PHYSICAL REVIEW VOLUME 184, NUMBER 4 20 AUGUST 1969

Off-Energy-Shell Effects in Proton-Proton Bremsstrahlung at 99 MeV*

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(Received 16 December 1968)

Calculations of the proton-proton bremsstrahlung cross section using off-energy-shell pole amplitudes are compared with calculations in which the off-energy-shell dependence is suppressed. The differences in these cross sections and 4½ times greater than the errors in the 99-MeV measurements of Sannes, Trischuk, and Stairs, and the off-energy-shell calculation clearly gives the better agreement with these data.

PROTON-PROTON bremsstrahlung has been studied in the hope of finding useful information about the off-energy-shell (OES) behavior of the nucleon-nucleon interaction. Low first showed[1] that OES effects do not occur in the first two terms of the expansion of the scattering amplitude in powers of the photon momentum. It has recently been suggested[2] that the photon momentum will be sufficient for the OES contribution to p-p bremsstrahlung to be observable in geometries in which the two protons each scatter at angles less than 30°. Unfortunately, when that paper was written no experiment with this geometry had yet been done with sufficient accuracy.

Recently a relatively precise experiment has been done at McGill University by Sannes, Trischuk, and Stairs,[3] and we have found that in the case of protons scattered at 25°-25° the effects of the OES contribution in our calculation can be observed.

In order to examine the importance of OES effects, we have performed two calculations. The first, denoted by O, is a calculation of the coplanar $pp\gamma$ cross section using OES pole amplitudes; the second, denoted by $O_{\rm el}$, suppresses the inelastic effects. That is, $O_{\rm el}$ is calculated from elastic scattering parameters, and the difference between O and $O_{\rm el}$ is entirely due to OES effects. In both calculations the first two terms in an expansion of the scattering amplitude in powers of the photon momentum, i.e., $A/K+BK^0$, are identical to those given by Low.[1]

The details of these calculations are given in Ref. 2. To summarize, the p-p scattering amplitude is calculated as an expansion in quasiphases, as described by Cromer and Sobel.[4] In our calculation the quasiphases are taken to be

$$\Delta(k',k)=\sin\delta(k)Z(k',k),$$

where $\delta(k)$ is the elastic phase shift. In the case of O, where the OES amplitudes are used, $Z(k',k)$ is given by

$$Z(k',k)=\Delta_B(k',k)/\Delta_B(k,k),$$

where $\Delta_B(k',k)$ is the quasiphase calculated from the one-pion-exchange contribution.

Our relatively simple calculation is not meant to provide all of the correct OES dependence, but rather to test the strength of these OES effects. A different parametrization would be of questionable value, since differences between the various calculations[2,7] are as small as some of the effects which we have ignored.

In the case of $O_{\rm el}$ we have taken $Z(k',k)=1$, so that $O_{\rm el}$ is calculated entirely in terms of elastic scattering parameters.

The results of these calculations for the integrated cross section $d\sigma/d\Omega_1 d\Omega_2$ are compared with the 99-MeV data in Fig. 1. As can be seen, the difference between O and $O_{\rm el}$, the OES contribution, becomes quite small as one approaches the soft-photon (elastic) limit at $\theta=45°$. At smaller angles (farthest from the elastic limit) the data favor O, and, furthermore, the experimental errors are considerably less than the difference between O and $O_{\rm el}$.

In Fig. 2 the differential cross section $d\sigma/d\Omega_1 d\Omega_2 d\theta_\gamma$ is compared with these two calculations for the $\theta=25°$ case. Again, the data are well represented by O but not by $O_{\rm el}$.

It should be emphasized that $O_{\rm el}$ is not equivalent to the calculation of Nyman.[5] Although both calculations use only elastic scattering parameters, Nyman evaluates his pole terms at an average energy and thus introduces additional errors[6] of $O(K)$ which our calculations avoid. Also, Nyman's calculation is based on a fully covariant theory, while ours is not.

In addition to possible covariant corrections as well as modifications of the static electromagnetic form factor, we have ignored rescattering terms, contributions from exchange currents, and Coulomb effects. In calculation at 160 MeV for $\theta=20°$, 30°, 35°, and 40°,

* Supported in part by a grant from the National Science Foundation.

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Brown has found[7] that rescattering effects tend to increase the integrated cross section, but by less than 5%. Furthermore, this effect decreases with decreasing beam energy. On the basis of one- and two-pion-exchange bremsstrahlung calculations,[8] we expect that the contributions from exchange currents (as manifested through nonlocality and velocity dependence in a nonrelativistic theory) are at least as small as rescattering effects. Signell and Marker have estimated that Coulomb effects account for 12% of the cross section at 20 MeV and 35°. Also, the influence of these effects

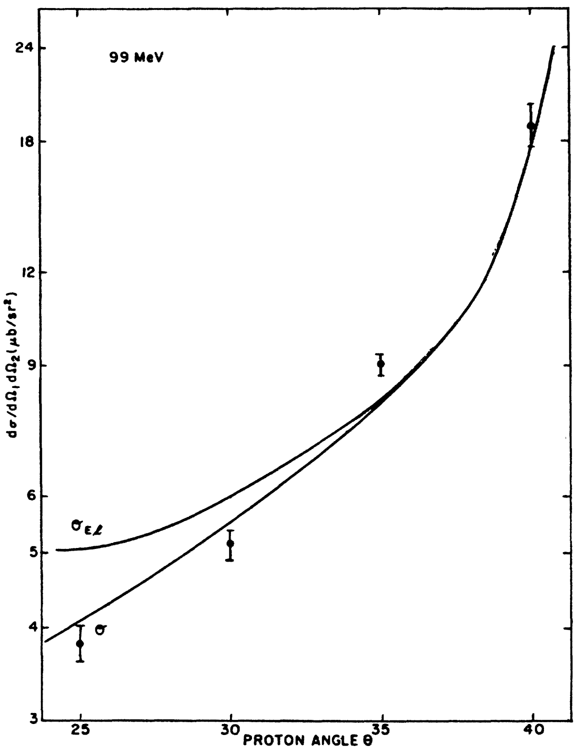

FIG. 1. $pp\gamma$ integrated cross section at 99 MeV as a function of proton angle. The off-shell quasiphases used in O are replaced by the sine of the elastic phase shift in $O_{\rm el}$. Data are those of Sannes, Trischuk, and Stairs.

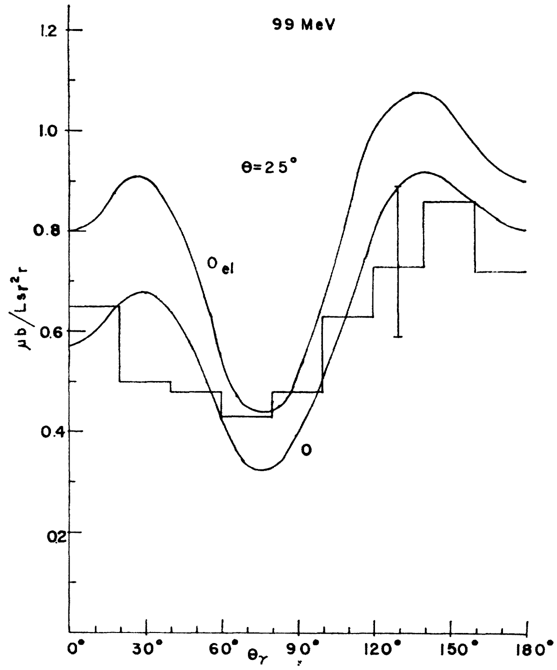

FIG. 2. $pp\gamma$ cross section as a function of θ_γ at 99 MeV for equal-angle coplanar scattering. The OES contribution is the difference between O and $O_{\rm el}$. Data are those of Sannes, Trischuk, and Stairs.

increases as the angle of scattering between the two protons decreases, since energy of the final-state nucleons decreases. Nevertheless, we expect that these Coulomb effects are considerably smaller at 99 MeV for all angles considered, since the strong interaction dominates.

Although we presently get agreement with the data by ignoring internal scattering (rescattering plus exchange), one may not use the pole terms along to make a detailed study of the OES effects, since the internal scattering contribution may be comparable in size with the differences in pole amplitudes calculated using different OES parametrizations.

It is a pleasure to thank B. Malenka, B. Gottschalk, and R. Arnowitt for profitable discussions. J.M. also wishes to acknowledge, with gratitude, a particularly enlightening discussion with L. Heller.

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