CM-P00057572

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Ref. TH.796

ON PROTON - PROTON BREMSSTRAHLUNG

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ABSTRACT

The cross-section for proton-proton bremsstrahlung has been calculated for soft photons in a model independent way. Comparison with experiments has been made.

In the last two years, much attention has been given to proton-proton bremsstrahlung because this process, in principle, measures the off-the-mass-shell proton-proton amplitude. Until recently, there existed an important disagreement between experiments and theoretical results obtained from potential models for the p-p interaction (the potentials, of course, were derived from the on-shell behaviour of the p-p interaction). There was thus the decided possibility that the off-shell properties of the p-p interaction differed strongly from expectations. We therefore decided to do a model independent calculation expressing the bremsstrahlung cross-section directly in terms of the on-the-energy shell physical p-p scattering amplitude. In this way, the question of the importance of the off-shell contributions can be tested without reference to a specific model and in a particularly transparent way. We extend the considerations of Feshbach and Yennie ¹⁾ to the proton-proton case and consider diagrams (a), (b), (c) and (d), where the photon is emitted before or after the scattering takes place :

In that case the bremsstrahlung amplitudes (which are off-shell for one proton) can be expressed in terms of the elastic scattering amplitudes evaluated at the initial and final proton energies. Diagram (e) includes a gauge term and a contribution from the interaction region, but for soft photons it can be neglected ¹⁾. This is because the emission of a photon with a wavelength which is long compared to the range of the interaction does not critically depend on the details of the scattering process. Sebel ²⁾, using a potential model for the p-p interaction, also estimated the contribution of diagram (e) to be negligible independent of the photon energy. One can think of what we do as taking a series expansion of the bremsstrahlung cross-section in powers of the photon energy and retaining only the two leading terms.

Note that this expansion differs from the Low series ³⁾ in that it depends on the on-shell proton scattering amplitude evaluated at both the initial as well as the final proton energy, rather than evaluated at the mean proton energy.

The elastic scattering amplitude was put into our calculations through the energy dependent Livermore phases ⁴⁾ (ranging from 25 MeV to 400 MeV). Although we used all given phase shifts (up to H-waves), it turned out that the most prominent contribution to the bremsstrahlung cross-section (about 90%) came from the p-waves alone.

Our results, which are exact in the soft photon limit (up to uncertainties in the pp-scattering amplitude), show relative good agreement with experiments ^{5),6)}, even at photon energies which are no longer small compared to the scattering energies involved.

Presently, work is in progress to extend our study to lower proton energies (the Livermore phases do not allow us to calculate scattering amplitudes for proton energies below 25 MeV) and to investigate how critically the result depends on the particular set of phase shifts used.

In conclusion, our model independent approach confirms the revised Sobel and Cromer result ⁷⁾ (obtained using potential models) that the proton-proton amplitude has a normal "off-shell dependence", but our results differ from theirs in details.

The author would like to thank T. Ericson for drawing his attention to the problem and for guidance as well as helpful discussions throughout the work.

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FIGURE CAPTIONS

Figure 1: Cross-section for p-p bremsstrahlung at 158 MeV. Coplanar geometry. θ_1 and θ_2 are lab. system scattering angles of the two final protons with respect to the incident direction. The points refer to experiments of Gottschalk, Schlaer and Wang ⁵⁾. The curves are calculated in the soft photon approximation.

Figure 2: Integrated cross-section $(d\sigma/d\Omega_1 d\Omega_2)_{\text{lab}}$ for coplanar geometry as a function of the incident proton energy. The experimental points are for proton angles $\theta = \theta_1 = \theta_2 = 30^\circ$ ($\bullet$) and $\theta = \theta_1 = \theta_2 = 35^\circ$ ($\square$). The experiments are coplanar measurements by Gottschalk et al. ⁵⁾, Warner ⁸⁾ and Slaus et al. ⁹⁾. The theoretical curves could not be extended to lower proton energies since the phase shifts used did not allow that.

Figure 3: Bremsstrahlung cross-section in the centre-of-mass $(d\sigma/d\Omega_\gamma dE_\gamma)_{\text{cm}}$ as a function of the photon energy for incident protons of 204 MeV. The histograms are given by Rothe et al. ⁶⁾. Note the $1/k$ dependence of the theoretical cross-sections.

FIG. 1

FIG. 2

FIG. 3