nucleons, whereas the sea-level mesons are the decay products of the high altitude mesons, (3) a weak coupling of sea-level mesons to nucleons follows from (2). It was not possible to make unique assignments for the spins and masses of the two types of mesons.

The striking experimental discoveries of Powell and his collaborators[5] and the Berkeley group[6] have provided complete confirmation of points (1) and (2). Thus, it is now established that the π-mesons are produced directly in the Berkeley cyclotron and in cosmic-ray stars while the μ-mesons arise indirectly from the decay of the π-mesons. It is furthermore established that π^--mesons are captured by light as well as heavy nuclei in contrast to the μ^--mesons which are only captured by heavy nuclei. These results are contrary to the cloud-chamber evidence[1] for the direct production of μ-mesons and it is likely that visual methods for estimating ionization are not sufficiently accurate to distinguish between π- and μ-mesons.

Definite support for point (3) is provided by the measured value of the half-life for the π–μ-decay, i.e. $0.9^{+0.25}_{-0.15}\cdot 10^{-8}$ sec.,[7] and the fact that nuclear capture of π^- converts an appreciable fraction of its rest energy into star energy,[5] whereas nuclear capture of μ^- converts a negligible fraction of its rest mass into star energy.[8] Both of these facts can be understood on the basis of (3) and assuming that the π-meson is a boson; thus, the scheme for the nuclear capture of μ^- becomes: $\mu^-+P\rightarrow\pi^-+Q+P\rightarrow N+Q$ where P and N are the proton and neutron in the nucleus and Q is the second particle into which the π-meson decays, i.e. $\pi\rightarrow\mu+Q$. The predicted half-life[2,9] for the π–μ-decay agrees well with the measured value considering the uncertainty of the nuclear matrix element. Our original calculation[4] for the half-life treated the π-meson as a fermion for the purposes of illustration; the value of 10^{-8} sec. obtained demonstrates the insensitivity of the half-life to the spin character of the π-meson.

An alternative interpretation of the half-life for π–μ-decay and of the qualitative features of the nuclear capture of negative π- and μ-mesons has been suggested:[3,9] One postulates a direct (weak) coupling between the μ-meson and nucleon and a direct (strong) coupling between the π-meson and nucleon and one *deduces* the π–μ-decay. This is a possible approach but against it two objections may be raised: (1) the calculation of the indirect decay of the π-meson through the virtual creation of nucleons leads to divergence difficulties and (2) the rough quantitative agreement found between the coupling constant for the μ-meson and the nucleon and the β-constant may not be significant in view of the uncertain status of β-decay theory.[10]

Additional experiments have fixed some of the other unknowns in the two-meson theory. The determination[7] of the ratio of masses of the π- and μ-mesons as 1.321 ± 0.006 and the absence of γ-rays[11] associated with the nuclear capture of μ^- prove that the particle Q is a neutrino. Consequently, the μ-meson is a fermion and must possess[12] spin $\frac{1}{2}$. This value of the spin is consistent with the apparently continuous electron spectrum from the μ-decay. The spin of the π-meson is still uncertain.

Major difficulties remain: the possibility of correlating nuclear β-decay with an electron decay of the π-meson appears to be excluded,[6] and it is not at all clear that a correct field theory of nuclear forces can be constructed with only one strongly coupled meson.[4]

[1] G. D. Rochester and C. C. Butler, Proc. Phys. Soc. **61**, 307 (1948).
[2] S. Hayakawa, Prog. Theor. Phys. **3**, 200 (1948).
[3] J. Tiomno and J. A. Wheeler, Rev. Mod. Phys. **20** (January, 1949, to be published).
[4] R. E. Marshak and H. A. Bethe, Phys. Rev. **72**, 506 (1947). S. Sakata and T. Inoue (Prog. Theor. Phys. **1**, 143 (1946)) and T. Tanikawa (Prog. Theor. Phys. **2**, 220 (1947)) independently introduced a two-meson hypothesis in order to remove the difficulties associated with the electron decay of the meson and its small nuclear scattering; they arrived at a half-life for the decay of the heavy into the light meson many orders of magnitude too small.
[5] G. P. S. Occhialini and C. F. Powell, Nature **162**, 168 (1948) and Camerini, Muirhead, Powell, and Ritson, Nature **162**, 433 (1948).
[6] E. Gardner and C. M. G. Lattes, Science **107**, 270 (1948) and C. M. G. Lattes, Science **108**, 588 (1948).
[7] R. Serber, private communication.
[8] See also Sard, Ittner, Conforto, and Crouch, Phys. Rev. **74**, 97 (1948).
[9] A. S. Lodge, Nature **161**, 809 (1948), L. I. Schiff, Phys. Rev. **74**, 1556 (1948), R. F. Christy, private communication.
[10] R. E. Marshak, Phys. Rev. **75**, 513 (1949).
[11] O. Piccioni, Phys. Rev. **74**, 1236 (1948).
[12] R. F. Christy and S. Kusaka, Phys. Rev. **59**, 414 (1941).

Erratum: Thermonuclear Reactions in the Expanding Universe

[Phys. Rev. **74**, 1198 (1948)]

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IT is regretted that Eq. (3) was incorrectly given; it should read:

$$d[\ln x_2]/dt=-pm_2/x_2. \tag{3}$$

Measurement of the Half-Life and Average Energy of Tritium Decay*

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RECENTLY, Novick[1] and Goldblatt *et al.*[2] have found the half-life period of tritium to be considerably less than the 30-year period previously accepted. We have made a determination of the half-life of tritium and obtained a value of 12.46 ± 0.2 years, in agreement with the 12.1 ± 0.5 years reported by Novick. In addition, we have measured the average energy of the tritium decay and found it to be 5.69 ± 0.06 kev.

To determine the half-life of tritium, a sample containing a measured amount of the isotope was prepared and the rate of He^3 evolution, and thus the disintegration rate, of the sample measured. The average energy of the decay was determined by calorimetric study of the quantitative sample.

In preparing the sample, several ml of a mixture of tritium and normal hydrogen were purified by passage through palladium, and the density of the mixture was then compared with that of helium by means of a gas density balance. The volume of the gas sample was then measured and the sample transferred to a Pyrex ampoule containing palladium in which the gas was absorbed. Calorimetric studies of the sample were then carried out.

In the determination of the disintegration rate, advantage was taken of the fairly rapid rate of diffusion of helium through silica glass at room temperature. Following the calorimetric measurement, the sample was converted to water by passage over hot copper oxide and collected and sealed in a small quartz ampoule. A calorimetric measurement of the heat evolved by the sample in this form showed that no significant amount of tritium was lost in the transfer. The sample was then placed in a soft glass container which was held at constant temperature and the He^3, collecting in the container during a two-week period, was measured with a McLeod gauge. These measurements were repeated at two-week intervals until the rate of collection of He^3, after correcting for decay, was constant. The rate was then assumed to be equal to the rate of He^3 formation within the ampoule. The time necessary for the steady-state pressure of He^3 to be built up within the ampoule was appreciably shortened by placing the ampoule in liquid nitrogen for several days prior to starting the measurements.

The gas density balance used in analyzing the sample was constructed of silica glass and the gas controlling system of Pyrex. All valves were of the mercury shut-off type so that no stopcock grease was in contact with the tritium. The absolute density of the tritium-hydrogen mixture was obtained by direct weighing of the reference helium.

The calorimeter was of an isothermal type operating at the temperature of liquid nitrogen and using the rate of evaporation of nitrogen at constant pressure as a measure of the heat input. Calibration of the calorimeter was made with a resistance heater.

Results of the various measurements, adjusted to a reference time, are shown below:

Fraction of tritium in H_2-T_2 mixture	0.497
Total quantity of tritium in sample	2.57_1 ml S.T.P.
Power generated by sample	$2.21_8\times10^{-4}$ watt
Disintegration rate of sample	$2.43_5\times10^{11}$ dis./sec.
Average energy of tritium decay	5.69 kev
Half-life period of tritium	12.46 years

A calorimetric measurement and a disintegration rate measurement were made on a second, smaller sample, and the average energy found in this case agreed within 0.5 percent with the value computed from the above data.

Curran, Angus, and Cockcroft[3] have recently determined the beta-spectrum of tritium from below 1 kev to its maximum, using a proportional counter. From the data presented in their paper, we have estimated the average energy of the distribution to be about 5.5 kev, which is in reasonable agreement with our figure.

An interesting phenomenon observed in the calorimetric study of tritium oxide seems worth mentioning here. The rate of heat evolution by the tritium absorbed in palladium was constant during the course of a measurement extending over a period of 8–10 hours. However, the sample of tritium in the form of the oxide showed an increase of several percent in the rate of heat evolution during the first few hours at −196°C. After the initial increase, the rate of heat evolution became constant and was then in agreement with the value obtained from the same amount of tritium absorbed in palladium. We believe this to indicate that a fraction of the decay energy is stored in the ice at −196°C. in some manner and that the amount stored reaches a steady-state value.

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[1] Aaron Novick, Phys. Rev. **72**, 972 (1947).
[2] M. Goldblatt, E. S. Robinson, and R. W. Spence, Phys. Rev. **72**, 973 (1947).
[3] S. C. Curran, J. Angus, and A. L. Cockcroft, Nature **162**, 302 (1948)