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PAIR PRODUCTION BY 6 MeV LINEARLY POLARIZED γ-RAYS

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Abstract: The production of electron pairs in nuclear emulsions by linearly polarized photons was investigated. It was found that more pair particles are emitted perpendicular to the photon polarization plane if the pair and the photon are coplanar. They are emitted preferentially in the polarization plane if they are not coplanar. The distribution of the angle θ between one pair particle and the incident photon and of the opening angle ω of the pairs was also determined. The results are in good agreement with recent calculations.

1. Introduction

It was suggested by Yang [1]) that electron pair production may be used to detect the linear polarization of photons by utilizing the correlation between photon polarization and the plane of production of the pair. Berlin and Madansky [2]) calculated this correlation for the case that the photon and the pair particles are exactly coplanar. They found that the pairs are emitted preferentially *perpendicular* to the photon polarization plane.

Wick [3]) pointed out, however, that from an experimental point of view it is more realistic to allow small deviations from coplanarity and he took this into account by using the Weizsäcker-Williams method to calculate the correlation. Surprisingly he found the opposite result, predicting the pairs to be emitted predominantly *in* the plane of photon polarization.

Because of this discrepancy an experimental investigation of this correlation seemed interesting and was started some time ago. This stimulated the theoretical interest and recently Maximon and Olsen [4]) could reconcile the two opposite results. They gave a quantitative theory showing that the cross section varies rapidly if the pair deviates from coplanarity. The experimental results of this paper are in very good agreement with these calculations.

The reaction $d(p, \gamma)He^3$ (proton energy about 1 MeV) was used as a source of completely polarized γ-rays with an energy of about 6 MeV. The pairs were produced in nuclear emulsions in a geometry such that the direction of the incident photon was known within 1°. By scanning the pairs with a microscope, not only the azimuthal angles necessary for the determination of the polarization correlation were measured but also the ange θ between a pair particle and the incident γ-ray and further the opening angle ω between the two pair particles.

The experimental distribution of θ is found to be in excellent agreement with the classical calculations of Bethe and Heitler [5]) (see fig. 5). Several authors [6]) measured the distribution of the opening angle ω of the pair and compared their results with the theoretical distribution derived by Borsellino [7]). It was found in all cases that the experimental distribution has a maximum at smaller angles than predicted theoretically. This is corroborated by the results presented here. The solution to this discrepancy is that Borsellino inferred the ω-distribution from the distribution of the transfered momentum which implies that a certain combination of opening angle and energy partition between the pair particles is assumed. Recently Olsen [8]) calculated the distribution without this restricting condition and his results are in excellent agreement with our measurements (see fig. 6).

2. Experimental Method

The reaction d(p, γ)He^3 proceeds almost entirely by electric dipole absorption yielding a radiation pattern with the typical $\sin^2 \vartheta$ angular distribution and the electric vector lying in the reaction plane. Therefore, it is an excellent source for linearly polarized γ-rays of about 6 MeV if the proton energy is 1 MeV as in our case. Wilkinson [9]) has used the photodisintegration of the deuteron to show that the polarization is indeed complete for this case.

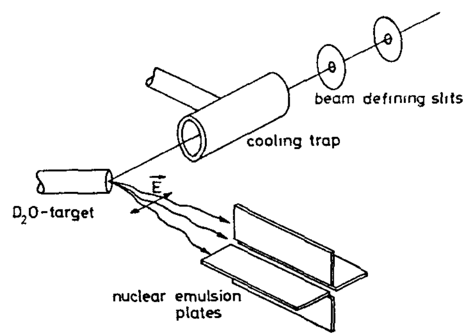

Fig. 1. Schematic diagram of experimental arrangement.

The apparatus used is shown schematically in fig. 1. Protons with an energy of 1.05 MeV impinge upon a thick heavy ice target with a diameter of 9 mm. Those γ-rays emitted approximately at 90° with respect to the proton direction were used to irradiate several nuclear emulsion plates 16 cm away from the target for some 30 h. The plates were set parallel to the γ-rays and are symmetrically arranged around the γ-ray axis. In particular two plates are in the plane of the electric vector and two perpendicular. Standard Ilford G5 emulsions 2.5×7.5 cm^2 large and 100 μm thick were used.

As the cross section for the d(p, γ)He^3 reaction is rather small, one must be careful that the γ-rays are not contaminated by unpolarized photons from background reactions. As the proton capture in F^{19} is the most significant source of background radiation the whole system and in particular the collimator and the target holder were carefully cleaned. A cold trap was used to avoid the deposition of carbon on the target. The γ-ray spectrum as measured with a NaI-crystal is shown in fig. 2 both for a H_2O and D_2O-target. As can be seen the background is almost negligible. As a further check the asymmetry of the angular distribution of the γ-rays was measured and found to be in agreement with that of an electric dipole transition.

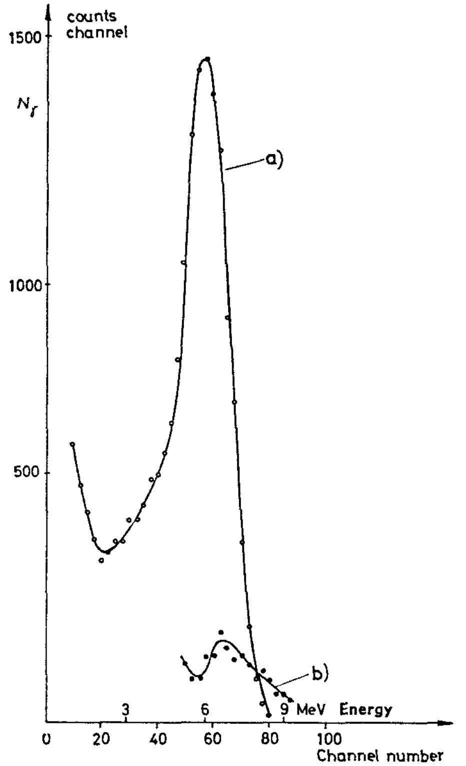

Fig. 2. γ-ray spectrum measured with a NaI spectrometer, for the reaction d(p, γ)He^3. (a) D_2O target, (b) H_2O target.

After development the emulsions were scanned for pairs with a high power microscope (magnification 2500). As the scanning turned out to be very tedious only two plates were scanned, one of them in the E plane and one perpendicular to it. During 1600 h of scanning time 457 pairs were found on an area of approximately 50 mm^2. Two examples are shown in fig. 3.

The following angles have to be determined for each pair (see fig. 4): The angles θ_1 and θ_2 between each pair particle and the photon direction, the opening angle ω of the pair, and the two azimuthal angles φ_1 and φ_2. This was achieved by measuring

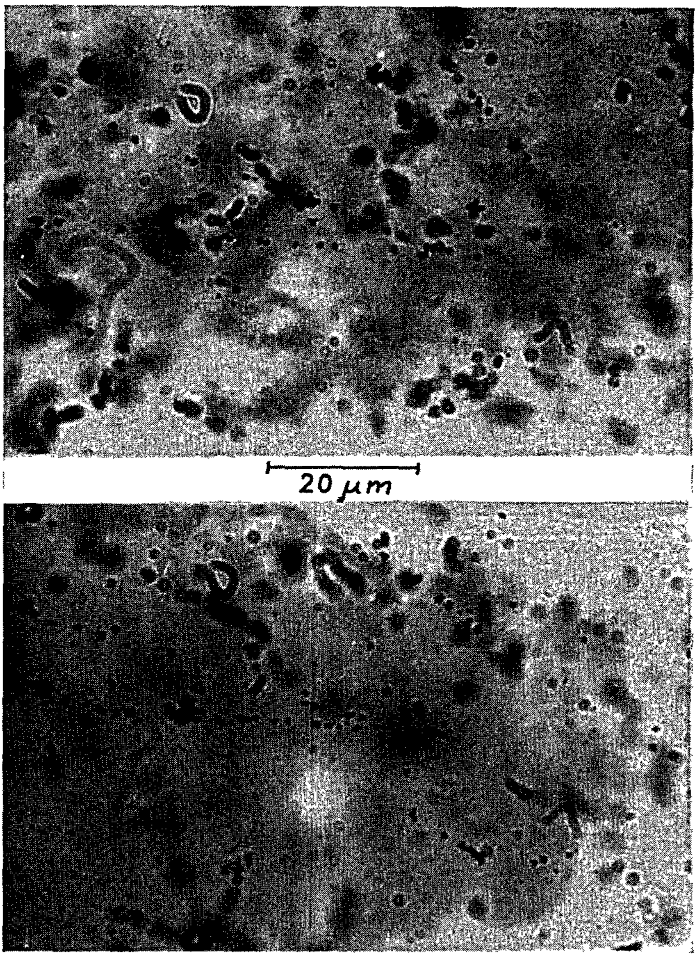

Fig. 3 Electron pairs in G5-emulsions.

the projected angles $\bar{\theta}_1, \bar{\theta}_2$ (assuming that the γ-ray came from the centre of the target), and $\bar{\omega}$ as seen in the microscope, the depth of the pair vertex and the depth of one more point of each track at a certain distance from the vertex. From these data the true angles θ_1 and θ_2 and the azimuthal angles φ_1 and φ_2 can easily be computed. The projected angles could be measured with an accuracy of about 0.3° which has to be combined with the inaccuracy of the γ-direction of about 1.1° in the case of the θ_i. The uncertainty in the depth determination was approximately 0.15 μm. The resulting total errors for θ_1, θ_2, φ_1 and φ_2 depend very much on the geometry of a special pair. Obviously the uncertainty of the azimuthal angles increases if θ_i is small. If $\theta_i \leqq 2°$ the azimuthal angles cannot be determined at all and such pairs were therefore excluded from the evaluation.

In order to determine the dip angle of each track (by measuring its depth at two different positions) the shrinking of the emulsions had to be taken into account. This was determined by measuring the emulsion thickness before and after the processing.

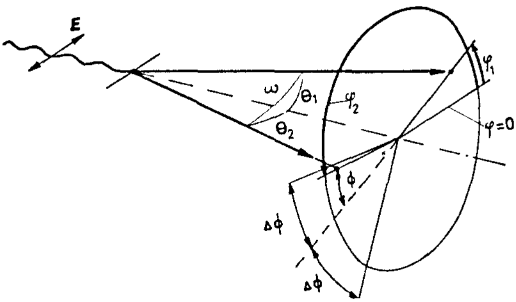

Fig. 4. Definition of angles.

As it is easier to find a pair whose plane is approximately parallel to the emulsion plane two plates were scanned. One plate was oriented parallel, the other perpendicular to the electric vector of the photons. In this way the different detection efficiencies should have little influence on the asymmetry. However, in order to be sure that such effects did not impair the determination of the polarization asymmetry, the number of single tracks as a function of the azimuthal angle was analysed in both emulsions, and indeed an azimuthal change of the scanning efficiency of about 18 % was found. As this change was approximately the same in both plates the total correction is small compared to the statistical errors. A determination of the energies of the pair particles was not possible. As the angular distributions and correlations to be studied depend only little on the energy partition this was no serious impairment for this experiment.

3. Results for the Angular Distributions

First we discuss the results for the distribution of the angle θ between a pair particle and the photon and then the results for the opening angle ω of the pairs.

The experimental results for the θ distribution are displayed in fig. 5. Pair particles were grouped into intervals of 2° for the angle θ.

Two theoretical curves are shown for comparison. Both were calculated in the Born approximation without screening and for the high energy limit, assuming that the energy of both pair particles is large compared with the electron rest mass. Curve (a) was calculated from the equation

$$d\sigma \propto d\theta\, \theta\xi^2 \tag{1}$$

given by Bethe [5]), where $\xi = [1+(\frac{1}{2}k)^2\theta^2]^{-1}$ and k is the photon energy in units of mc^2.

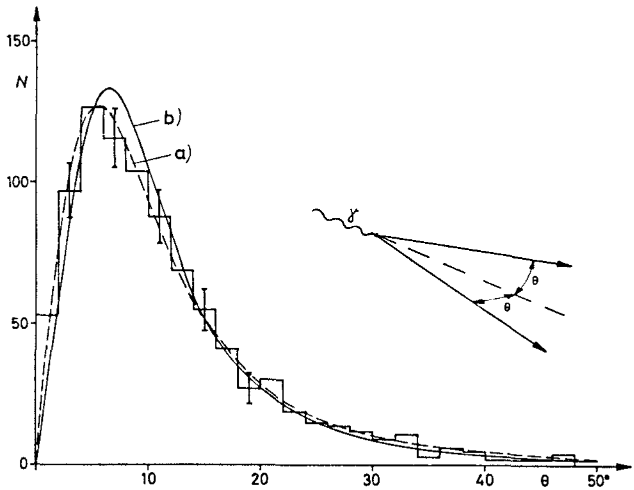

Fig. 5. Distribution of θ for $k \approx 6$ MeV/mc^2. (a) calculated from eq. (1) (Bethe [5]), (b) calculated from eq. (2) (Olsen and Maximon [10]).

More recently Olsen and Maximon [10]) derived the expression

$$d\sigma = \tfrac{1}{8}(\sigma_0 k)dE_1\, d\theta\theta\xi^2\{2\ln(\tfrac{1}{2}k)+k^2\theta^2\xi^2[\ln(\tfrac{1}{2}k)-2]\}, \tag{2}$$

which holds if the energies of the two pair particles are equal. Here $\sigma = 4(e^2/mc)(\hbar/mc)(Zc^2/\hbar c)^2$ and E_1 is the total energy of one pair particle. A deviation from this equipartition changes the distribution only very little. Curve (b) in fig. 5 was calculated from this equation.

As can be seen from this figure the difference between the two curves is not appreciable. The agreement with the experimental results is surprisingly good taking into account that for $k = 12$ the high energy approximation cannot be expected to be very good.

In fig. 6 the experimental results for the distribution of the opening angle ω of the pairs are shown. The measured values of ω were collected into groups with an angular range of 5°.

In the past experimental determinations of ω were compared with theoretical distributions derived by Borsellino [7]) and in all cases it had been found that the experimental distribution is peaked at smaller angles than predicted by theory. A simple explanation, although not noticed thus far, is that Borsellino calculated the cross section as a function of the invariant pair energy $4Q^2 = (E_1+E_2)^2-(p_1+p_2)^2$, where E_1, E_2 and p_1, p_2 are the energies and momenta of the two pair particles. From this he derived a cross section as a function of ω obtaining a distribution function of a certain combination of opening angle and energy partition rather than the cross section for fixed values of both ω and energy partition. Nevertheless Borsellino's formula has even be used to infer γ-ray energies from measured opening angles [11]).

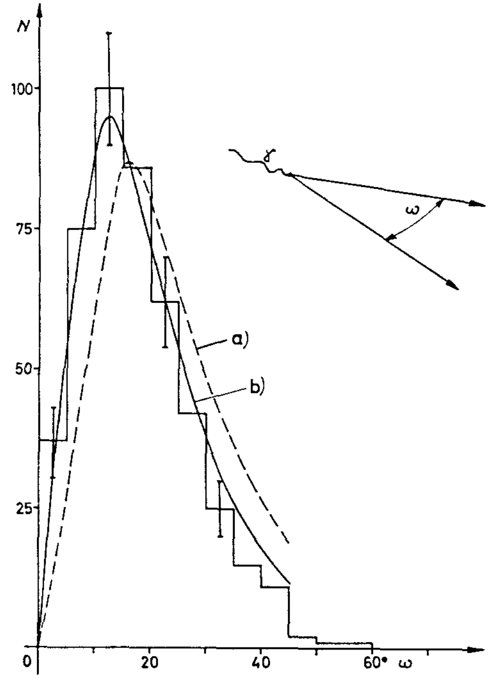

Fig. 6. Distribution of ω for $k \approx 6$ MeV/mc^2. (a) calculated according to Borsellino [7]), (b) calculated from eq. (3) (Olsen [8]), both for equal energies of the pair particles.

Quite recently the distribution of ω for fixed energy partition has been calculated by Olsen [8]) in the Born approximation and in the high energy limit. He also showed that the distribution integrated over all particle energies differs only little from the distribution for equipartition. This is given for the case of no screening by

$$\mathrm{d}\sigma = (\tfrac{1}{4}\sigma_0 k)\mathrm{d}E_1\,\mathrm{d}\omega\,\omega^2\zeta^2\{\ln k[1+2(\tfrac{1}{4}k)^2\omega^2\zeta^2] \\ -[\tfrac{1}{4}+3(\tfrac{1}{4}k)^2\omega^2\zeta^2]-(\gamma/(4\sinh\gamma))[3+2(\tfrac{1}{4}k)^2\omega^2]\}, \quad (3)$$

where

$$\zeta = [1+(k/4)^2\omega^2]^{-1} \quad , \quad \cosh(\tfrac{1}{2}\gamma) = \zeta^{-\frac{1}{2}}.$$

Curves calculated for $k = 12$ from this equation and from Borsellino's expression are also shown in fig. 6. As in previous experiments Borsellino's curve has a maximum at larger angles than the experimental distribution. Olsen's calculations on the other hand are even at this low photon energy in excellent agreement with the experiment.

It might be mentioned that the ω and θ distributions are very similar except that the ω distribution is twice as wide as the θ distribution. This stems mainly from the difference of a factor of 2 in ζ and ξ and means that to a first approximation ω is the sum of θ_1 and θ_2.

An experimental determination of the mean opening angle $\langle\omega\rangle = \int\omega(\mathrm{d}\sigma/\mathrm{d}\omega)\mathrm{d}\omega/\int(\mathrm{d}\sigma/\mathrm{d}\omega)\mathrm{d}\omega$ is sometimes used for an estimate of the γ-energy. Hence a comparison of experiment and theory for this quantity is also of interest. From eq. (3) Olsen inferred

$$\langle\omega\rangle = \frac{15\pi}{8k}\frac{\ln k - \frac{41}{30}}{\ln(\frac{1}{2}k)-\frac{1}{2}}, \tag{4}$$

which is valid for no screening. For $k = 12$ one obtains $\langle\omega\rangle = 24.3°$ which has to be compared to the experimental value $\langle\omega\rangle_{\mathrm{exp.}} = 17.5°\pm0.5°$. The reason for the discrepancy is that in $\langle\omega\rangle$ large angles are rather important and the high energy approximation used is poor for these cases. The large angle contribution has been calculated approximately by Olsen [8]) and he found that eq. (4) should be multiplied by $(1-24/5k)$. This yields a corrected value $\langle\omega\rangle_{\mathrm{corr.}} = 14.6°$ which is in fair agreement with the experimental results although it seems that the correction has been overestimated slightly.

4. The Polarization Asymmetry

Maximon and Olsen [4]) defined the polarization asymmetry

$$R = \frac{\mathrm{d}\sigma(\varphi_1 = 0, \Delta\phi)}{\mathrm{d}\sigma(\varphi_1 = \frac{1}{2}\pi, \Delta\phi)} = \frac{\mathrm{d}\sigma_{\parallel}(\Delta\phi)}{\mathrm{d}\sigma_{\perp}(\Delta\phi)}, \tag{5}$$

where $\varphi_1 = 0$ and $\varphi_1 = \frac{1}{2}\pi$ means that one pair particle was emitted parallel and perpendicular to the electric vector of the photon, respectively, whereas the second particle was emitted at an angle $\phi = \pi+\varphi_1-\varphi_2$ within a certain range $\Delta\phi$ (see fig. 4). Obviously $\phi = 0$ implies that the two pair particles and the photon are coplanar and therefore ϕ is a measure of the deviation from coplanarity.

In an experiment, however, the requirement $\varphi_1 = 0$ and $\varphi_1 = \frac{1}{2}\pi$ cannot be realized as a finite range of φ_1 must be admitted. In order to get a reasonable statistical accuracy all cases with $-45° \leqq \varphi_1 \leqq +45°$ and $135° \leqq \varphi_1 \leqq 225°$ were taken for $\mathrm{d}\sigma_{\parallel}$ and all pairs with $45° \leqq \varphi_1 \leqq 135°$ and $225 \leqq \varphi_1 \leqq 315°$ were used for $\mathrm{d}\sigma_{\perp}$ and thus a ratio $\overline{R} = \overline{\mathrm{d}\sigma_{\parallel}}/\overline{\mathrm{d}\sigma_{\perp}}$ averaged over φ_1 was obtained. Maximon and Olsen showed that the cross section is of the form $\mathrm{d}\sigma = a\,(\Delta\phi)+b(\Delta\phi)\cos^2\varphi_1$ and from this the relation

$$\overline{R} = \frac{R+0.222}{1+0.222R} \tag{6}$$

can easily be deduced and it can be seen that the reduction of R is tolerable.

After establishing whether a pair particle had been emitted parallel or perpendicular to the electric vector the angle $\phi = \pi + \varphi_1 - \varphi_2$ was determined. Finally the number of pairs with ϕ between 0 and $\Delta\phi$ with $\Delta\phi$ increasing in steps of 10° were counted. Naturally in this way each pair, except those in the highest $\Delta\phi$ interval, is counted several times and the statistical errors of the individual points are not independent.

The experimental values of $\bar{R}$ as a function of $\Delta\phi$ are shown in fig. 7. Although the statistical errors are still large it can be seen at least qualitatively that more pair particles are produced perpendicular to the electric vector if $\Delta\phi$ is small whereas the parallel case is favoured for large $\Delta\phi$. The first case corresponds to the coplanarity condition of Berlin and Madansky [2]) whereas the averaging over a larger range of ϕ leads to Wick's results [3]). According to the calculations of Maximon and Olsen[4])

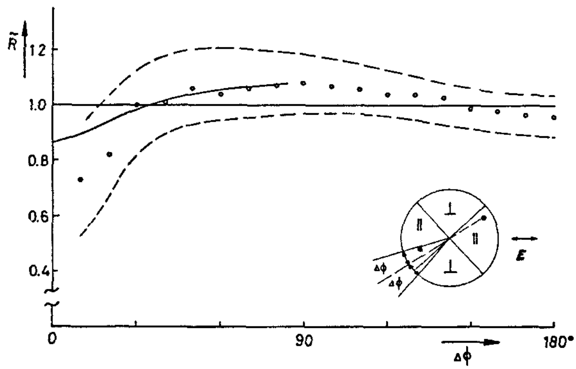

Fig. 7. The asymmetry ratio $\bar{R} = \overline{d\sigma_{\parallel}}/\overline{d\sigma_{\perp}}$ as a function of $\Delta\phi$. Here $\Delta\phi$ describes the mean deviation from coplanarity. The broken lines indicate the statistical errors. The full curve is taken from Maximon and Olsen [4]) and is valid for $\Delta\phi \ll 1$.

$\bar{R} = 1$ should be reached at $k\,\Delta\phi \approx 8$. As the photon energy $k = 12 \approx 6$ MeV$/mc^2$ in this experiment was rather low the cross-over occurs at a rather large angle and was accessible to observation.

In fig. 7 a theoretical curve for $\bar{R}$ calculated from eq. (6) is also shown. The asymmetry ratio R was taken from ref. [4]) and had been obtained by averaging over the particle energies. It is valid for $\Delta\phi \ll 1$. In view of the theoretical approximations and the statistical uncertainties the agreement is satisfactory.

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