A SEARCH FOR BREMSSTRAHLUNG PRODUCED IN ELASTIC SCATTERING OF NEGATIVE PIONS BY PROTONS

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In 1500 cases of elastic scattering of 128- and 162-Mev π^- mesons in a hydrogen-filled cloud chamber, no cases were found in which the angle of emission of the recoil proton exceeded the angle calculated from the conservation laws by more than 3°. On this basis, it was found that the upper limit for the bremsstrahlung cross section for π^- mesons scattered by nuclei is 5×10^{-29} cm^2.

1. INTRODUCTION

THE emission of bremsstrahlung by π mesons in a nuclear force field has been considered from the theoretical viewpoint.[1-5] In particular, Solov'ev[2] used perturbation theory to calculate the angular and energy distributions of the γ quanta and the total cross section for the process $\pi^- + p \rightarrow \pi^- + p + \gamma$ for a π^--meson kinetic energy close to the π-meson rest mass. The theory has been further developed by Low,[3] who showed that one can calculate in general form not only the first term of the expansion of the differential cross section in powers of the γ-quantum energy (as was done by Solov'ev[2]), but also the second term, which contains derivatives of the nonradiative scattering amplitude with respect to the energies and angles. This theory was used by Cutkosky[4,5] to calculate, in the fixed-nucleon approximation model, the basic characteristics of bremsstrahlung emission by π^+ mesons of energy close to 200 Mev scattered by protons. In particular, it was shown[5] that the high-energy γ-quantum intensity is smaller than that determined from perturbation theory.[2]

The emission of bremsstrahlung by π^+ mesons has been studied experimentally in the 80 — 300 Mev range in a freon bubble chamber.[6] On the basis of 25 observed cases of bremsstrahlung emission, the cross section for the process was found to be about 7×10^{-27} cm^2 in the case of the fluorine nucleus, which is in satisfactory agreement with the theoretical estimates. We recently learned of the results obtained by Deahl et al,[7] who studied elastic scattering of 225-Mev π^- mesons by protons (1570 cases) in a liquid-hydrogen bubble chamber. They observed five cases of bremsstrahlung of energy $E_{\gamma \text{lab}} > 50$ Mev, which corresponds to a cross section of 5×10^{-29} cm^2.

In the present experiment we have attempted to estimate the bremsstrahlung cross section in elastic scattering of 128- and 162-Mev π^- mesons by protons in a hydrogen-filled cloud chamber.

2. METHOD AND RESULTS

In a previous experiment,[8] we studied the elastic scattering of π^- mesons by protons in a cloud chamber operating at a hydrogen pressure of 23 atm in a magnetic field of 9000 oe. In 90 000 stereophotographs we found 385 and 1136 cases of elastic scattering for pion kinetic energies E_0 of 128 ± 8 and 162 ± 10 Mev, respectively. Since most of the γ quanta from the process $\pi^- + p \rightarrow \pi^- + p + \gamma$ should be of low energy, it was not possible to separate the cases of radiative scattering by means of measurements in which the scattered π^--meson and recoil-proton momenta are determined from the radii of curvature or by measurements of the noncoplanarity angle, since the accuracy of measurement of these quantities is of the same order as the expected variation. (If, however, the proton momentum is determined from the range, then the accuracy of the momentum measurement is 2.5% when the range measurement error is 10%.)

Hence, to search for cases of bremsstrahlung, we employed measurements of the quantity

$$\Delta\theta = \theta_p^{\text{obs}} - \theta_p^{\text{calc}}(\theta_\pi^{\text{obs}}), \qquad (1)$$

i.e., the difference between the measured recoil-proton angle θ_p^{obs} and the proton angle $\theta_p^{\text{calc}}(\theta_\pi^{\text{obs}})$ corresponding to the kinematical conditions for elastic scattering of a π meson by the measured angle θ_π^{obs}. From the total number of cases of scattering at the two energies, we selected cases satisfying certain criteria based on the following: a) the angle between the scattering plane and the horizontal should be less than 60°; b) the length of the projection of each of the three tracks on the horizontal plane should be greater than 2 cm; in those cases in which the proton range could be determined, the length of the range should be at least 5 mm; c) the incident π^- meson should not be deflected from the basic beam direction by more than 5°.

A total of 844 cases satisfied the selection criteria. For these cases, we measured simultaneously the angles θ_p and θ_π on a reprojector; the measurements were always made in the azimuthal plane which simultaneously coincided best with the projections of the scattered π-meson and proton tracks on the reprojector screen. The histogram of Fig. 1 represents the distribution of all measured cases of elastic scattering as a function of the quantity $\Delta\theta$. The smooth curve represents the normal distribution $A \exp[-(\Delta\theta)^2/2\delta^2]$ with a standard deviation of $\delta = 0.7°$. As seen from Fig. 1, no cases of elastic scattering were observed with $\Delta\theta > 3°$.

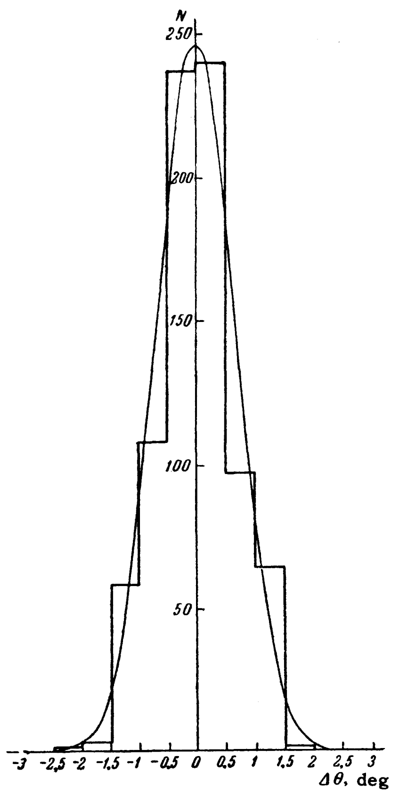

FIG. 1. Experimental distribution of cases of elastic scattering as a function of the quantity $\Delta\theta$ in the laboratory system. The smooth curve represents the normal distribution with a standard deviation of 0.7°.

Figure 2 represents the c.m.s. momentum distribution of the protons for cases in which this momentum could be determined from the measured range of the proton (the total number of cases at the two energies was 112). The numbers beside the arrows indicate the proton momentum for elastic π^-p scattering at the given meson energy. These distributions also indicate the absence of bremsstrahlung, since no cases with smaller momentum were found, within the limits of error of the measurements. (For example, for $E_\gamma = 20$ Mev, the c.m.s. proton momentum for the process $\pi^- + p \rightarrow \pi^- + p + \gamma$ should have values from 201 to 170 Mev/c for $E_0 = 162$ and from 176 to 143 Mev/c for $E_0 = 128$ Mev).

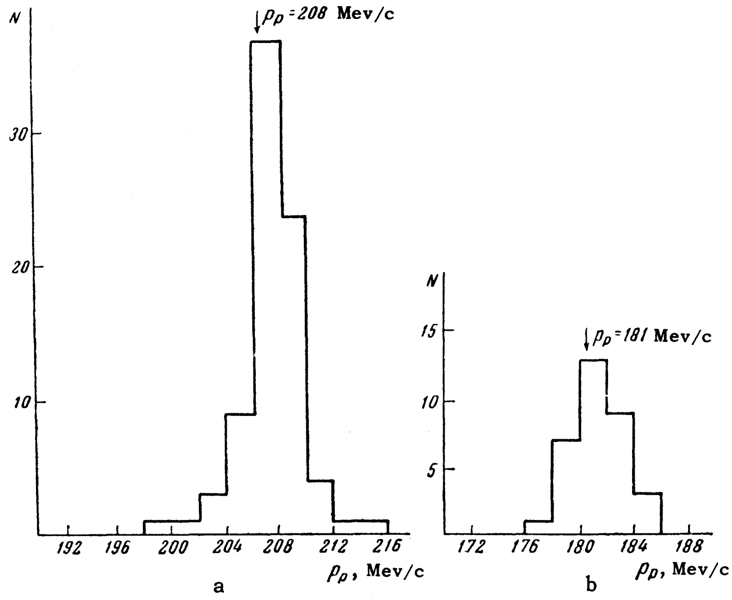

FIG. 2. Recoil proton c.m.s. momentum distribution determined from the ranges: a – $E_0 = 162$ Mev; b – $E_0 = 128$ Mev.

The main process which can resemble bremsstrahlung production in our experiment is quasi-elastic π^-p scattering by complex nuclei of impurities (methyl alcohol). Analysis of the stars produced on complex nuclei indicated that none could have been attributed to the process under investigation.

3. ESTIMATE OF THE UPPER LIMIT OF THE CROSS SECTION FOR THE PROCESS $\pi^- + p \rightarrow \pi^- + p + \gamma$

The bremsstrahlung cross section was calculated in the form

$$\sigma_\gamma < \sigma_{el} C/NK, \qquad (2)$$

where σ_{el} is the elastic scattering cross section for 154-Mev π^- mesons and was taken as the weighted mean for the number of cases at each energy; N is the total number of cases of elastic scattering; C is a correction to the number N which takes into account the contribution from Coulomb scattering and interference between Coulomb and nuclear scattering; K is the relative number of cases of scattering with radiation for the entire spectrum of γ quanta with $\Delta\theta > 3°$. The quantity K is determined from the expression

$$K = \frac{\int\limits_{E_\gamma = 10\ \text{Mev}}^{E_{\gamma\ max}} \omega(E_\gamma)\, a(E_\gamma)\, dE_\gamma}{\int\limits_{E_\gamma = 10\ \text{Mev}}^{E_{\gamma\ max}} \omega(E_\gamma)\, dE_\gamma}, \qquad (3)$$

where $\omega(E_\gamma)$ is the theoretical c.m.s. energy spectrum of the γ quanta, which was taken from [5]; the function $a(E_\gamma)$ expresses the probability of bremsstrahlung production with a change in angle $\Delta\theta > 3°$ as a function of the γ-quantum energy. For simplicity, this function was first calculated without taking into account the angular correlation between the direction of scattering of the π meson and the γ quantum; the angular distribution of the scattered π mesons was taken in the same form as that obtained in [8]. The lower limit of integration over E_γ in formula (3) was chosen as 10 Mev, since the probability of recording γ quanta with $E_\gamma < 10$ Mev was small under our conditions.

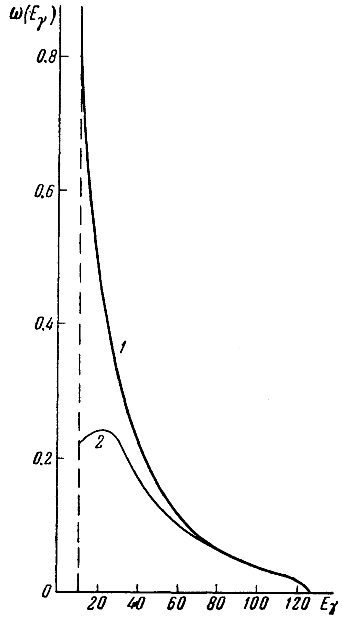

FIG. 3. 1 – C.m.s. energy spectrum of γ quanta $\omega(E_\gamma)$; [5] 2 – effective energy spectrum $\omega(E_\gamma)\, a(E_\gamma)$.

In Figure 3, curve 1 represents the energy spectrum $\omega(E_\gamma)$ and curve 2 represents the product $\omega(E_\gamma)\, a(E_\gamma)$, i.e., the effective energy spectrum. Graphical integration of these curves gave the value $K = 0.6$. A correction taking into account the angular correlation between the π meson and γ quantum, given by Eq. (1) in Solov'ev's article, [2] was then applied to this value of K. The calculation showed that the average value of this correction over the entire γ-quantum spectrum is about 20%. We finally obtained for K the value 0.5. The upper limit of the total cross section for the production of bremsstrahlung with $E_\gamma > 10$ Mev, calculated from formula (2), is 5×10^{-29} cm^2.

The obtained value can be compared with the total cross section calculated from the perturbation theory formula [2]

$$\sigma_\gamma = \frac{\alpha}{\pi} \ln \frac{E_0}{E_{\gamma\ min}} \left(\frac{1}{\beta_0} \ln \frac{1+\beta_0}{1-\beta_0} + \frac{1}{\beta'} \ln \frac{1+\beta'}{1-\beta'} - 4 \right) \sigma_{el}, \qquad (4)$$

where $E_{\gamma\,min} = 10$ Mev; β_0 and β' are the mean velocities of the π^- mesons before and after scattering. For a meson energy of 154 Mev, the cross section σ_γ found from formula (4) is 2.3×10^{-28} cm^2. However, integration of the energy spectrum obtained by Cutkosky [5] for bremsstrahlung production by π^+ mesons gives for the ratio $\sigma_\gamma/\sigma_{el}$ a value approximately 1/1.5 — 1/1.8 as great as that calculated from (4). (The ratio $\sigma_\gamma/\sigma_{el}$ for π^- mesons should not differ essentially from this ratio for π^+ mesons.) Hence, the upper limit 5×10^{-29} cm^2 obtained by us for the bremsstrahlung cross section is evidently not in sharp contradiction to the theoretical estimates. Comparison of this result with the cross section obtained by Deahl et al. [7] is difficult because of the lack of detailed information on that experiment, but estimates made with allowance for the difference in π-meson energies, different cut-off energies in the γ-quantum spectrum, and the experimental errors indicate that these results are not in contradiction with one another.

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