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Pair Production as an Analyser of Circular Polarization of γ Rays from Neutral Particle Decays (*).

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Measurement of the circular polarization of high energy γ rays from the decay of neutral elementary particles seems to provide important information concerning the polarization and decay properties of these particles. The method which is best suited for analysing the circular polarization of photons of lower energy, viz. Compton scattering on polarized electrons, has also been used for photons of 70 MeV from π^0 decay (1). This method is, however, difficult to use because of the small Compton scattering cross-section at high energies.

In this note we discuss the use of pair production for measuring the circular polarization of high energy photons. This method has a large efficiency in that both the cross-section for pair production and its polarization dependence are large. We discuss later some possible experiments to which it is hoped that this method may be applied.

The method uses the correlation between the circular polarization of the γ ray and the direction of motion of the pair particles. The differential cross-section for pair production by completely circularly polarized high-energy photons has been derived previously (2) and is, after summing over positron and electron spins, of the form

$$\text{(1)} \qquad d\sigma = a + b(i\boldsymbol{e}\times\boldsymbol{e}^*)\cdot(\boldsymbol{u}\times\boldsymbol{v}) ,$$

where $\boldsymbol{u}$ and $\boldsymbol{v}$ are, respectively, the components of the momenta $\boldsymbol{p}_1$ and $\boldsymbol{p}_2$ of the positron and the electron perpendicular to the photon momentum $\boldsymbol{k}$. $\boldsymbol{e}$ is the complex photon polarization vector and $i\boldsymbol{e}\times\boldsymbol{e}^*=\pm\hat{\boldsymbol{k}}$, the upper and lower signs referring to right and left circular polarization, respectively (3). a and b are positive quantities dependent on $\boldsymbol{k}, \boldsymbol{p}_1$ and $\boldsymbol{p}_2$ and on the energies of the positron and electron, ε_1 and ε_2, as well as on the atomic number Z of

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(1) R. L. GARWIN, G. GIDAL, L. M. LEDERMAN and M. WEINRICH: *Phys. Rev.*, **108**, 1589 (1957).

(2) HAAKON OLSEN and L. C. MAXIMON: *Phys. Rev.*, **114**, 887 (1959). Note p. 893, eq. (4.10). However, in the second term in this equation the factor $|\boldsymbol{J}\cdot\boldsymbol{e}^*|^2$ should read $|\boldsymbol{J}\cdot\boldsymbol{e}|^2$.

(3) We use the usual convention, as in J. M. BLATT and V. F. WEISSKOPF: *Theoretical Nuclear Physics* (New York, 1952); note p. 807, eq. (5.1).

the nucleus. Energies and momenta are measured here in units of mc^2 and mc, respectively.

The quantity b is zero in the first order Born approximation. This may be understood in the following way: For electromagnetic interactions the cross section must be invariant under both space and time reversal. Under time reversal not only should the direction of motion of the particles and their spin directions be reversed, but also the direction of motion of the spherical waves in the scattering states describing the initial and final states must be reversed. Thus an ingoing particle which is accompanied by spherical outgoing waves is, under time reversal, changed into an outgoing particle accompanied by spherical incoming waves, and vice versa. Since $(i\boldsymbol{e}\times\boldsymbol{e}^*)\cdot(\boldsymbol{u}\times\boldsymbol{v})$ changes sign upon time reversal b must also change sign in order that the cross section be invariant under time reversal. Since b depends on the vectors $\boldsymbol{k}$, $\boldsymbol{p}_1$ and $\boldsymbol{p}_2$ only through their scalar products the only effect of the time reversal on b can be that due to the change of the ingoing to outgoing waves and vice versa. Since the first order Born approximation cross-section is independent of the use of ingoing or outgoing waves in the initial and final states (4), the contribution to b must come from higher order Born approximations (5).

With $\boldsymbol{k}$ as the z axis the polar and azimuthal angles of the positron and electron are denoted by θ_1, φ_1 and θ_2, φ_2 respectively. For a right circularly polarized photon the cross section $\mathrm{d}\sigma_{R,r}$ for emission of the electron to the right of the positron production plane, viewed in the direction of $\boldsymbol{k}$ with $\boldsymbol{u}$ pointing upwards, is then obtained by integrating eq. (1) over all values of θ_1 and θ_2 and over $\varphi_2-\varphi_1$ from 0 to π. Also for a right circularly polarized photon, the cross section $\mathrm{d}\sigma_{L,r}$ for emission of the electron to the left of the positron production plane is obtained by integration over all θ_1 and θ_2 and over $\varphi_2-\varphi_1$ from 0 to $-\pi$. For a partially circularly polarized photon beam the corresponding cross sections are denoted by $\mathrm{d}\sigma_R$ and $\mathrm{d}\sigma_L$. The right-left electron (6) emission asymmetry in pair production by a photon beam with circular polarization $\pm P_{\mathrm{ph}}$, upper and lower signs referring to right and left polarization respectively, is then found to be for complete screening, in the lowest non-vanishing order in Z,

$$(2)\qquad \frac{\mathrm{d}\sigma_R-\mathrm{d}\sigma_L}{\mathrm{d}\sigma_R+\mathrm{d}\sigma_L}=\pm P_{\mathrm{ph}}\,Z\,\frac{e^2}{\hbar c}\cdot \frac{(\varepsilon_1^2+\varepsilon_2^2)2\pi\ln 2}{(\varepsilon_1^2+\varepsilon_2^2+\frac{2}{3}\varepsilon_1\varepsilon_2)\ln(183Z^{-\frac{1}{3}})-\frac{1}{9}\varepsilon_1\varepsilon_2}\,.$$

For partial screening eq. (2) is modified only in that the denominator on the right-hand side is replaced by (7)

$$(2a)\qquad (\varepsilon_1^2+\varepsilon_2^2+\tfrac{2}{3}\varepsilon_1\varepsilon_2)[\tfrac{1}{4}\Phi_1(\gamma)+\ln Z^{-\frac{1}{3}}]-\tfrac{1}{6}\varepsilon_1\varepsilon_2[\Phi_1(\gamma)-\Phi_2(\gamma)]\,.$$

The asymmetry is directly proportional to Z, which shows that the con-

(4) HAAKON OLSEN, L. C. MAXIMON and H. WERGELAND: *Phys. Rev.*, **106**, 27 (1957) Note Sect. **4**, pp. 31, 32.

(5) This also follows from the fact that b is proportional to the imaginary part of the matrix element. Thus, since the first order Born approximation matrix element is real, only higher order Born approximations contribute to b. For a more detailed discussion see H. KOLBENSTVEDT and HAAKON OLSEN: *Nuovo Cimento*, **22**, 610 (1961); note Sect. **2** and Appendix A.

(6) The roles of electron and positron may of course be interchanged in the above discussion; this merely changes the sign of the asymmetry.

(7) The functions Φ_1 and Φ_2 of

$$\gamma = 100\,kZ^{-1/3}/\varepsilon_1\varepsilon_2\,,$$

are given in H. A. BETHE and W. HEITLER: *Proc. Roy. Soc.* (*London*), A **146**, 83 (1934) and ref. (2), pp. 900, 901.

tribution from the first order Born approximation is absent, as discussed above. The asymmetry is large for heavy elements: For Pb and completely circularly polarized photons it is 0.50 for $\varepsilon_1=\varepsilon_2$ and 0.57 when pair particles of all energies are observed.

We next consider some possible experimental applications. The sign and magnitude of the (transverse) polarization of the Σ^0 hyperon produced in the reaction $\pi^-+p^+\rightarrow\Sigma^0+K^0$ can be determined by measuring the circular polarization of the γ rays from the Σ^0 decay $\Sigma^0\rightarrow\Lambda^0+\gamma$ [8]. The circular polarization of the γ ray in the laboratory system is given by

$$(3)\qquad \boldsymbol{P}_{\text{ph}}=\frac{2M_\Sigma k}{M_\Sigma^2-M_\Lambda^2}(\boldsymbol{P}_\Sigma\cdot\hat{\boldsymbol{k}})\hat{\boldsymbol{k}}\,,$$

where M_Σ and M_Λ are the masses of the Σ^0 and Λ^0 hyperons, respectively, and $\boldsymbol{P}_\Sigma$ is the polarization of the Σ^0, the average spin of the Σ^0 in units of $\frac{1}{2}\hbar$.

Equation (3) is easily derived by looking at the Σ^0 decay in the system in which the Σ^0 is at rest. Take the z axis along the direction of the polarization of the Σ^0. The polarization P_Σ may be thought of as the difference in probabilities w_+ and w_- for the Σ^0 having z components of spin $+\frac{1}{2}\hbar$ and $-\frac{1}{2}\hbar$, respectively. Consider the case in which the photon is emitted in the direction of the positive z axis. From conservation of angular momentum it follows that when the z component of the spin of the Σ^0 is $+\frac{1}{2}\hbar$, then the z components of the photon spin and the Λ^0 spin are $+\hbar$ and $-\frac{1}{2}\hbar$, respectively, and conversely when the z component of the spin of the Σ^0 is $-\frac{1}{2}\hbar$ then the z components of the photon spin and the Λ^0 spin are $-\hbar$ and $+\frac{1}{2}\hbar$, respectively.

Thus in Σ^0 decay the probabilities for right and left circularly polarized photons are w_+ and w_- respectively, and thus $\boldsymbol{P}_{\text{ph}}=\boldsymbol{P}_\Sigma$. When the photon is not emitted in the direction of $\boldsymbol{P}_\Sigma$, then the circular polarization of the photon is given by the component of $\boldsymbol{P}_\Sigma$ along the momentum of the photon, $\boldsymbol{k}_{CM}$:

$$(4)\qquad \boldsymbol{P}_{\text{ph}}^{CM}=(\boldsymbol{P}_\Sigma\cdot\hat{\boldsymbol{k}}_{CM})\boldsymbol{k}_{CM}\,.$$

$\boldsymbol{k}_{CM}$ is the momentum of the photon in the system in which the Σ^0 is at rest. Performing a Lorentz transformation to the laboratory system and noting that the Σ^0 is transversely polarized, the photon polarization in the laboratory system is

$$(5)\qquad \boldsymbol{P}_{\text{ph}}=\frac{M_\Sigma}{E_\Sigma-\boldsymbol{p}_\Sigma\cdot\hat{\boldsymbol{k}}}(\boldsymbol{P}_\Sigma\cdot\hat{\boldsymbol{k}})\hat{\boldsymbol{k}}\,,$$

where E_Σ and $\boldsymbol{p}_\Sigma$ are the energy and momentum of the Σ^0, respectively. The factors of $(\boldsymbol{P}_\Sigma\cdot\hat{\boldsymbol{k}})\hat{\boldsymbol{k}}$ in eqs. (3) and (5) are easily seen to be equal by energy and momentum conservation.

Measurement of the polarization of the photon from the Σ^0 decay by observing the right-left electron emission asymmetry with respect to the positron plane, eq. (2), thus gives the possibility of determining both the magnitude and sign of the Σ^0 polarization.

As the efficiency of pair production as a polarisation analyser is proportional to Z it is important that the pair production should take place in the field of a heavy nucleus. On the other hand, from the lack of transverse polarization of Λ^0 hyperons produced in π^- collisions on Xe nuclei [9] it may be expected that in order to obtain sizeable Σ^0

(8) L. MICHEL and H. ROUHANINEJAD: *Phys. Rev.*, **122**, 242 (1961). Note Sect. **8**, p. 247.

(9) E. V. KUZNETSOV, I. A. IVANOVSKAYA, A. PROKESH and I. V. CHUVILO: *Tenth Annual International Conference on High-Energy Physics* (Rochester, 1960), p. 383.

polarization the Σ^0 production should take place in collisions of π mesons with light nuclei, preferably protons. Thus it seems that a propane bubble chamber with an admixture of CH_3I might be appropriate for this experiment ([10-12]). For iodine ($Z=53$) the asymmetry is 0.37 when pair particles of all energies are observed.

From the definition of the asymmetry it is apparent that the electron and positron must be distinguished. In other respects the experimental difficulties inherent in this method at high energies, viz., the accurate determination of the photon direction and the effect of multiple scattering of the pair particles, are the same as in measurements of the *linear* polarization of photons, for which the pertinent theory has been worked out by KARLSON ([13]) in connection with π^0 decay and by MICHEL and ROUHANINEJAD ([8]) in connection with Σ^0 decay.

Also the coefficient, α, of the correlation between the momentum of the π^- meson, $\boldsymbol{p}_\pi$, and the polarization $\boldsymbol{P}_\Lambda$ of the Λ^0 in Λ^0-decay, $\Lambda^0 \to \pi^- + p$, may be determined by the present method, as an alternative to the method utilizing the correlation between the momentum of Λ^0 and the spin of the decay proton ([14]). For simplicity we consider only the case of slow Σ^0 particles. The differences between the rest systems of the Σ^0 and Λ^0 and the laboratory system may then be neglected.

The angular distribution of the π^- meson relative to the polarization of the Λ^0 is of the form

$$1 + \alpha \hat{\boldsymbol{p}}_\pi \cdot \boldsymbol{P}_\Lambda \,. \tag{6}$$

From the discussion above it follows that $\boldsymbol{P}_\Lambda = \mp \boldsymbol{k}$, the upper and lower signs referring to right and left circularly polarized photons, respectively. Thus (6) becomes

$$1 \mp a \hat{\boldsymbol{p}}_\pi \cdot \hat{\boldsymbol{k}} \,.$$

Measurement of the correlation between the direction of motion of the π^- meson and the circular polarization of the γ ray may thus be used to determine the sign and magnitude of α.

Finally, it should be mentioned that the method may be applied to measurements of circular polarization of photons from π^0 decay, testing TP invariance in π^0 decay ([1-15]), and from K^0 decay, discussed recently by DREITLEIN and PRIMAKOFF ([16]).

([10]) D. V. BUGG in O. R. FRISCH: *Progress in Nuclear Physics*, vol. **7** (New York, 1959), p. 1. Note pp. 34, 35.

([11]) R. W. WILLIAMS: *Can. Journ. Phys.*, **37**, 1085 (1959).

([12]) Also for such a liquid the radiation length is reasonably small. See Table V in ref. ([10]) and Table I in ref. ([11]).

([13]) E. KARLSON: *Ark. Fys.*, **13**, 1 (1958).

([14]) T. D. LEE and C. N. YANG: *Phys. Rev.*, **108**, 1645 (1957); E. BOLDT, H. S. BRIDGE, D. O. CALDWELL and Y. PAL: *Phys. Rev. Lett.*, **1**, 256 (1958); R. W. BIRGE and W. B. FOWLER: *Phys. Sev. Lett.*, **5**, 254 (1960); J. LEITNER, L. GRAY, E. HART, S. LICHTMANN, J. WESTGARD, M. BLOCK, B. BRUCKER, A. ENGLER, R. GESSAROLI, A. KOVACS, T. KIKUCHI, C. MEITZER, H. O. COHN, W. BUGG, A. PEVSNER, P. SCHLEIN, M. MEER, N. T. GRIMELLINI, L. LENDINARA, L. MONARI and G. PUPPI: *Phys. Rev. Lett.*, **7**, 264 (1961); E. F. BEALL, B. CORK, D. KEEFE, P. G. MURPHY and W. A. WENZEL: *Phys. Rev. Lett.*, **7**, 285 (1961).

([15]) J. BERNSTEIN and L. MICHEL: *Phys. Rev.*, **118**, 871 (1960).

([16]) J. DREITLEIN and H. PRIMAKOFF: *Phys. Rev.*, **124**, 268 (1961).

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