dent that H_2 does not alter greatly at a minimum of the rosette, while at a maximum the value of $\Delta\Phi(H)/\Delta\Phi(0)$ first strongly increases and then tends to saturation. The measured maximum value of H_2 is in good agreement with that calculated for the case of concentration of the current lines in the sector denoted by T in Fig. 4. A random distribution of semicircular grooves (radii 0.5—1 mm), produced by means of a chemical "knife," almost completely destroyed the effect (Fig. 5), indicating the importance of the role of surface quality in the observed phenomenon.

The author expresses his deep gratitude to B. G. Lazarev and V. I. Khotkevich for valuable discussions and M. Ya. Azbel' for his interest in this work.

---

1) The technique of growing single crystals with an inner channel from easily melted metals, and the technique of chemical treatment for reduction to the required dimensions will be reported in a separate communication.

[1] M. Ya. Azbel', JETP **44**, 983 (1963), Soviet Phys. JETP **17**, 667 (1963).

[2] B. N. Aleksandrov, JETP **43**, 399 (1962), Soviet Phys. JETP **16**, 286 (1963).

Translated by A. Tybulewicz
206

MEASUREMENT OF THE CROSS SECTION OF THE REACTION $C^{12}(p, pn)C^{11}$ *AT* 9 BeV

B. I. BEKKER, V. S. PANTUEV, V. A. SVIRIDOV, and M. N. KHACHATURYAN

Joint Institute for Nuclear Research

Submitted to JETP editor July 20, 1963

J. Exptl. Theoret. Phys. (U.S.S.R.) **45**, 1269-1270 (October, 1963)

A determination of the proton flux inside an accelerator is necessary for the performance of many experiments [1]. The reaction $C^{12}(p, pn)C^{11}$ can be used for this purpose. The presently available data on this reaction pertain for the most part to the energy range up to 6 BeV [2-4].

We have measured the cross section of this reaction for 9.0-BeV protons, using 3 × 3 × 3 cm plastic-scintillator plates. The emulsion was placed to the rear of the scintillator. The plastic was exposed together with the emulsion to a spatially-dispersed proton beam inside the accelerator vacuum chamber. The total proton flux was $\sim 2 \times 10^6$ protons/cm^2 and was determined by counting tracks in an emulsion 200 μ thick. The contribution of the secondary particles in the emulsion was determined by measuring the angular distribution of the beam. Tracks with inclination up to ±45° were classified as primary. The estimated contribution of the secondary particles is 1.5%. The corresponding correction, accounting for the protons knocked out of the beam by interactions in the scintillator, is 5.5%.

To estimate the contribution of the secondary particles participating in the production of the C^{11} nuclei, a separate experiment was set up, in which three plastic scintillators in tandem, each measuring 3 × 3 × 1 cm, were exposed to the proton beam. It was found that 16% of the C^{11} nuclei were produced by the secondary particles. The number of C^{11} nuclei produced was determined with the aid of scintillation counters by measuring the β^+ activity of the C^{11} nuclei ($C^{11} \rightarrow \beta^+ + B^{11} + \nu$). The proton-activated sample was placed between two photomultipliers connected for double coincidence with a resolution 10^{-8} sec. The third counter with NaI(Tl) recorded the gamma quanta resulting from the annihilation of the positrons in the scintillator material [5]. The system described made it possible at the same time to measure the β-particle counting efficiency, which was found to be (95 ± 0.5)% in the experiment.

Three exposures yielded cross section values 25.2, 26.1, and 27.2 mb with a statistical error $\Delta\sigma = 1.0$ mb. The systematic measurement error is ~ 4%. Taking all errors into account, the final value is $\sigma = 26.2 \pm 1.5$ mb.

The table lists the cross sections of the $C^{12}(p, pn)C^{11}$ reaction in the BeV energy region.

It is seen from the table that our cross section agrees well with the values obtained by others, and confirms that the cross section of the $C^{12}(p, pn)C^{11}$ reaction is constant in the energy interval from 2 to 28 BeV.

In conclusion, the authors consider it their pleasant duty to thank the scientists M. G. Shafranova and L. Strunov of the High-energy Laboratory for help with the measurement and for useful discussions.

E, BeV	σ, mb	E, BeV	σ, mb
2.0	26.2±0,9[2]	6.0	29.5±1.6[3]
3.0	26,8±1.0[2]	9.0	26.2±1.5 present work
3,0	29.5±1.6[3]		
4,5; 27	27.4±1.4[3]	28.0	25.9±1.2[4]

---

[1] Bekker, Kirillova, Nomofilov, Nikitin, Pantuev, Sviridov, Strunov, Khachaturian, and Shafranova, International Conference on High-energy Physics at CERN, 1962.

[2] Cumming, Friedlander, and Swartz, Phys. Rev. **111**, 1386 (1958).

[3] N. Horwitz and J. J. Murray, Phys. Rev. **117**, 1361 (1960).

[4] Cumming, Friedlander, and Katcoff, Phys. Rev. **125**, 2078 (1962).

[5] J. B. Cumming and R. Hoffman, Rev. Sci. Instr. **29**, 1104 (1958).

Translated by J. G. Adashko
207

THE SCATTERING OF LIGHT BY LIGHT

V. M. ARUTYUNYAN, F. R. ARUTYUNYAN,
K. A. ISPIRYAN, and V. A. TUMANYAN

State Atomic Energy Comm. Institute, Erevan

Submitted to JETP editor July 30, 1963

J. Exptl. Theoret. Phys. (U.S.S.R.) **45**, 1270-1272 (October, 1963)

It is well known that in classical electrodynamics as a direct consequence of the linearity of Maxwell's equations, waves propagate independently of one another. Quantum effects of the interaction of electromagnetic waves with the vacuum electron-positron field lead to the nonlinear effect of photon-photon scattering. The theoretical problem of the scattering of light by light has been solved in a number of papers.[1-3] A number of attempts were made to observe the effect experimentally.[4] There has, however, been no success in discovering the scattering of light by light: this is explained by the extremely small value of the cross section for such a process.

In the range of frequencies $\omega \ll m$ (m is the electron mass) a quantum electrodynamic calculation gives for the value of the cross section, in the center of mass system,

$$d\sigma = \frac{1}{(2\pi)^2}\frac{139}{90^2}\alpha^4\frac{1}{m^2}\left(\frac{\omega}{m}\right)^6(3+\cos^2\theta_0)^2\,d\Omega, \tag{1}$$

where $\alpha = 1/137$ and θ_0 is the scattering angle ($\hbar = c = 1$). It is easy to see that in the optical range of frequencies the cross section has an insignificant value ($\approx 10^{-64}$ cm^2) and therefore, despite the existence of powerful sources of optical photons, experimental observation of the scattering of light by light in this range of frequencies is extremely difficult.[5]

Because the cross section increases sharply with increasing frequency, it appears hopeful that this interesting process might be observed experimentally at high frequencies. In particular, the cross section attains a value $\sigma \approx 10^{-35}$ cm^2 for $\omega \approx 10^5$ eV. Such frequencies can be realized when γ quanta with energies of several BeV are scattered by optical photons, a preferable source of which can be modern optical quantum generators.

If the energies of the colliding photons in the laboratory system are ω_1 and ω_2, where $\omega_1 \gg \omega_2$, the photon-photon scattering cross section integrated with respect to the scattered photons up to some value ω_3 will be

$$\sigma = \frac{16}{\pi}\frac{139}{90^2}\alpha^4\frac{1}{m^2}\frac{\omega_1^3\omega_2^3}{m^6}\frac{\omega_3}{\omega_1}. \tag{2}$$

For $\omega_1 = 6 \times 10^9$ eV and $\omega_2 = 1.78$ eV (the photon energy of a ruby laser) the cross section will be

$$\sigma = 2.56\cdot 10^{-35}\,\omega_3/\omega_1,\ \text{cm}^2. \tag{3}$$

The frequency of the scattered photon is given in terms of the scattering angle in the laboratory system by:

$$\omega_3 = \frac{2\omega_1\omega_2}{(\omega_1+\omega_2)-(\omega_1-\omega_2)\cos\theta}. \tag{4}$$

It follows from (3) and (4) that the principal contribution to the cross section is provided by scattered photons with large energies, where these photons are scattered mainly inside very small angles relative to the direction of the photon with energy ω_1. For example, when scattered photons with energies up to $\omega_3 = 500$ MeV are recorded, the cross section is $\sigma = 2.1 \times 10^{-36}$ cm^2. The angle within which the scattered photons are emitted increases with diminishing energy, and is 1.2×10^{-4} for $\omega_3 = 500$ MeV.

We estimate the number of recorded events which can be obtained when beams of γ quanta from modern high energy electron accelerators and the most intense beams of laser photons are used. If γ quanta with energies $\omega_1 = 5$—6 BeV are used, created by electrons with 6 BeV energy (the number of electrons in a pulse of length 10^{-6} sec is 10^{11}; the cross section of the electron beam is 0.03 cm^2), and photons generated by a ruby laser with 500 joules energy[6] with a flash length of 10^{-6} sec are used (the number of photons in the laser flash will be 2×10^{21}), then the frequency of recorded events when the laser is worked with a