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PROTON-PROTON BREMSSTRAHLUNG AT SMALL ANGLES*

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ABSTRACT

In principle nucleon-nucleon bremsstrahlung remains one of the most direct and least ambiguous ways of investigating the off-energy-shell behaviour of the NN interaction. Model calculations, such as that by Heller,[1] indicate that in the symmetric Harvard geometry[2] the off-shell effects are largest for high bombarding energies and small proton opening angles. Heller's calculation also shows that for the particular model and geometry he used, off-shell effects are fairly small for the conditions of previous experiments. Thus motivated we have measured ppγ cross sections at a somewhat higher bombarding energy (200 MeV) and over proton angles significantly smaller than in previous experiments. Two sets of data were taken covering intervals centered at 13° and 16.3°, respectively. Preliminary results from the 16.3° data are reported here.

EXPERIMENTAL TECHNIQUE

The measurement utilized an ultrapure natural hydrogen gas target at 0.95 atm pressure. The proton beam from the TRIUMF cyclotron entered the gas through a 20 μm thick titanium window 2.3 m upstream of the scattering chamber and exited through a 25 μm thick steel window 3.6 m downstream. A carefully designed system of five collimators in the beam pipe upstream of the scattering chamber was used to eliminate beam halo, especially that caused by scattering in the entrance window.

The two protons from the $p + p \rightarrow p + p + \gamma$ reaction exited from the target gas through 76 μm thick Kapton windows and were detected in coincidence in two identical detector telescopes. A permanent magnet was placed inside the target chamber to deflect delta rays. Each telescope provided two independent measures of the proton's energy: the times of flight over a 2.5 m flight path and the energies deposited in a thick plastic scintillator. A thin (0.793 mm) plastic scintillator at the entrance to the telescope provided timing resolution without destroying trajectory information. The thick scintillator was sufficient to stop the ppγ protons but not the elastic protons. This feature allowed a veto detector to be used behind the total energy detector to eliminate most coincidences involving elastic protons. The proton trajectories were determined using two x-y multiwire counters in each telescope. Helium bags minimized the multiple scattering in the flight path between the multiwire counters. The detector telescopes limited the effective length of the target to 25 cm along the beam direction and the total angular acceptance to ±0.4° in θ and ±4° in ϕ. Figure 1 shows the layout of the experiment.

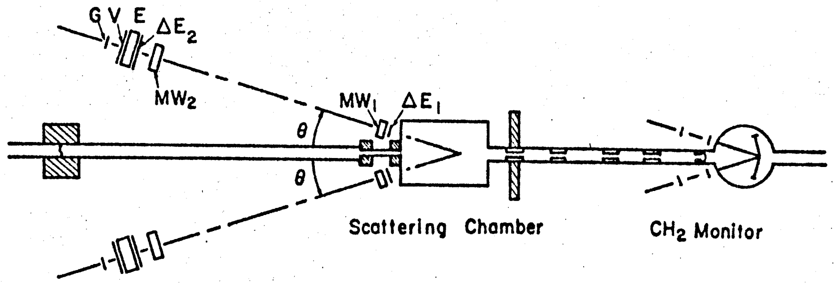

Fig. 1. Layout of ppγ experiment showing collimator system and makeup of proton telescopes.

An on-line computer recorded 60 words of information on magnetic tape for each detected event. In addition to the ppγ events the computer simultaneously recorded elastic scattering events defined by small scintillators located beyond the veto counters. These were acquired independently in the left and right counter telescopes in order to measure indirectly the combined target thickness, beam intensity and electronics dead time. An independent measure of the normalization was also made using a direct beam current monitor.[3]

The experiment utilized beam currents of 10 to 20 nA which gave a ppγ counting rate of approximately 10 per hour. About 300 h of cyclotron beam time was required for both data-taking and calibration.

PRELIMINARY DATA ANALYSIS

We have made the conventional "θ_γ spectrum" choice, expressing $d^5\sigma/d\Omega_{p1}d\Omega_{p2}d\theta_\gamma$ as a continuous function of the photon polar angle θ_γ for fixed proton angles (Ω_{p1} and Ω_{p2}). ppγ events were identified by requiring simultaneous detection of two protons with measured energies approximately satisfying the ppγ kinematics, i.e. that the missing mass[4] M_γ be approximately zero. The missing-mass distribution

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consisted of a flat background underlying a ppγ peak centered at $M_\gamma^2=0$, whose width reflected primarily the energy resolution of the detectors. In this preliminary analysis the criterion for acceptance was that the missing mass lie within the observed ppγ peak, while θ_γ was taken to be simply the polar angle of the missing momentum. Errors introduced by this procedure are estimated to be small even near $\theta_\gamma=90°$, where the uncertainty in the energy calibration is greatest.

The conversion factor from scintillator pulse height to proton energy was determined as a function of position across the large scintillators by utilizing pp elastic scattering from a CH_2 target. Corrections for energy loss effects were included in both pulse height and time-of-flight calculations. The conversion to energy was verified both by comparison with time-of-flight and by noting that the centroid of the missing-mass spectrum was near zero mass over the entire allowed ppγ kinematic region.

The coordinates from the multiwire detectors determined the proton trajectories and accurately defined the solid angle acceptance. The acceptance was adjusted in the analysis to exclude visible sources of background due to plural scattering of elastic protons from the edges of the exit window of the scattering chamber. The trajectories were corrected for the small deflection caused by the delta-ray suppression magnet.

Two types of background were measured separately and subtracted from the ppγ missing-mass distribution. The first type was due to p,2p from contaminants in the target gas arising from small leaks and outgassing of the chamber walls. This background was approximated by data acquired after filling the target chamber with air. The normalization of the background was adjusted to match the ppγ distribution in a region far from the ppγ peak. The second type of background consisted of accidental coincidence events, the contribution of which was determined from data in which the protons originated during adjacent cyclotron rf cycles.

The most significant source of inefficiency was dead time in the multiwire and scintillation counters resulting from the high singles rates. These dead times were monitored during data acquisition by using a pulser to randomly trigger each detector in the entire system. Contributions to the dead time could then be measured by counting the number of pulser signals surviving various cuts as a fraction of the number presented. A small correction was made for reactions in the scintillators using the calculation of Measday and Richard-Serre.[5]

Two independent techniques to measure the absolute (beam-target) normalization were employed. In the first technique, integrated beam current was measured directly by a CH_2 scattering monitor which had been previously calibrated with a Faraday cup.[6] The temperature and pressure of the target gas were measured by standard transducers. As a second technique, prescaled elastic scattering events from the hydrogen gas target were acquired along with the ppγ data. This allowed computation of the ppγ cross section relative to the known hydrogen elastic cross section. The two methods of measuring the beam-target normalization agree within 5%, which we take to be the estimated overall normalization error.

RESULTS

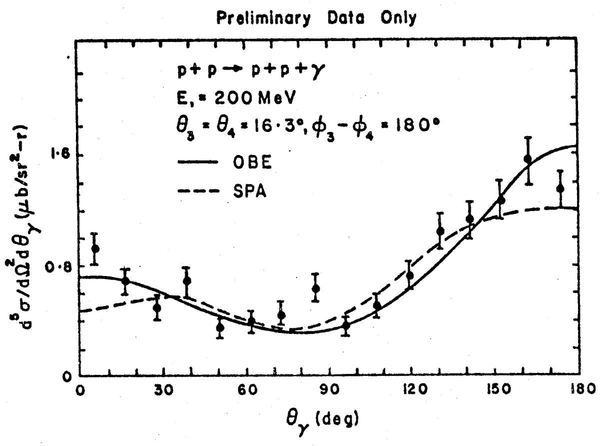

Fig. 2. Preliminary ppγ cross sections for 16.3° compared with soft photon approximation (SPA) of Fearing and One-Boson-Exchange model (OBE) of Kamal and Szyjewicz.[7]

Figure 2 shows the θ_γ spectrum of the data analyzed to date, which are about 2/3 of the total data acquired at 16.3°. The curve labeled OBE is the one-boson exchange model calculation of Kamal and Szyjewicz,[7] which is an improved version of the earlier calculation of Baier, Kuhnelt, and Urban.[8] The dashed curve is the soft-photon approximation to the ppγ cross section, computed at TRIUMF by Fearing.[9]

The statistical uncertainties of the data are indicated by the error bars. In addition there is a ±5% normalization uncertainty. The statistical uncertainties of the analyzed data will become smaller as more of the data recorded on tape are analyzed. Systematic errors in the preliminary analysis are estimated to be small and will be investigated fully in later analysis. Corrections which have not yet been made involve primarily improvements in energy calibration and the method of determining θ_γ. It is not expected, however, that the 16.3° data will ultimately change by more than one standard deviation.

Because of the finite angular acceptance of the counter system, the measured cross sections are actually the integral of the differential cross section over a small region of phase space. Of the calculated cross sections presented here, only the soft-photon calculation of Fearing has been integrated to simulate this averaging effect, which was found to be negligible.[10] We would therefore expect the effect to be negligible for other theoretical calculations as well.

From the analysis performed so far we conclude that the data are in qualitative agreement with the theoretical calculations. The slight tendency to favour the OBE calculation over SPA near 0° and 180°, where off-shell effects should be largest, is encouraging as it indicates that our data may be precise enough to actually distinguish the presence of non-soft-photon terms. Data at smaller angles (13°)

remain to be analyzed. Off-shell effects should be larger there and so may be more easily distinguishable.

REFERENCES AND NOTES

1. These (unpublished) calculations performed by Leon Heller and M. Rich have been discussed briefly at several conferences. They are mentioned most recently by Heller in: Few Body Problems in Nuclear and Particle Physics, edited by R.J. Slobodrian, B. Cujec, and K. Ramavataram (Les Presses de L'Université Laval, Québec, 1975) p. 206.
2. "Symmetric Harvard Geometry" means that the protons are detected in counters placed symmetrically on either side of the beam and in a plane containing the beam. The γ-ray is not detected. See Ref. 1, p. 195.
3. Details on beam current normalization are contained in A.W. Stetz, J.M. Cameron, D.A. Hutcheon, R.H. McCamis, C.A. Miller, G.A. Moss, G. Roy, J.G. Rogers, C.A. Goulding, W.H. van Oers, submitted to Nucl. Phys.
4. The missing mass M_γ is calculated by $M_\gamma^2=E_M^2-P_M^2$ where E_M and $\vec{P}_M$ are the difference between the initial and final energy and momentum, respectively, of the two scattering protons. A non-zero value of M_γ implies a corresponding error in θ_γ.
5. D.F. Measday and C. Richard-Serre, CERN report 69-17 (1969).
6. A Faraday cup similar to the one we used was found to have an accuracy of ±1%. See R.J. Barrett, B.D. Anderson, H.B. Willard, A.N. Anderson, and Nelson Jarmie, Nucl. Instr. & Meth. 129, 441 (1975).
7. A.N. Kamal and Adam Szyjewicz, contribution to these proceedings and private communication; Kamal and Szyjewicz, Nucl. Phys. A (in press).
8. R. Baier, H. Kuhnelt, and P. Urban, Nucl. Phys. B11, 675 (1969).
9. H.W. Fearing, contribution to these proceedings.
10. The soft-photon approximation results were numerically integrated using a coarse mesh over the angular acceptance and the resulting cross section was found to differ negligibly from the differential cross section calculated at the centre of the detector system. The shape of the spectrum is affected, since non-coplanar events are excluded from the regions near $\theta_\gamma=0°$ and $\theta_\gamma=180°$, but we expect this effect to be confined to redistribution of those events within the bins corresponding to the first and last points of Fig. 2 (bin size = 11.25°). We do not estimate the drop in cross section near 180° apparent in Fig. 2 to be due to this effect.