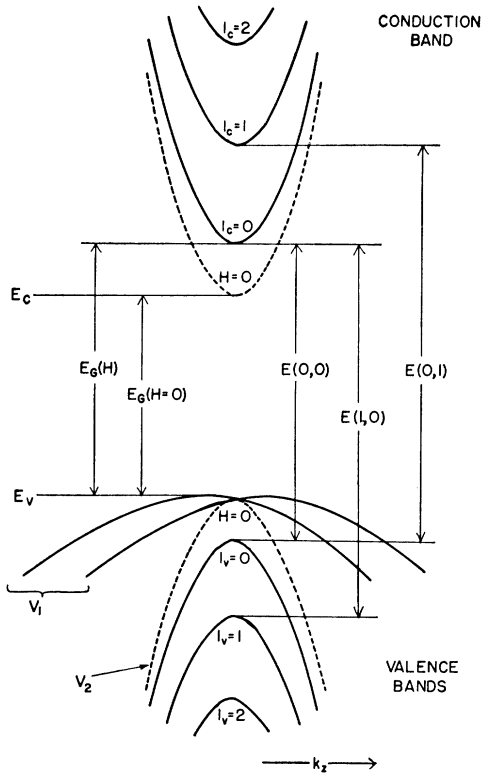

FIG. 3. Schematic energy-momentum diagram of the conduction and valence bands of InSb in the presence of a magnetic field showing the magnetic sub-bands ($l_v=0, 1, 2$) of the V_2 (light hole) valence band and those ($l_c=0, 1, 2$) of the conduction band. The nonparabolic character of the bands and the quantum effects in the valence band have not been taken into account, and it is assumed that the V_1 (heavy hole) valence bands are not appreciably affected by the magnetic field. The V_3 valence band which is split away from the V_1 and V_2 valence bands by spin-orbit interaction is also not shown.

the value of $0.015m$ obtained from infrared cyclotron resonance experiments[5] at comparable magnetic fields.

The effect of magnetic field on optical interband transitions, the interband magneto-optic (IMO) effect, is related to cyclotron resonance in the same way that the Zeeman effect is related to paramagnetic resonance. Both the IMO effect and cyclotron resonance involve the coalescence of energy band levels in a magnetic field. However, the IMO effect involves optical transitions between magnetic sub-bands belonging to different energy bands, whereas cyclotron resonance involves optical transitions between magnetic sub-bands belonging to the same energy band. For intrinsic absorption, the IMO effect does not depend on the presence of free carriers and can therefore be studied under conditions where the free carrier concentration is either too small or too large for cyclotron resonance experiments. Furthermore, the IMO effect should be particularly useful for obtaining information about energy surfaces away from the band edge, as well as about the effective masses of energy bands whose edges occur away from the forbidden energy gap.

We wish to express our appreciation to F. Blatt, E. O. Kane, and R. F. Wallis for valuable discussions. We are also indebted to S. Slawson for preparing the polished thin sections used in the experiments, to A. Mister and R. Anonson for operating the NRL Bitter Magnet, to S. Adler and W. M. Cole for assistance in designing and setting up the optical equipment, and to B. W. Henvis for a number of the calculations.

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Distribution, Production Rate, and Possible Solar Origin of Natural Tritium*

HARMON CRAIG

Scripps Institution of Oceanography, University of California, La Jolla, California

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LIBBY and co-workers have estimated the production rate of natural tritium as $\bar{Q}=0.14$ T atom/cm^2 of earth surface (cm$_e^2$)-sec, based on their measurements of the tritium content of natural waters.[1,2] $\bar{Q}$ was calculated separately from material balance considerations over (1) the oceans, and (2) the continents, equating the cosmic-ray production rate with the net loss from the oceanic and continental atmospheres by precipitation; the values obtained were, respectively, 0.12 and 0.16, in good agreement.[2] A $\bar{Q}$ value of 0.14, coupled with an average surface ocean concentration (pre-thermonuclear tests) of 0.24 atom T per 10^{18} atoms H (0.24 tritium unit or T.U.), was calculated as indicating uniform mixing of the sea to a depth of about 100 meters, assuming no T to be stored below this depth.[2]

Tritium production by high-energy protons on nitrogen and oxygen has been measured; the cross sections are about 30 mb with excellent agreement between two sets of data.[3,4] From these measurements and considerations of the cosmic-ray primary flux and neutron contribution, $\bar{Q}$ is calculated, independently of observed concentrations, to be approximately[3] 0.2 T atom/cm$_e^2$ sec, and, more precisely,[4] $0.14_{-0.03}{}^{+0.10}$, in agreement with the rate indicated by the natural concentrations.

However, the tritium production rate must be a good deal higher than the figures quoted above. The average residence time of water below the oceanic thermocline is very probably less than 500 years, and certainly less than 1000 years, as determined by oceanographic measurements,[5,6] data on the heat flux through the ocean floor,[7] and measurements of, and calculations based on, the distribution of radiocarbon in the atmos-

phere and sea.[8–10] These times correspond to residence times in the mixed layer of the sea of 10–20 years, comparable to the 18-year mean life of tritium. Equations relating the atmospheric production rate of a radioactive isotope to its concentration in the atmosphere, in the sea above and below the thermocline, and to the various mixing rates involved, were derived and applied to the distribution of radiocarbon,[9] and of tritium.[10] The tritium calculations show that for reasonable limits on the average deep-sea residence time of water of 100–500 years, the tritium flux into the sea ($\bar{Q}$ units) must be from 5.4 to 1.7 times the tritium concentration in surface sea water (T units). Taking the surface concentration as 0.24 T units,[2] the tritium flux into the sea should be between 1.3 and 0.4 T atom/cm_e^2 sec.

Accordingly, the T production rate over the North American continent was recalculated, using Libby's data[2] but taking into account removal of T from the continent by the outgoing water vapor flux,[11] as well as by runoff. The average net T production in the North American atmosphere is found to be about 1.2 ± 0.5 atom/cm_e^2 sec, the main uncertainty being the storage time of continental water.

To calculate $\bar{Q}$, the effects of geomagnetic latitude, and of holdup in the stratosphere consistent with the 10-year stratospheric residence time of Sr^{90} from weapons tests, reported by Libby,[12] must be considered. About half of the cosmic-ray production probably takes place above the tropopause, and horizontal mixing in the stratosphere appears to be rapid enough to overcome geomagnetic effects in that region.[12] $\bar{Q}$ was calculated by two different assumptions:

(1) All T is made by cosmic rays (assuming an undetected mechanism), half above, and half below, the tropopause, with a 10-year holding time in the stratosphere and geomagnetic correction to be applied only to the tropospheric production. Then $\bar{Q}$ (total world average) is 1.0, and the net flux of T into the sea is 0.8, both in atoms/cm_e^2 sec.

(2) Only 0.2 T atom/cm_e^2 sec are produced by cosmic rays, as indicated by experimental data, the remainder being accreted from an extraterrestrial source into the stratosphere. With correction factors similar to those used in (1), then $\bar{Q}$ (from accretion plus cosmic rays) is 1.7, with a net flux into the sea of about 1.0 atom/cm_e^2 sec.

From these figures the average residence time of water below the oceanic mixed layer is calculated to be about 150–200 years, in good agreement with the few reliable C^{14} data,[8,9] measurements of the secular decrease of dissolved oxygen in deep Atlantic water,[6] and the oceanographic estimates.[5] Moreover, a direct calculation of the T/H ratio in tropospheric molecular hydrogen, based on the mixing rate through the tropopause and the water vapor content of the stratosphere, predicts a T concentration of the order of 10^5 T units, in excellent agreement with recent extensive measurements by Begemann and Libby (personal communication). The low production rate calculated from the measured transfer of T into the sea by oceanic precipitation,[2] indicates that most of the tritium enters the sea by direct molecular exchange across the sea surface. The world inventory of natural tritium is found to be about 20 kg, or 200 megacuries, most of which is in the deep sea with a predicted concentration of about 0.015 T units.

Details of the present study will be published elsewhere. The purpose of this note is to point out that approximately 1 ± 0.5 T atom/cm_e^2 sec, i.e., the bulk of the world production, cannot be accounted for by present estimates of the contribution from cosmic rays; the discrepancy is about one order of magnitude. The cross section for production by protons on N_2 and O_2 has been found to be the same, within experimental error, at 450 Mev and 2.2 Bev[4]; thus it appears unlikely that cosmic-ray production can account for the tritium flux into the atmosphere. Tritium production in rocks by neutrons on lithium has been shown to be negligible.[13] Moreover, a lower limit for the production rate of He^3, computed from an estimated terrestrial production and escape rate of He^4, may be as much as 10 atoms/cm_e^2 sec,[14] an order of magnitude higher yet than the presently computed tritium production rate.

If these elements are being accreted by solar emission, it may well be that the production of light elements on the surfaces of stars is a more widespread and common occurrence than has been estimated as possible by the proponents of the idea,[15] and serious attention should be given to experimental attempts to detect accretion of these and other light elements. Solar contribution of heavy nuclei ($Z\gtrsim10$) has recently been suggested[16] as an explanation of an observed daily variation in intensity without an associated neutron intensity variation.

A discussion of possible explanations of the high T flux will be communicated by the writer and B. Feld, who suggested the possible solar origin on the basis of his preliminary confidence in the present evaluation of cosmic-ray contributions.[17] I wish to thank Bruno Rossi for discussions on the primary cosmic-ray flux, and F. Begemann and M. Rubin for unpublished data on tritium and carbon 14.

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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*

L. W. Alvarez, H. Bradner, F. S. Crawford, Jr., J. A. Crawford,† P. Falk-Vairant, M. L. Good, J. D. Gow, A. H. Rosenfeld, F. Solmitz, M. L. Stevenson, H. K. Ticho, and R. D. Tripp

Radiation Laboratory, University of California, Berkeley, California

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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]

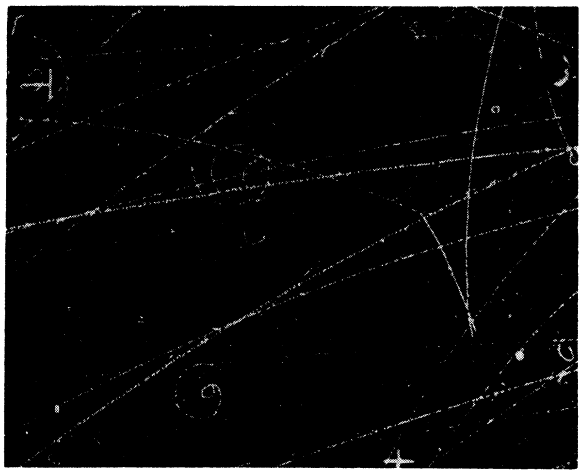

Fig. 1. Example of H-D reaction catalyzed by μ^- meson. The incident meson comes to rest, drifts as a neutral mesonic atom, is ejected with 5.4 Mev by the H-D reaction, comes to rest again after 1.7 cm, and decays.

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