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RADIATION LABORATORY

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It has been pointed out by Yang,<sup>1</sup> that pair production may provide a method for detecting the polarization of  $\gamma$ -rays in the high energy range:  $h\nu \gg mc^2$  ( $m$  being the electron mass) where the usual Compton recoil method becomes insensitive. The idea is to utilize the azimuthal dependence of the pair production cross section  $d\sigma$ , the azimuth  $\phi$  being measured around the direction  $\underline{k}$  of the incident quantum and from the plane containing  $\underline{k}$  and the electric polarization vector  $\underline{\xi}$  of the quantum. Actually, of course, one has to consider two azimuths  $\phi_+$  and  $\phi_-$  for the positive and negative electron respectively. Berlin and Madansky,<sup>2</sup> from whose paper our notations are borrowed, have made a careful study of the dependence of  $d\sigma$  on  $\phi_-$  when  $\phi_+ = \phi_- + \pi$ . In this case the plane of the pair contains exactly the direction  $\underline{k}$  of the incident quantum, and one may speak simply of the azimuth  $\phi = \phi_-$  of the plane of the pair with respect to the plane of polarization. From the experimental standpoint it will be practically impossible to select the pairs which satisfy the Berlin-Madansky condition. Both electrons will be emitted within a narrow cone around  $\underline{k}$ , and the plane of the pair will always make a very small angle with  $\underline{k}$ . No matter whether pairs are observed in a photographic emulsion or produced in a thin target and detected with counters, scattering within the emulsion or respectively the target will unavoidably distort the initial directions to a considerable extent. It seems more reasonable, therefore, to set as our goal

<sup>1</sup> C. N. Yang, Phys. Rev. 77, 722 (1950).

<sup>2</sup> T. H. Berlin and L. Madansky, Phys. Rev. 78, 623 (1950).

the measurement of the angle between the plane of the pair and the plane of polarization without any selection. The question then arises whether the case considered by Berlin and Madansky is sufficiently representative to permit a rough prediction of what to expect in the general case. The result of the following calculation may indicate that it is not.

The Bethe-Heitler formula for  $d\sigma$  has a quite complicated dependence on the various parameters involved, so that the sign and magnitude of the effect to be expected can be seen only at the end of a laborious integration. In order to get a simpler picture we have used the Weizsäcker-Williams approximation.<sup>3</sup> In order to deal with pair production, Williams makes a Lorentz-transformation parallel to  $k$  with velocity  $v = c(\xi - 1)/(\xi + 1)$ , with  $\xi = hv/mc^2$ . In the new system the quantum has an energy  $h\nu_1 = mc^2$ . The method can be applied if  $\xi \gg 1$  so that  $v$  is very close to  $c$ ; the field of the nucleus may then be approximately substituted by a spectrum  $\sim (C/\nu)d\nu$  of virtual quanta,  $C$  being a slowly variable function of  $\nu$ , which we shall treat as a constant. These quanta move in the direction  $-k$  and if one of them, having an energy  $h\nu_2 > mc^2$ , collides with the real quantum, a pair may be produced. It is characteristic of the Weizsäcker-Williams method that the transfer of momentum to the nucleus is represented by the removal of a virtual quantum from the field, and is hence parallel to  $k$ . Consequently the planes of all pairs produced contain  $k$  exactly. The difference between this statement and the apparently similar language of the Berlin-Madansky condition may be understood as follows. Presumably in the more accurate theory the probable values of the difference  $\theta_+ - \theta_- - \pi$  are rather small; if this is true the procedure we follow is equivalent to averaging the Bethe-Heitler cross section over the above mentioned difference, rather than considering the case when the difference is equal to zero. The virtual quanta are, on the whole, unpolarized. Hence we need the pair production cross section for two quanta moving in opposite direc-

<sup>3</sup> C. F. von Weizsäcker, Zeits. f. Phys. 88, 612 (1934).  
E. J. Williams, K. Danske Vidensk. Selsk. Mat.-fys. Medd. 13, Nr. 4 (1935) and Phys. Rev. 45, 729 (1934).

tions, one of them linearly polarized, one unpolarized. This is known<sup>4</sup> to be, in the center of mass of the two quanta:

$$d\sigma = (\beta r_0^2 / 2x^2) \left\{ (1 - \beta^2 \cos^2 \theta)^{-1} - (1/2) + 2\beta^2 (1 - \beta^2) (1 - \beta^2 \cos^2 \theta)^{-2} \right. \\ \left. \sin^2 \theta \cos^2 \phi \right\} \sin \theta \, d\theta \, d\phi$$

where  $\beta c$  is the velocity of either electron,  $r_0 = e^2/mc^2$ ,  $x = h\nu/mc^2 = (1 - \beta^2)^{-\frac{1}{2}}$ ,  $\theta$  is the angle between the electrons and the photons, while  $\phi$  is the azimuth of the plane containing electrons and photons measured from the plane of polarization of the polarized photon. We integrate over  $\theta$  since we are only interested in the dependence on  $\phi$ . Finally we must transform the frequencies to the system in which one of the quanta has an energy  $h\nu_1 = mc^2$ , and integrate over a spectrum  $Cd\nu_2/\nu_2$  for the other quantum. The result is:

$$d\sigma = (2/3) Cr_0^2 (1 + \frac{1}{3} \cos^2 \phi) d\phi$$

which exhibits an azimuthal dependence of comparable magnitude to that found by Berlin-Madansky in their special case. The sign, however, is the opposite: the plane of the pair prefers to be parallel to the electric vector.

The applicability of the Weizsäcker-Williams method to the present problem may be doubted; in particular one may fear that the transverse momentum transfer to the nucleus, which is neglected in this method, might affect the directions of the particles in such a way as to alter the correlation between polarization and directions of motion entirely. It may be pointed out, however, that the transverse momenta of the pair are of the order of  $mc$ , while the momentum transfer to the nucleus is  $\ll mc$  in a majority of the collisions (if  $h\nu \gg mc^2$ ).<sup>5</sup> We believe, therefore, that the Berlin-Madansky conclusions apply only if the condition they postulate ( $\phi_+ = \phi_- + \pi$ ) is strictly

<sup>4</sup> G. Breit and J. A. Wheeler, Phys. Rev. 46, 1087 (1934).

<sup>5</sup> H. A. Bethe, Proc. Camb. Phil. Soc. 30, 524 (1934).

R. Jost, J. M. Luttinger, M. Slotnick, Phys. Rev. 80, 189 (1950).

satisfied. An investigation of the Bethe-Heitler formula under more general conditions is under way.

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