{\lambda_e}{\lambda_e+\lambda_\beta}(e^{\lambda t_0}-e^{\lambda t})\left(\frac{2.60}{100}\right)(4\times10^6)\left(\frac{0.0119}{100}\right)2.8=76\times13.5\times\frac{1.44}{100}$$

by equating the mass of K^{40} per cm² of the earth's surface which has decayed to the actual amount of argon observed.

Using

$$\lambda_e/(\lambda_e+\lambda_\beta)=0.13/1.13,\quad \lambda=5.45\times10^{-10}/\text{yr},$$

we get for the limits of t_0, 3.5×10^9 and 3.1×10^9 yr.

While considerable uncertainty must be attached to these figures, it is perhaps of interest that they agree so well with the age of the earth as calculated by the lead method by Holmes and others.[7]

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Radioactive Strontium Produced by Deuteron Bombardment of Rubidium

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THE bombardment of rubidium by protons has been reported[1,2] to produce a strong activity in the chemically separated strontium fraction. These studies[1] disclosed the presence of three activities which were assigned to Sr^{85m} (70-min half-life, gamma-ray and internal conversion electron emission), Sr^{87m} (2.75-hr half-life, gamma-ray and internal conversion electron emission), and Sr^{85} (66-day half-life, K-capture decay and gamma-ray emission). The radiations from these isotopes have been reinvestigated using a 14-cm radius of curvature, uniform field, semicircular magnetic spectrometer.[3]

Radioactive samples were prepared through the bombardment of rubidium chloride with 10-Mev deuterons in the Washington University cyclotron. After bombardment the RbCl was dissolved in water, a small amount of strontium carrier was added in the form of $SrCl_2$, and the strontium precipitated by the addition of Na_2CO_3. This precipitate was washed several times.

A small fraction of one of the separated samples was mounted in a plastic holder, and its decay followed for a period of 140 days. The results indicate a half-life of 65 ± 3 days, in good agreement with the value reported by DuBridge and Marshall.[1]

The secondary electrons ejected from a 50-mg/cm² uranium radiator shows K and L shell photo-electron peaks for the 65-day activity, corresponding to a gamma-ray of energy 513 ± 3 kev. This was at first thought to be annihilation radiation. However, an uncovered electron source revealed a relatively strong internal conversion peak whose energy also corresponds to a transition energy of 513 kev. This indicated that at least part of the radiation was really gamma-radiation and not annihilation radiation. The experimental data are shown in Fig. 1.