Elastic scattering of low-energy photons by protons, and electromagnetic polarizability of the proton

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We measured the differential cross section for elastic scattering of photons by protons at angles 90° and 150° in the energy interval from 70 to 110 MeV. The experimental data were used to determine the coefficients of the electric and magnetic polarizabilities of the proton, $\bar{\alpha}=(10.7\pm1.1)\times10^{-43}$ cm^3 and $\bar{\beta}=(-0.7\pm1.6)\times10^{-43}$ cm^3, respectively.

Measurements of the differential cross section of elastic scattering of photons by protons were carried out with the synchrotron of our Institute at maximum bremsstrahlung spectrum energies 127 and 148 MeV. The investigated process $\gamma+P\to\gamma+P$ was separated by registering the scattered photons. The target dimensions and the angular and energy intervals were chosen such as to practically eliminate the influence of the background process. The main difficulty in the organization of the experiment was the need for ensuring a 1–2% accuracy in the absolutization of the measured cross sections, since the contribution of the structure corrections for the photon polarizability to the differential cross section amounted to 15–20% at a photon energy 100 MeV and at photon scattering angles $\theta=90$–150°. Direct methods of measuring the absolute cross sections at this accuracy are difficult because of a number of errors connected with measurements of the intensity and the shape of the incident-photon spectrum, the registration efficiency, etc. Most of these errors can be eliminated by registering in succession, using one and the same γ telescope in identical energy intervals, two processes: the main process $\gamma+P\to\gamma+P$, and a monitoring process $\gamma+e\to\gamma+e$ whose cross section can be calculated with the necessary accuracy. The differential cross section of the monitoring process $\gamma+e\to\gamma+e$ was measured at an angle 1°46′, corresponding to the best agreement with the kinematic conditions of the registration of the main process $\gamma+P\to\gamma+P$ at an angle $\theta=90°$. A detailed description of the experiment will be published later. The differential cross section of the monitoring process was calculated by the Klein-Nishina-Tamm formula with account taken in the lowest order in $\alpha=1/137$, of the radiative corrections for the emission of the additional hard photon. [1] The need for taking into account the latter correction is dictated by the fact that the energy interval of the registered photons was approximately 40 MeV. The calculations were made with a computer and took into account the geometry of the experiment, the variant of the assembly of the γ telescope (I or II), the shape of the bremsstrahlung spectrum, and the energy dependence of the efficiency of the γ telescope. The table lists the experimental results for the cross section $d\sigma/d\Omega=f(\gamma+P\to\gamma+P)$, absolutized relative to the cross section $d\sigma/d\Omega=f(\gamma+e\to\gamma+e)$. The error in the values of the cross sections take into account the random measurement and reduction errors, and the small systematic error (about 1%) of the absolutization of the cross sections against the monitoring process. The value of the cross section $d\sigma/d\Omega=f(\gamma+P\to\gamma+P)$ obtained in the present paper agree with the values given in other papers (see, e.g., the review[2]), but the total errors are much smaller.

Experimental results for elastic scattering of photons by protons, absolutized against a monitor process.

Variant of assembly of telescope	θ, lab system, deg.	ω, MeV	Ratio of cross sections of the main and of the minotor process	$\frac{d\sigma}{d\Omega}\,10^{32}$ cm²/sr
I	90	85.4	$(1.52\pm0.05)\cdot10^{-7}$	1.09 ± 0.04
II	90	80.9	$(1.60\pm0.09)\cdot10^{-7}$	1.15 ± 0.06
I	150	86.3	$(1.92\pm0.14)\cdot10^{-7}$	1.37 ± 0.20
II	150	81.9	$(2.02\pm0.17)\cdot10^{-7}$	1.44 ± 0.12
I	90	109.9	$(1.44\pm0.07)\cdot10^{-7}$	1.03 ± 0.06
I	150	111.1	$(2.02\pm0.06)\cdot10^{-7}$	1.44 ± 0.06
II	150	106.7	$(2.22\pm0.09)\cdot10^{-7}$	1.60 ± 0.08

The differential cross section for the elastic scattering of a photon by a proton in the laboratory system, expanded in the energy ω of the incident photon ($\hbar=c=1$) with allowance of the ω^3 terms, is given by[3–5]:

$$\frac{d\sigma}{d\Omega}=\left(\frac{d\sigma}{d\Omega}\right)^{\text{point}}-\frac{e^2}{M}\omega^2[\bar{\alpha}(1+\cos^2\theta)+2\bar{\beta}\cos\theta]\times\left[1-3\frac{\omega}{M}(1-\cos\theta)\right]+0(\omega^4), \tag{1}$$

where

$$\left(\frac{d\sigma}{d\Omega}\right)^{\text{point}}=\frac{1}{2}\left(\frac{e^2}{M}\right)^2\left\{\left[1-2\frac{\omega}{M}(1-\cos\theta)+3\left(\frac{\omega}{M}\right)^2(1-\cos\theta)^2-4\left(\frac{\omega}{M}\right)^3(1-\cos\theta)^3\right](1+\cos^2\theta)+\left(\frac{\omega}{M}\right)^2[(1-\cos\theta)^2+f(\theta)]\times\left[1-3\frac{\omega}{M}(1-\cos\theta)\right]\right\};$$

$$f(\theta)=a_o+a_1\cos\theta+a_2\cos^2\theta$$

$$a_o=2\lambda+\frac{9}{2}\lambda^2+3\lambda^3+\frac{3}{4}\lambda^4;$$

$$a_1=-4\lambda-5\lambda^2-2\lambda^3;$$

$$a_2=2\lambda+\frac{1}{2}\lambda^2-\lambda^3-\frac{1}{4}\lambda^4;$$

In Eq. (1), e, M, and λ are the charge, mass, and the anomalous magnetic moment of the proton (in nuclear magnetons), $\bar{\alpha}$ and $\bar{\beta}$ are generalized coefficients of the electric magnetic polarizability of the proton, respectively, and θ is the photon scattering angle. The first term in (1) is the cross section for the scattering of the photon by a pointlike charged particle with spin 1/2 and an anomalous magnetic moment λ,[6] and the second term is the structure correction for the proton polarizability. Approximating the experimental data by formula (1), we obtain the following values of the polarizability coefficients: $\bar{\alpha}^{\mathrm{exp}} = (10.7 \pm 1.1) \times 10^{-43}$ cm^3, and $\bar{\beta}^{\mathrm{exp}} = (-0.7 \pm 1.6) \times 10^{-43}$ cm^3. The errors in $\bar{\alpha}^{\mathrm{exp}}$ and $\bar{\beta}^{\mathrm{exp}}$ are determined by the total errors of the cross section $(d\sigma/d\Omega)(\gamma + P \to \gamma + P)$. It is assumed here that the contribution of the terms discarded in (1) is small. An estimate with the aid of the Kramers-Kronig dispersion relation[7] for the forward scattering amplitude of the photon has shown that their contribution to the cross section (1) at $\omega = 100$ MeV and $\theta = 0°$ is less than 2%.

Let us compare the sum $(\bar{\alpha} + \bar{\beta})^{\mathrm{exp}} = (10.0 \pm 2.3) \times 10^{-43}$ cm^3 (the error was calculated with allowance for the correlations of the values of $\bar{\alpha}^{\mathrm{exp}}$ and $\bar{\beta}^{\mathrm{exp}}$), with the theoretical values given by the sum rule

$$(\bar{\alpha} + \bar{\beta})^{\mathrm{theor}} = \frac{1}{2\pi^2} \int_{\omega_{\mathrm{thr}}}^{\infty} \frac{\sigma(\omega)}{\omega^2} d\omega, \qquad (2)$$

which is the consequence of the Kramer-Kronig dispersion relation and of the definition of the coefficients $\bar{\alpha}$ and $\bar{\beta}$.[8,9] In Eq. (2), $\sigma(\omega)$ is the total cross section of the hadronic photoabsorption by a proton. Substituting in (2) the experimental data on the total cross section up to $\omega = 30$ GeV and the usual Regge extrapolation into the region at higher energies,[10,11] we obtain $(\bar{\alpha} + \bar{\beta})^{\mathrm{theor}} = (14.1 \pm 0.3) \times 10^{-43}$ cm^3.

Thus, there is a small excess (about two standard deviations) of the theoretical $(\bar{\alpha} + \bar{\beta})$ over the experimental one: $(\bar{\alpha} + \bar{\beta})^{\mathrm{theor}} - (\bar{\alpha} + \bar{\beta})^{\mathrm{exp}} = (4.1 \pm 2.3) \times 10^{-43}$ cm^3. If this excess is taken seriously, then it must be borne in mind that it is larger than the possible contribution to $\bar{\alpha} + \bar{\beta}$ of a fixed pole with $I = 2$, bounded from above by the quantity 0.25×10^{-43} cm^3.[12,13]

The experimental values of $\bar{\alpha}$ and $\bar{\beta}$ are in good agreement with the results of a calculation based on the dispersion relations for six amplitudes: $\bar{\alpha}^{\mathrm{theor}} = 10.4 \times 10^{-43}$ cm^3 and $\bar{\beta}^{\mathrm{theor}} = 0.7 \times 10^{-43}$ cm^3.[14] These theoretical values differ strongly from the values obtained in[15] on the basis of two dispersion relations for the forward and backward scattering amplitudes.

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1K. Mork, Phys. Rev. **4A**, 917 (1971).
2P. Barranov, L. Filkov, and G. Sokol, Fortschritte der Phys. **16**, 595 (1968).
3V. A. Petrun'kin, Zh. Eksp. Teor. Fiz. **40**, 1148 (1961) [Sov. Phys.-JETP **13**, 808 (1961)].
4V. Barashenkov, H. Kaiser, and A. Ogreba, Phys. Lett. **2**, 33 (1962).
5V. A. Petrun'kin, Trudy FIAN **41**, 165 (1967).
6J. Powell, Phys. Rev. **75**, 32 (1949).
7M. Gell-Mann, M. Goldberger, and W. Thirring, Phys. Rev. **95**, 1612 (1954).
8A. Baldin, Nucl. Phys. **18**, 310 (1960).
9L. I. Lapidus, Zh. Eksp. Teor. Fiz. **43**, 1358 (1962) [Sov. Phys.-JETP **16**, 964 (1963)].
10P. Joos, Preprint DESY-HERA 70-1, September, 1970.
11A. Belousov *et al.*, Preprint 19, Lebedev Phys. Inst. 1973.
12S. Drell, Comments Nucl. and Part. Phys. **1**, 196 (1967).
13J. Walker, Phys. Rev. Lett. **21**, 1618 (1968).
14V. K. Fedyanin, Zh. Eksp. Teor. Fiz. **44**, 633 (1963) [Sov. Phys.-JETP **17**, 429 (1963)].
15J. Bernabeu, T. Ericson, and C. Ferro Fontan, Preprint TH 1804-CERN, 1974.