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Scattering of Photons by Protons

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IN CONNECTION with the beginning of experimental investigation of the scattering of photons by protons,[1] we feel it would be of interest to examine this process, starting from the general properties of the S-matrix and elementary physical considerations. The purpose of the present note is to obtain information on the structure of the S-matrix and the minimum number of parameters necessary for describing the process in question.

We shall use the following approach to the problem. We write out the S-matrix in the representation in which its properties are most simply expressed, *i.e.*, in the representation of the total momentum I and its projection M, the total isotopic spin T and its projection T_z, and the parity Π. All the quantities are defined in the center-of-mass system

$$S_{\mu\nu} = (m'\alpha' \mid S^{I\Pi} \mid m\alpha)\ \delta_{(J'J)}\, \delta(M'M)\, \delta(\Pi'\Pi)\, \delta(T'_z T_z), \tag{1}$$

where the m's are the other variables characterizing the channel α. The S-matrix is examined on an energy surface. Next we enumerate all the open channels with the given energy (we restrict our examination to the region of energies under 300 Mev) and all quantum numbers characterizing these channels. In our analysis we shall examine only the following α channels: γ-quantum and proton (γ) and π-meson and nucleon (π). Taking account of the other channels would not substantially affect our results. It must be noted, however, that the channel with the formation of an electron-positron pair is an exception; the matrix element of the S-matrix describing the transition in this channel is not small.

Actually the process of pair formation leads to so-called scattering in the Coulomb field. However, this process, as has been shown by Bethe and Rohrlich,[2] is characterized by a sharply limited forward angular distribution. It can be shown that if we do not consider scattering angles of the order of $m_e c^2/E_\gamma$ this effect can be neglected.

Let us impose the requirements of unitarity and symmetry on the S-matrix.

$$SS^+ = 1,\ S_{\mu\nu} = S_{\nu\mu};\ S_{\mu\nu} = r_{\mu\nu} e^{i\varphi_{\mu\nu}}. \tag{2}$$

Each of the indices μ and ν goes through eight values. The first condition in (2) is of course approximated with an accuracy equal to the value of the matrix elements describing the transitions in the rejected channels. The second condition in (2) is a consequence of the reciprocity theorem[3] and of the fact that the selected representation does not comprise projections of spins and directions of velocities. These conditions represent the system of transcendental equations which $\alpha_{\mu\nu}$ and $r_{\mu\nu}$ must satisfy. Before attempting to solve the system, we make two simple assumptions which actually follow from experiment: (1) we use the long-wave approximation, whereby we consider the interaction of only dipole quanta (electric and magnetic) with the proton and (2) we assume that the moduli of the matrix elements linking channels γ and γ', γ and π and π with π' are related, respectively, as

$$e^2/\hbar c : \sqrt{e^2/\hbar c} : 1. \tag{3}$$

Part of the S-matrix describing the meson scattering contains isotopic invariant terms regarding which we also assume that they are of the order of $e^2/\hbar c$. The first assumption follows, for example, from experiments on electron-nucleon scattering which show that the dimensions of a nucleon are less than $\hbar/\mu c$ (*i.e.*, smaller than the photon wavelength at the energies under consideration) and also from experiments on scattering and photoproduction of mesons.

The last approximation makes it possible to solve the system of equations by the method of successive approximations, expressing $\alpha_{\mu\nu}$ and $r_{\mu\mu}$ in terms $\alpha_{\mu\mu}$ and $r_{\mu\nu}$, where $\mu \neq \nu$. The ratios between the scattering and photoproduction matrix element obtained in the calculations agree within the limit of small corrections with analogous ratios obtained by Watson.[4] In order to obtain the angular distribution of the scattered photons one must bring the S-matrix to the angular representation, square its modulus, average over the initial and sum over the final spin states of the nucleons and polarizations of the photons. However, we can make direct use of the results of Morita, Sugie and Yoshida[5] who deduced a general expression for the differential cross section for photon scattering from a particle with an arbitrary spin, but without examining the conditions of (2):

$$\frac{d\sigma}{d\Omega}=\frac{1}{32k_{\gamma}^{2}}\{[4\,|X|^2-2\,\mathrm{Re}\,X^*Y+7\,|Y|^2+4\,|Z|^2-2\,\mathrm{Re}\,Z^*Y+7\,|W|^2]$$

$$+4\,\mathrm{Re}\,[X^*(2Z+W)+Y^*(Z+5W)]\cos\theta+3\,[2\,\mathrm{Re}\,X^*Y+|Y|^2+2\,\mathrm{Re}\,Z^*W+|W|^2]\cos^2\theta\}, \quad (4)$$

$$X=(11\ \gamma\,|\,R^{1/2-}\,|\,11\ \gamma),\ Y=(11\ \gamma\,|\,R^{3/2-}\,|\,11\ \gamma),\ Z=(10\ \gamma\,|\,R^{1/2+}\,|\,10\ \gamma),$$

$$W=(10\,\gamma\,|\,R^{3/2+}\,|\,10\ \gamma), \quad (4a)$$

$$R=S-1. \quad (4b)$$

Here X, Y, Z and W are the matrix element of the matrix $(L'p'\alpha'\,|\,R^{J\,\mathrm{II}}\,|\,Lp\alpha)$, where L is the total moment of the photon, p is a parity symbol which has a value of 0 for magnetic radiation, and a value of 1 for electric radiation. The remaining notation is clear from what has been said above.

Solution of the system of equations yields the following expressions for the matrix elements:

$$X+1=\sqrt{1-r_1^2-r_2^2}\,e^{i\gamma}\approx 1-{}^1/_2\,r_1^2-{}^1/_2 r_2^2+i\gamma,$$

$$Y+1=\sqrt{1-\rho_1^2-\rho_2^2}\,e^{i\delta}\approx 1-{}^1/_2\rho_1^2-{}^1/_2\rho_2^2+i\delta,$$

$$Z+1=\sqrt{1-r_3^2-r_4^2}\,e^{i\alpha}\approx 1-{}^1/_2\,r_3^2-{}^1/_2\,r_4^2+i\alpha, \quad (5)$$

$$W+1=\sqrt{1-\rho_3^2-\rho_4^2}\,e^{i\beta}\approx 1-{}^1/_2\,\rho_3^2-{}^1/_2\,\rho_4^2+i\beta,$$

where α, β, γ and δ are real parameters and r_i and ρ_k are moduli of the matrix elements of meson photoproduction. At γ-quanta energies below the photoproduction thresholds, they vanish:

$$r_1=\left|\left(11\gamma\,|\,S^{1/2-}\,|\,0\tfrac{1}{2}\,\pi\right)\right|,\quad r_2=\left|\left(11\gamma\,|\,S^{1/2-}\,|\,0\tfrac{3}{2}\,\pi\right)\right|,\quad r_3=\left|\left(10\gamma\,|\,S^{1/2+}\,|\,1\tfrac{1}{2}\,\pi\right)\right|,$$

$$r_4=\left|\left(10\gamma\,|\,S^{1/2+}\,|\,1\tfrac{3}{2}\,\pi\right)\right|$$

$$\rho_1=\left|\left(11\gamma\,|\,S^{3/2-}\,|\,2\,\tfrac{1}{2}\pi\right)\right|,\quad \rho_2=\left|\left(11\gamma\,|\,S^{3/2-}\,|\,2\,\tfrac{3}{2}\,\pi\right)\right|, \quad (5a)$$

$$\rho_3=\left|\left(10\gamma\,|\,S^{3/2+}\,|\,1\,\tfrac{1}{2}\,\pi\right)\right|\quad \rho_4=|\,(10\,\gamma\,|\,S^{3/2+}\,|\,1\tfrac{3}{2}\,\pi)\,|.$$

The arrangement of indices in Eqs. (5a) is the following: $S_{m'm}=(Lp\alpha'\,|\,S^{J\,\mathrm{II}}\,|\,lT\alpha)$, where l is the relative orbital momentum in channel α. Expansion of the exponents and roots is allowable inasmuch as it is known from experiments that the total cross section for the Compton effect on protons is of the order of 10^{-31} cm^2. It is interesting to note that the differential cross section for the process under consideration subdivides into two parts $f_1(\theta)$ and $f_2(\theta)$, of which the former depends on α, β, γ, and δ, and the latter on r_i and ρ_k. This follows directly from formula (5) and the general expression for the differential cross section (4). Thus, by determining experimentally the coefficients A, B and C characterizing the angular distribution of the photons,

$$d\sigma\,/\,d\Omega=(1\,/\,32\ k_{\gamma}^2)\,(A+B\cos\theta+C\cos^2\theta), \quad (6)$$

we will not be able to find α, β, γ and δ inasmuch as we will obtain three equations with four unknowns. We assume that r_i and ρ_k can be determined from experimental data on photomeson production on nucleons. Consequently, for unambiguous determination of the parameters α, β, γ and δ we must have additional data. These can be obtained from experiments with polarized particles. We might also call attention to another possible effect, *viz.* the interference of ordinary scattering with scattering in the Coulomb field. This effect might be detected in investigating small angle scattering of photons.

It would be expedient to examine separately the case of small energies, *i.e.*, the region in which the cross section differs little from the cross section given by Thomson's formula. In this case we can write

$$\alpha = \Delta_1, \ \beta = \Delta_2, \ \gamma = \Delta_3 + a, \ \delta = \Delta_4 + a. \qquad (7)$$

If $\Delta_i = 0$, Eq. (4) with $a^2 = (16/9)k_\gamma^2(e^2/Mc^2)$ goes over into Thomson's formula

$$d\sigma/d\Omega = {}^1/_2(e^2/Mc^2)^2(1+\cos^2\theta). \qquad (8)$$

If we express X, Y, Z and W in (4) in terms of Δ_i and a and neglect the terms $\Delta_i\Delta_k$, we obtain

$$d\sigma / d\Omega = (1/32\, k_\gamma^2)[(9a^2 + 6\bar{X}a)(1+\cos^2\theta) + 12\, a\bar{Y}\cos\theta]. \qquad (9)$$

Here $$\bar{X} = \Delta_3 + 2\Delta_4, \ \bar{Y} = \Delta_1 + 2\Delta_2. \qquad (9a)$$

Comparison of Eq. (9) with experiment should make it possible to check the assumptions made in deriving it and enable us to determine $\bar{X}$ and $\bar{Y}$, which is important inasmuch as $\bar{X}$ is expressed only through quantities connected with electric radiation, while $\bar{Y}$ is expressed only through quantities connected with magnetic radiation.

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Use of a Mixture of Two Liquids in Bubble Chambers

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AS THE SIZE of bubble chambers is increased, the technical difficulties involved in their operation become ever greater in view of the necessity of producing and maintaining the temperatures and pressures approprite to the liquid employed. These difficulties could be largely obviated if it were possible to work at close to room temperature. Of the substances employed in bubble chambers hitherto, the two having a working temperature closest to room temperature are propane ($t_{\text{work}} \approx 64°$ C) and Freon-13 ($t_{\text{work}} \approx 0°$ C). We assumed that a convenient working temperature could be obtained by using appropriate mixtures of two liquids.

For the purpose of exploring the possibility of employing mixtures we carried out a series of experiments with a bubble chambe filled with a mixture of Freon-12 (CCl_2F_2) and Freon-13 ($CClF_3$). For Freon-12 the critical temperature and pressure are 111.5° C and 39.6 atmospheres; for Freon-13 the respective values are 28.8° C and 39.4 atmospheres. The chamber described in an earlier communication[1] was used for the tests. Inasmuch as this chamber has a pressure-actuated device for limiting the expansion, the sensitivity of the chamber was controlled by varying the lower level of the pressure drop at constant temperature. With a Co^{60} γ-source mounted in front of the chamber window it was possible to observe and photograph the electron tracks and establish at what temperature, pressures and concentrations observation of the tracks was feasible.

We used two different mixtures, containing about 40 and 75 percent molar Freon-12. In the first case the pressure of the saturated vapor of the mixture was 21 atmospheres at 19° C; in the second case 21.6 atmospheres at 43° C. The temperatures and pressures at which particle tracks could be observed in each case are shown in Fig. 1. The tests were carried out at temperatures ranging from 19 to 38° C for the first mixture and from 43 to 52° C for the second. Curves 1 and 5 in the figure are drawn through the points corresponding to the sensitivity threshold. With pressure drops to a lower level there was observed an increase in sensitivity (shaded areas in figure). Curves 3 and 6 denote the lower boundary of the pressure drops. At these pressures fog was