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[17] *Note added in proof.*—The results of these calculations were discussed with F. Begemann and W. F. Libby during the summer of 1956; they now find that their recent data on the tritium balance in the Mississippi Valley, taking into account outward vapor transport of tritium as discussed above, indicate a production rate over that area equal to the value calculated above for North America. Recently J. Arnold has also concluded from consideration of the present calculations that tritium is probably being accreted from the sun.

Catalysis of Nuclear Reactions by μ Mesons*

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(Received December 17, 1956)

In the course of a recent experiment involving the stopping of negative K mesons in a 10-inch liquid hydrogen bubble chamber,[1] an interesting new reaction was observed to take place. The chamber is traversed by many more negative μ mesons than K mesons, so that in the last 75 000 photographs, approximately 2500 μ^- decays at rest have been observed. In the same pictures, several hundred π^- mesons have been observed to disappear at rest, presumably by one of the "Panofsky reactions."[2] For tracks longer than 10 cm, it is possible to distinguish a stopping μ meson from a stopping π meson by comparing its curved path (in a field of 11 000 gauss) with that of a calculated template. In addition to the normal π^- and μ^- stoppings, we have observed 15 cases in which what appears (from curvature measurement) to be a μ^- meson coming to rest in the hydrogen, and then giving rise to a secondary negative particle of 1.7-cm range, which in turn decays by emitting an electron. (A 4.1-Mev μ meson from $\pi-\mu$ decay has a range of 1.0 cm.) The energy spectrum of the electrons from these 15 secondary particles looks remarkably like that of the μ meson: there are four electrons in the energy range 50 to 55 Mev, and none higher; the other electrons have energies varying from 50 Mev to 13 Mev. The most convincing proof of the fact that the primary particle actually comes to rest, and does not—for example—have a large resonant cross section for scattering at a residual range of 1.7 cm, is the following: in five of the fifteen special events, there is a large gap between the last bubble of the primary track and the first bubble of the secondary track. This gap is a real effect, and not merely a statistical fluctuation in the spacing of the bubbles, since in some cases the tracks form a letter X (see Fig. 1), and in another case the secondary track is parallel to the primary, but displaced transversely by about 1 mm at the end of the primary. These real gaps appear also (although perhaps less frequently) between some otherwise normal-looking μ^- endings and the subsequent decay electron; they are thought to be the distance traveled by the small neutral mesonic atom.[3]

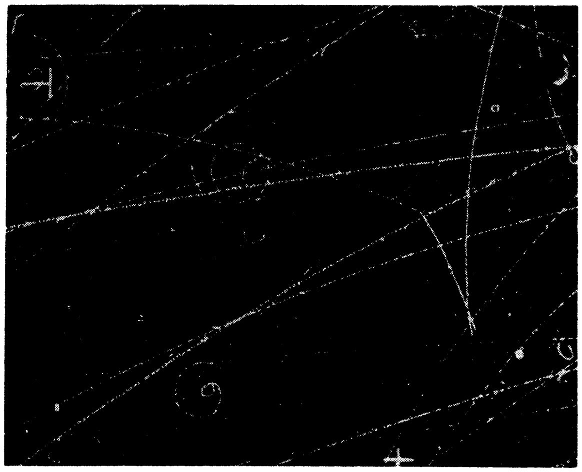

FIG. 1. Example of H-D reaction catalyzed by μ^- meson. The incident meson comes to rest, drifts as a neutral mesonic atom, is ejected with 5.4 Mev by the H-D reaction, comes to rest again after 1.7 cm, and decays.

One may quickly dispose of the most obvious suggestion that the events are $\pi^- - \mu^- - e^-$ decays. If, by some unknown process, negative π mesons could decay at rest in hydrogen, their secondary μ's would have a range of 1.0 cm, rather than the observed unique range of 1.7 cm. But, most importantly, the curvature of the stopping particles definitely precludes any possibility that they are π's. Therefore, if one is to explain the new observations in terms of known particles, he must say that the primary is a μ meson (as determined by curvature and range), and the secondary is also a μ meson (as determined by its decay-electron spectrum). The problem presented is then to find the source of the energy that "rejuvenates" the μ meson after it has come to rest. The energy that must be supplied to the μ meson is 5.4 Mev, as determined from the range-energy relationship in hydrogen. (We explored the possibility that one of the particles was an ordinary μ meson, while the other was either heavier or lighter by about 6 Mev. In this case, the heavier could not decay into the lighter in free space, as a π decays into a μ, because this process requires more of a mass difference between the two particles than was allowed by the measurements. One could just stay within the experimental limits by assuming that the decay took place in the field of a proton, and that the lighter particle then decayed in the usual μ-meson manner.)

The following explanation seems satisfactory.[4] If the $\mu-p$ mesonic atom referred to above finds a deuteron, and the deuteron becomes bound in the mesonic equivalent of an H-D molecular ion, then the mean H-D spacing is about 1/200 as large as that in the ordinary H-D molecular ion. The meson, in effect, confines the two nuclei in a small box. Rough estimates of the barrier penetration factor (approximately 10^{-5}) and the vibration frequency (approximately 10^{17} per second) indicate that the time required for a nuclear reaction between H and D should be small compared with the life of the μ meson. In some yet unknown fraction of the cases, the reaction energy is taken up by the μ meson, which appears in the bubble chamber with a kinetic energy of 5.4 Mev, i.e., nearly the mass difference between $H+D$ and He^3. (The recoil He^3 should not be visible in any case.)

If, as we believe, the explanation outlined above is correct, several apparent discrepancies must be resolved. For example, early suggestions that deuterium might have something to do with the observations were discarded because the ratio of 1.7-cm μ's to decay electrons is about 1/200 whereas the deuteron contamination in the bubble chamber is only about 1/5000. It seems possible to overcome this difficulty if a deuteron is able to rob the meson from a proton. The μ mesons will be bound more tightly by deuterons than by protons, because of the 5% larger reduced mass. This amounts to 135 ev for the ground state. This effect, and several others of a similar nature, are being investigated experimentally by increasing the concentration of deuterium in the bubble chamber.

It may also be that the surprisingly long gaps at the end of some of the stopping μ's can be understood by invoking the 135 ev available for recoil when the deuteron robs the μ^- from a $\mu-H$ mesonic atom during a collision.

It is interesting to speculate on the practical importance of this process if a sufficiently heavy, negatively charged, weakly interacting particle more long-lived than the μ is ever found. The particle observed by Alikanian *et al.*[5] in the cosmic rays has a mass of about 500 m_e, and was observed to come to rest in a cloud chamber without interacting or ejecting a decay fragment. A bubble chamber filled with liquid deuterium should be an excellent detector for such particles. One might expect to see large "stars" at the end of the heavy meson track, due to a sequence of catalyzed reactions that would continue until the meson disappeared by decay.

We wish to express our thanks to the bubble chamber crews, under the direction of R. Watt and G. Eckman, and to our scanners. We are also indebted to the three new members of our group, M. Cresti, L. Goldzahl, and K. Gottstein; and to E. Teller for an interesting discussion.

Note added in proof.—We have obtained preliminary results on the effect of increasing the deuterium concentration. The following numbers come from spot-checking and fast scanning only:

Deuterium Concentration:	Natural	0.3%	4.3%
$\mu^- \rightarrow e^-$	2541	2959	1269
$H+D \rightarrow He^3+\mu^-$	15	57	32
$He^3+\mu^-$ per μ^- ending	0.6%	2%	2.5%

Preliminary analysis indicates that the frequency of visible gaps in $\mu-e$ decays at first increases with increasing deuterium concentration; however, at the 4.3% concentration, gaps are no longer seen. We have seen one case where the same μ^- catalyzes the $He^3+\mu^-$ reaction twice. We have seen a few events which we interpret as the reaction $D+D \rightarrow H^3+H^1$.

* This work was done under the auspices of the U. S. Atomic Energy Commission.

† Astronomy Department, University of California, Berkeley, California.

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[2] Panofsky, Aamodt, and Hadley, Phys. Rev. **81**, 565 (1951).

[3] We have telephoned to inquire if other groups observe these gaps. R. H. Hildebrand has noticed occasional 1-mm gaps of $\mu-e$ decays in the Chicago hydrogen bubble chamber. Leon Lederman reports that no surprising gaps have been noticed by the Columbia diffusion chamber group [C. P. Sargent, thesis, Columbia University, 1951 (unpublished)].

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Nuclear Electric Quadrupole Moment of K^{39}

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(Received December 11, 1956)

THE authors of a recent communication[1] appear to have overlooked a previous determination made in this laboratory two years ago.[2] The experiments there briefly described have now been completed: a full account will shortly be published.[3] The Columbia result $Q_{K^{39}}=(0.07\pm0.02)\times10^{-24}$ cm^2 is not in disagreement with our final value, $+(0.11_3+0.02)\times10^{-24}$ cm^2, which is based on a complete analysis of the hyperfine structure of 5 $^2P_{\frac{3}{2}}$ in weak and strong magnetic fields. No assumptions are made concerning the ratio of the a factors in the $P_{\frac{1}{2}}$ and $P_{\frac{3}{2}}$ levels: these are determined independently of each other. The sign of Q is determined unambiguously in our experiments. Our final value differs from the preliminary value by an amount within the limits of error of the latter.

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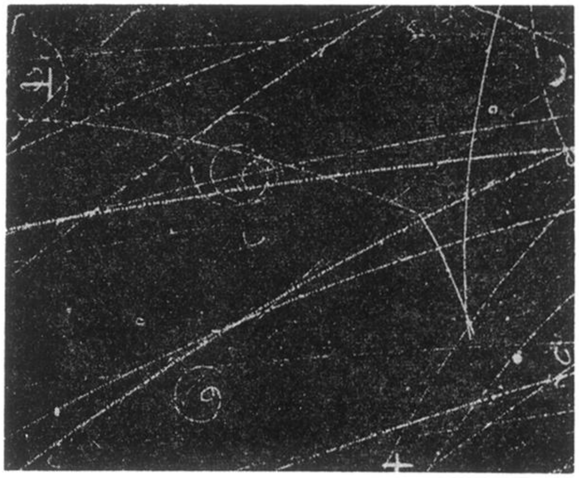

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