RADIATIVE PION-PROTON SCATTERING IN THE STATIC CHEW-LOW MODEL

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We present the results of a non-relativistic calculation of $\pi^{\pm}$ -proton bremsstrahlung cross-sections at the pion laboratory kinetic energy of 298 MeV for backward photon angles. The πp interaction is described by the static Chew-Low model.

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Recently a series of experiments [1] on pion-proton bremsstrahlung have been performed with incident pions of about 300 MeV kinetic energy and for photons emerging in the backward direction with respect to the participating charged particles. This is just the kinematic situation for the $\pi^+ p \rightarrow \pi^+ p \gamma$ reaction thought to be most favorable to the observation of the $\Delta^{++}(1236)$ resonance.

The possibility of measuring its magnetic dipole moment was first advocated by Kondratyuk and Ponomarev [2] and was subsequently supported by others [3]. These calculations are based either on some Lagrangian model for the resonant pion-nucleon interaction or on a resonant version of the Low theorem. These studies are also characterized by an off-shell electromagnetic vertex and an on-shell strong interaction amplitude. All predict a peak near the photon energy of 70 MeV where the pion and proton have an invariant mass of 1236 MeV in the kinematical situations considered in ref. [1]. Contrary to the predictions however, the observed cross-section turns out to be smaller and to fall more or less monotonically with increasing photon energy, without any apparent manifestation of the Δ^{++} resonance.

In this article we report our first results on pion-proton radiative scattering. We use a static P-wave pion-nucleon interaction and a non-relativistic model of the bremsstrahlung reaction. We feel that such a model can be of great use in our understanding of the experimental results if the calculation is rigorously executed. The non-relativistic approach based on the combination of an on-shell photon vertex and an off-shell hadronic scattering amplitude has been successful in describing radiative proton-proton scattering [4]. Thompson [5] has performed calculations along these lines for $\pi^+ p$ bremsstrahlung. His partial

results show that this non-relativistic approach is promising as do the results of Huffman [6].

The differential cross-section, which is to be compared with the data of ref. [1], is given by the following expression:

$$d^5\sigma/dk d\Omega_k d\Omega_1 = (2\pi)^4 (J/P_1 m_2) \bar{\Sigma} |(e'_1 e'_2 k)^{1/2} T_{fi} (e_1 e_2)^{1/2}|^2 \quad (1)$$

where initial spin-averaging and final spin summation as well as photon polarization summation must be performed. The mass, momentum, and energy of the pion are designated by m_1 , $\vec{P}_1$, and $E_1 = (P_1^2 + m_1^2)^{1/2}$ respectively; while those of the proton are m_2 , $\vec{P}_2$, and $E_2 = (P_2^2 + m_2^2)^{1/2}$ respectively. The primed symbols in Eq. (1) refer to pion and proton variables in the final state. The photon energy is indicated by k , and $J \equiv P_1' k / E_2'$ is a phase space factor. We use relativistic equations for the kinematics of the reaction. We note that although Eq. (1) is written in the laboratory system, the quantity $(e'_1 e'_2 k)^{1/2} T_{fi} (e_1 e_2)^{1/2}$ is Lorentz-invariant and may be evaluated in any convenient system.

If we leave aside for the present internal radiation, the bremsstrahlung amplitude T_{fi} includes single-scattering terms, which are also known as the external emission terms, and counter-terms designed to satisfy gauge invariance. The single-scattering contributions are given by:

$$\langle \vec{P}_1' \vec{P}_2' k | t(E') G(E') v_{em} + v_{em} G(E) t(E) | \vec{P}_1 \vec{P}_2 \rangle, \quad (2)$$

where $G(E)$ is the free two-particle Green function, $E = E_1 + E_2$, and $E' = E_1' + E_2'$. The non-relativistic photon vertex v_{em} has its standard form [4].

We use the static P-wave model of Chew and Low [7] to describe the πN interaction. This model is incomplete and of limited validity; still it has some basis in field theory and is amenable to further refinements. In addition, the model is accurate enough to indicate whether or not our approach is correct. In the πN center-of-mass system the scattering matrix t is written as a sum over four terms, the four total isospin and total angular momentum states, $n = (2T, 2J) = (11, 13, 31, 33)$. Each term is proportional to a function, $h_n(Z)$, of the pion energy. The complex functions $h_n(Z)$ satisfy a system of coupled integral equations. We solve the related set of equations [8] for $g_n(Z) \equiv \lambda_n / (2h_n(Z))$, where the $\lambda_n = 2/3(0.08/m_1^2)(-4, -1, -1, 2)$. The resulting amplitudes satisfy crossing symmetry. A form factor $v(q)$ is included to provide a high-energy cut-off. We assume $v(q) = \exp(-q^2/2q_0^2)$ and vary q_0 to position the (33) resonance at the desired energy. The results we present are for $q_0 = 7m_1$. This cut-off parameter yields fair fits of the cross-sections (see Fig. 2 of ref. [9]) and of the phase shifts, except in the (11) channel whose phase shift comes out very poorly.

In order to conserve charge, an instantaneous current flow exists inside the nucleon core during radiation. We use the interaction current given by Cutkosky [10]; his expression is valid in the dipole approximation for the static P-wave model.

We present our results for an incident pion kinetic energy of 298 MeV and for several of the geometries considered in ref. [1]. In Fig. 1 the detailed contributions of the single-scattering terms (SS) and the interaction current and its interference with single-scattering (IC), and the cross-section of the $\pi^+ p \rightarrow \pi^+ p \gamma$ reaction are presented and compared with the experimental data for photon detector G1. Figure 2 shows the

differential cross-section for some other geometries as well as the experimental data averaged over the 10 photon detectors. The theoretical curves remain high but are smooth, except for the slight suggestion of a resonance near 70 MeV, at which point the experimental curve also shows a hint of a rise.

The details of the mechanisms involved in π^-p radiative scattering are somewhat different than those found in the π^+p reaction. Firstly, the strong (3 3) channel is no longer quite so dominant, and secondly, the meson and nucleon radiation terms now interfere constructively instead of destructively as in the positive pion case which makes an accurate calculation of the latter difficult. For these reasons any proposed model should be tested against both processes. Figures 3 and 4 show our calculated π^-p bremsstrahlung cross-sections for several situations. Here we are in better agreement with the experimental spectrum.

In conclusion, the results show that our approach is basically sound. The remaining discrepancies require further investigations of the importance of a more realistic hadronic interaction as well as that of the internal radiation including, in the case of the π^+p process, the role of the $\Delta^{++}(1236)$ resonance. In addition, the off-shell electromagnetic vertex needs more attention for Picciotto [11] has shown how its effects are model-dependent and how the vertex model strongly affects the π^-p radiative cross-sections for photon energies above 60 MeV.

We are presently preparing a more detailed account of our work that also includes results obtained with proton recoil. In general, the addition of recoil does not improve our results. As seen here in

Figs. 1 and 3, the curve labeled IC does not show a resonant effect; however, the corresponding curves for our recoil models do show a geometry-dependent bump. The single-scattering term (SS) falls smoothly in both cases.

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Figure Captions

- Fig. 1 Differential cross-section for the π^+p radiative scattering (SS+IC); contributions from single-scattering alone are shown in curve SS; those from the interaction current and interference are shown in curve IC. Lab pion kinetic energy is 298 MeV and the experimental data is for the coplanar detector G1.
- Fig. 2 Differential cross-section for the π^+p radiative scattering for different geometries defined in ref. [1]. The experimental data is averaged over the 10 photon detectors G1 to G10.
- Fig. 3 Differential cross-section for the π^-p radiative scattering for the same kinematical situation as in Fig. 1.
- Fig. 4 Differential cross-section for the π^-p radiative scattering, otherwise as in Fig. 2.

Fig. 1

Fig. 2

Fig. 3

Fig. 4