The large discrepancy between the calculated and experimental values is surprising. If the experiments are correct, something is wrong with the calculations of meson-molecular formation rates, or the mechanisms (Figs. 1 and 2) supposed to lead to nuclear catalysis are incorrect.

The analysis given here indicates that in liquid hydrogen containing >1% deuterium, all absorptions of μ^- by protons will be from a $(p\mu^- d)$ molecule. For liquid hydrogen containing <1% deuterium, it is not at present possible to know the molecular or atomic states from which muons are captured. However, even for absorptions from $(p\mu^- d)$ molecules, capture and absorption of the muon by the He^3 reaction product will seriously complicate the interpretation of experimental data.

Work is presently in progress on an extension of this experiment, with a smaller concentration of hydrogen, which should allow a more precise determination of λ_{DH} and λ_{DD}.

We would like to thank Gale Pewitt, John Deahl, and Leo Fatur for assistance in obtaining the data, and Anna Marie Bankowski and Donna Stasak for scanning the film.

*Supported in part by the U. S. Atomic Energy Commission.

[1]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, Phys. Rev. 105, 1127 (1957).

[2]F. C. Frank, Nature 160, 525 (1947).

[3]P. G. Burke, F. Haas, and I. C. Percival, Proc. Phys. Soc. (London) 73, 912 (1959); Y. B. Zel'dovich and S. S. Gershtein, J. Exptl. Theoret. Phys. U.S.S.R. 35, 649 (1958) [translation: Soviet Phys.-JETP 35(8), 451 (1959)]; Y. Mizuno, T. Izuyama, and M. Shimizu, Progr. Theoret. Phys. (Kyoto) 21, 479 (1959). References to other work can be found in these papers.

[4]T. D. Jackson, Phys. Rev. 106, 330 (1957).

[5]T. H. R. Skyrme, Phil. Mag. 2, 910 (1957).

[6]S. Cohen, D. L. Judd, and R. J. Riddell, Jr., Phys. Rev. (to be published).

[7]Ta-You Wu, R. L. Rosenberg, and H. Sandstrom, Nuclear Phys. (to be published).

[8]It is expected[3-7] that $\lambda_{pd} \gg \lambda_{HD}$. If it is assumed that λ_{HD} is of the order of λ_{pd} in magnitude, the results of the analysis of the present experiment are only slightly altered provided λ_{HD} does not approach $100\lambda_{DH}$ in magnitude.

[9]M. Cresti, K. Gottstein, A. H. Rosenfeld, and H. K. Ticho, Atomic Energy Commission Report UCRL-3782, 1957 (unpublished).

[10]A. Ashmore, R. Nordhagen, K. Strauch, and B. M. Townes, Proc. Roy. Soc. (London) 71, 161 (1958).

[11]We have associated λ_{fast} of reference 10 with λ_{DH} on the basis of the results of the present experiment.

[12]W. R. Arnold, J. A. Phillips, G. A. Sawyer, E. J. Stovall, Jr., and J. L. Tuck, Phys. Rev. 93, 483 (1954).

HIGH-ENERGY BREMSSTRAHLUNG FROM A SILICON SINGLE CRYSTAL

G. Bologna, G. Diambrini, and G. P. Murtas
Laboratori Nazionali di Frascati del Comitato Nazionale per le Ricerche Nucleari, Frascati, Italy
(Received May 3, 1960)

In a previous Letter[1] we reported the results relative to electron pair production from a silicon single crystal. In this Letter we give the results relative to several measurements on bremsstrahlung from a similar target. We also compare these results with the theoretical prediction by Überall[2] and Schiff.[3]

We used about the same experimental arrangement described in reference 1. The only differences are that the single crystal is now mounted within the synchrotron chamber and that the spectrometer converter is an aluminum one; moreover we added another counting channel, for measuring simultaneously at two different photon energies.

The silicon single crystal is in the form of a half-circular plate 15 mm in diameter and 2.7×10^{-3} radiation length in thickness; it is cut perpendicular to the axis [111] within ±4 mrad, as determined by a Laue x-ray back-reflection method.[4] A goniometric device allows the single crystal to be rotated both about a horizontal and a vertical axis; the precision in the measurement of the angles is ±0.5 mrad.

First we successively measure the numbers $N(\theta,k)$, $N(\theta,k_0)$ of symmetrical pairs per fixed number of monitor units (corresponding to 10^{10} equivalent quanta), as a function of the angle θ between the incident 1-Gev electron beam and the crystal axis, and for the central values k,k_0 of the photon energies. We subtract for delayed coincidences and for background as in the previous work.[1]

We choose $k_0 \approx 900$ Mev because, as follows from Überall's theory,[2] the bremsstrahlung intensity at such an energy has a negligible dependence on θ, so that $N(\theta, k_0)$ may be used as a normalization factor. The γ-ray beam monitor units cannot be used, because the shape of the spectrum depends on θ. $N(\theta, k_0)$ ranges from ~8000 to ~12 000 counts/monitor unit.

Due to the multiple traversals of the electrons through the crystalline target, the γ-ray beam intensity after the extreme collimation (0.8×10^{-3} rad) is still rather strong: $\sim 3\times 10^9$ equivalent quanta/minute.

On the other hand we have determined the number of pairs $N(k, \theta)$ as a function of k, for several fixed values of θ.

Some of the results obtained are shown in this Letter. In Figs. 1(a) and 1(b) we give the experimental ratio $R_{\rm ex}$:

$$R_{\rm ex}(\theta) = \frac{N(\theta, k)}{N(\theta, k_0)}\,\frac{\sigma_p(k_0)}{\sigma_p(k)}, \qquad (1)$$

where $\sigma_p(k)dk$ is the cross section for symmetrical pair production in aluminum at the photon energy between k and $k+dk$. The solid line in both figures represents the value of the theoretical ratio $R_{\rm th}$:

$$R_{\rm th}(\theta) = I(\theta, x)/I(\theta, x_0), \qquad (2)$$

where

$$I(\theta, x) = I_n(\theta, x) + I_e(x); \qquad (3)$$

I_n, a quantity proportional to the bremsstrahlung intensity in the field of the nuclei of the single crystal, has been calculated by Überall.

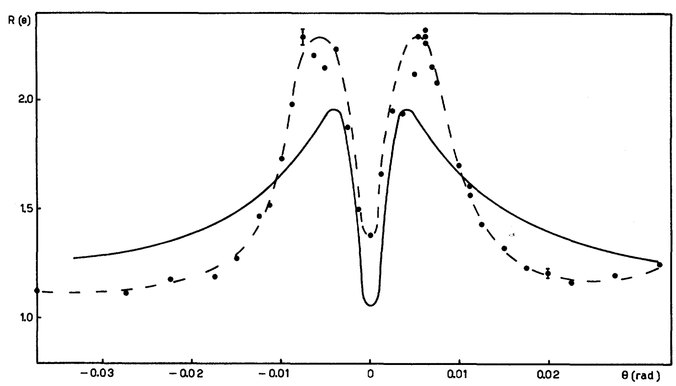
I_e is a quantity proportional to the bremsstrahlung intensity in the electron field of a noncrystalline target.[5] We have[2]

$$I_n(\theta, x) = [1 + (1-x)^2]\Big[\psi_1^{\,c}(\delta) + \psi_1^{\,0}(\theta/\delta) + \sum_{h=1}^{\infty}\psi_1^{\,h}(\theta, \delta)\Big] - \tfrac{2}{3}(1-x)\Big[\psi_2^{\,c}(\delta) + \psi_2^{\,0}(\theta/\delta) + \sum_{h=1}^{\infty}\psi_2^{\,h}(\theta, \delta)\Big], \qquad (4)$$

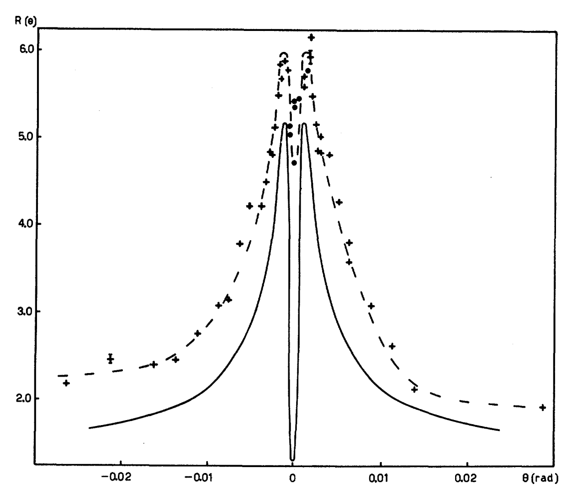
where $x = k/E$, $E = 1$ Gev electron energy, and $\delta = (mc^2/2E)[x/(1-x)]$ = minimum momentum transferred to the nucleus in units of mc.

The numerical values involved in formula (4) are the same as those used in reference 1, with the only difference that now we take the lattice spacing relative to the axis [111]. We computed the series $\sum_{h=1}^{\infty}\psi_1^{\,h}$, $\sum_{h=1}^{\infty}\psi_2^{\,h}$ only for the case $\theta = 0$.

In Fig. 1(a) we have $k = 240$ Mev and $k_0 = 910$ Mev. The experimental data show two symmetrical peaks at the left and right side of $\theta = 0$ and a central minimum in good qualitative agreement with Überall's calculations obtained in the Born approximation. Formula (4) results from an integration over the angles of the emitted photon and of the scattered electron; but the coherence



(a)



(b)

FIG. 1. Intensity of the bremsstrahlung produced in a Si single crystal ($T = 293$°K) versus θ (the angle between the 1-Gev electron beam and the crystal axis [111]). The solid curves of the figures represent $R_{\rm th}(\theta)$ given by formula (2), while the experimental points represent $R_{\rm ex}(\theta)$ given by formula (1). The dashed curves are simply drawn for visualizing the behavior of the experimental points. The statistical error (~2%) is indicated for some points. (a) $k = 240$ Mev; $k_0 = 910$ Mev. (b) $k = 80$ Mev; $k_0 = 865$ Mev.

effect among nuclei shows a strong dependence on the angle of the emitted photon.[6] This enables us to explain the fact that the maximum value of the measured effect is larger than the theoretical one; this might be due to the enrichment suffered by the γ-ray beam in photons emitted at small angles, owing to the sharp collimation employed.

In Fig. 1(b) we have $k = 80$ Mev and $k_0 = 865$ Mev. In the measurements shown in this figure the localization of the central minimum is very critical. The spacing between the two maxima is about 2 mrad and the curve is very sharp, while the goniometric device has an angular reproducibility of ± 0.5 mrad. We then proceed in the following manner. For small angles we have

$$\theta = (\theta_h^2 + \theta_v^2)^{1/2},$$

where θ_h, θ_v are the angles of rotation of the crystal about a horizontal and a vertical axis, respectively.

After a preliminary approximate alignment of the crystal axis with the electron beam, we rotate the crystal about a horizontal axis until we find a relative minimum, for which we put $\theta_h = 0$. We then rotate it about the vertical axis by an angle $\delta\theta_v = \theta_v^* = 1$ mrad, to find the absolute minimum for which we put $\theta_v = 0$ (remember that the effect has an axial symmetry).

In Fig. 1(b) we plot the values R_{ex} obtained by rotation about the horizontal axis (crosses) versus the angle

$$\theta = (\theta_h^2 + \theta_v^{*2})^{1/2},$$

and the ones obtained by rotation about the vertical axis (circles) versus $\theta = \theta_v$.

Since the error $\Delta\theta/\theta$ is very small for $|\theta_h/\theta_v^*| \ll 1$, we have good angular resolution for the crosses near the maxima.

The analysis of the data plotted in Figs. 1(a) and 1(b) shows that the central minimum does exist, even if less marked than the theoretical one, especially as far as Fig. 1(b) is concerned. At this date we do not know if this difference between theory and experiment really exists or if it is due to insufficient angular resolution of the experimental arrangement. A better goniometric device is under construction for a more precise analysis of the effect.

At these energies it seems that the correction to the Born approximation near the minimum is smaller than the one predicted by Schiff,[3] according to which the central minimum would be completely washed out for $k = 100$ Mev.

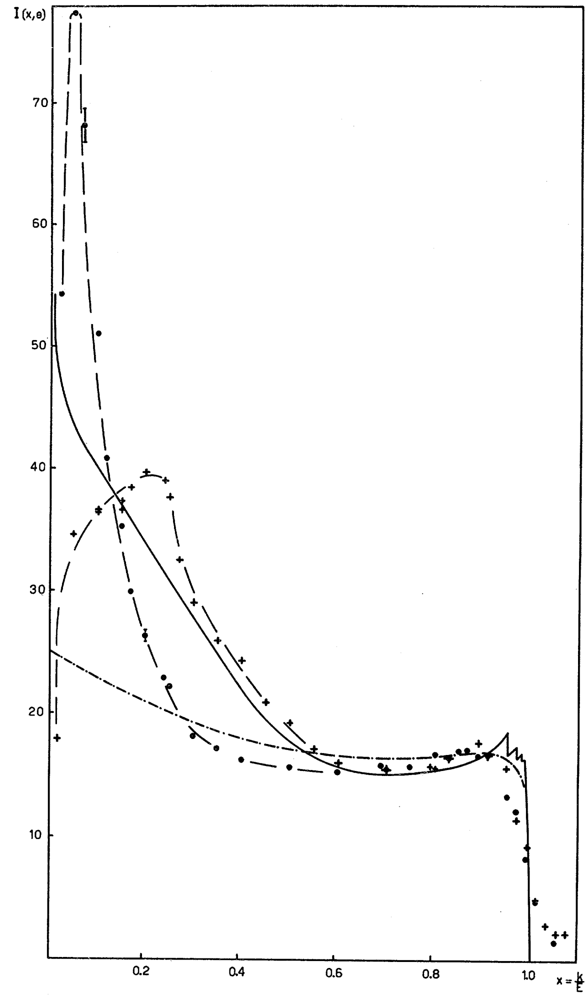


FIG. 2. Intensity of the bremsstrahlung produced in a Si single crystal ($T = 293°$K) versus $x = k/E$ (the fractional energy of the photon with respect to the electron energy $E = 1$ Gev). The solid curve represents $I(x,\theta)$ given by formula (3) for $\theta = 6$ mrad. The dash-dot line represents the same quantity for a noncrystalline target [H. Bethe and W. Heitler, Proc. Roy. Soc. (London) A146, 83 (1934); Wheeler and Lamb, reference 4]. The experimental points represent the quantity (5). The circles are relative to $\theta = 6 \pm 0.5$ mrad, while the crosses are relative to $\theta = 1 \pm 0.5$ mrad.

In Fig. 2 we plot the quantity $I(x,\theta)$ given by formulas (3) and (4), as a function of x, for $\theta = 6$ mrad (solid curve) and the bremsstrahlung intensity from a silicon noncrystalline target for comparison (dot-dash curve). We also plot the experimental quantity

$$\lambda N(k,\theta)/\sigma_p(k), \qquad (5)$$

where λ is a normalization factor, so chosen that the experimental value is coincident with the theoretical one at 900 Mev. The data for 6 mrad confirm that the collimation operates an angular selection of the photons. For $\theta \approx 1$ mrad we do not draw the theoretical curve because at these angles the dependence on θ is very strong, and for the experimental data we have $\theta = 1 \pm 0.5$ mrad.

The preceding experiments[7,8] have shown a dependence on θ of the bremsstrahlung intensity without showing any central minimum. We think that this is due to insufficient angular resolution with respect to the low-energy detected photons.

We thank Dr. G. Barbiellini for the collaboration given in this work.

[1]G. Bologna, G. Diambrini, and G. P. Murtas, Phys. Rev. Letters 4, 134 (1960).

[2]H. Überall, Phys. Rev. 103, 1055 (1956); 107, 223 (1957).

[3]L. I. Schiff, Phys. Rev. 117, 1394 (1960).

[4]We are indebted to Dr. F. Sgarlata, of the Istituto Superiore di Sanità, Roma, for this analysis.

[5]J. A. Wheeler and W. E. Lamb, Phys. Rev. 55, 858 (1939).

[6]H. Überall, CERN Report 58-21, September, 1958 (unpublished).

[7]O. R. Frisch and D. H. Olson, Phys. Rev. Letters 3, 141 (1959).

[8]W. K. H. Panofsky and A. N. Saxena, Phys. Rev. Letters 2, 219 (1959); A. N. Saxena, Phys. Rev. Letters 4, 311 (1960).

MUON ABSORPTION IN LIQUID HYDROGEN*

Steven Weinberg
Lawrence Radiation Laboratory, University of California, Berkeley, California
(Received May 2, 1960)

The long-awaited measurement of the rate of μ^- absorption on protons could conceivably use hydrogen in any form, but there are technical advantages in working with liquids, as in bubble chambers. However, many physicists have expressed pessimism about the utility of such an experiment, because in liquid H_2 muons form p-μ-p molecular ions in addition to p-μ atoms. We shall show here how it is nevertheless possible to interpret the observable rate of muon absorption in liquid hydrogen in terms of the basic $pn\mu\nu$ interaction. The main problem is to calculate the rate for the process

$$(p-\mu-p) \to n+\nu+p \tag{1}$$

in terms of the muon absorption in atoms; because of the extreme spin dependence of the V-A interaction,[1] this requires knowledge of the orientation of proton and muon spins as well as the overlap of their wave functions at the instant of absorption. Almost all of our remarks will apply to solid as well as to liquid hydrogen, and we will confine ourselves to the case of isotopically pure $(H^1)_2$.

The only two bound orbital states of the p-μ-p system[2] are a para $1s\sigma g$ ground state with rotational angular momentum $L=0$ and binding energy 2771 ev, and a $1s\sigma g$ ortho state with $L=1$ which is $\Delta E = 148$ ev higher. The formation of these states by electron ejection in a collision of a p-μ atom with an H_2 molecule is respectively an $E0$ or $E1$ process, and hence the ratio of the formation rates is of order[3]

$$\text{Para/Ortho} \sim k_e^{\,2} a_\mu^{\,2} \sim 2\times10^{-4}, \tag{2}$$

where k_e is the wave number of the ejected electron. Actually, detailed calculations[2] show this ratio to be less than 3×10^{-5}, so virtually all p-μ-p's are formed in the ortho state.

It seems furthermore that the p-μ-p's formed in the ortho state stay there during the few microseconds of muon lifetime. If we define the ortho→para electric dipole transition matrix element to be

$$|\langle P|\int\rho\vec{R}|O\rangle| \equiv e a_\mu D, \tag{3}$$

then the rate for de-excitation accompanied by ejection of an electron from a hydrogen molecule in a collision is

$$\omega_e(O\to P) = 16\pi n_e m_e a_\mu^{\,2} e^4 D^2/3k_e$$
$$= 2.7\times10^{10} D^2 \text{ sec}^{-1}. \tag{4}$$

(Here n_e is the number density of electrons in a bubble chamber, $n_e = 3.5\times10^{22}$ cm^{-3}, and $k_e = [2m_e(\Delta E - E_H)]^{1/2}$, where $\Delta E = 148$ ev, and $E_H = 15.6$ ev is the electron separation energy in H_2.) It is also possible that the p-μ-p forms "ordinary" atoms or molecules with electrons