Asymmetric Neutron-Proton Bremsstrahlung at 208 MeV*

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Additional data on neutron-proton bremsstrahlung measurements at 208-MeV neutron energy are presented. These are at $(\theta_n, \theta_p) = (40°, 30°)$ and $(45°, 30°)$. Also, the analysis of the symmetric-angle data reported earlier has been improved resulting in small changes in the cross sections.

INTRODUCTION

Most nuclear-physics calculations require a description of the nucleon-nucleon (N-N) interaction. For example, several rather complicated and sophisticated potential models provide such a description. These potentials are derived mainly from what are called elastic or on-shell experiments. However, the implications of such potentials transcend considerably the special elastic case where the nucleons are initially and finally free particles.

In many calculations, such as those of nuclear structure, the two nucleons interacting are initially and finally bound or off the energy shell. A discriminating test of the various potentials as to their off-shell validity cannot in general be provided by such calculations, because of the other approximations in the models which are themselves under test.

Nucleon-nucleon bremsstrahlung is essentially a form of inelastic N-N scattering ($N+N \rightarrow N+N+\gamma$). The nuclear interaction allows the electric and magnetic currents of the nucleons to interact with the electromagnetic field (vacuum) and create real photons. This process can provide off-shell tests for the N-N interaction and for the potentials. Possibly it will allow one to discriminate among potentials which give similar on-shell predictions, and possibly it will shed new light on the N-N interaction.

Here results from neutron-proton bremsstrahlung ($np\gamma$) measurements at 208 MeV for asymmetric and symmetric coplanar angles are given. The latter were reported[1] earlier after a preliminary analysis and are slightly changed in this final analysis.

EXPERIMENTAL RESULTS

Details of the experiments are contained in an earlier report[1] and in a thesis.[2] Briefly a 208-MeV neutron beam from the Lawrence Radiation Laboratory 184-in. cyclotron was collimated to strike a liquid-hydrogen target. Neutrons and protons were detected at nonconjugate (nonelastic) but coplanar angles with a scintillating plastic neutron detector and a proton telescope. A second noncoplanar telescope, in conjunction with the neutron detector, viewed background events from a part of phase space just outside the $np\gamma$ kinematic region, and gave additional checks on random and double-scattering events, as well as coherent events from the target walls. The results were consistent with background measured in the primary telescope-neutron-detector combination and with calculated double scattering.

The $np\gamma$ cross sections, $d^2\sigma/d\Omega_n d\Omega_p$, in μb/sr^2 are given in Table I for the various pairs of coplanar angles (θ_n, θ_p). The random errors quoted are largely due to counting statistics. Uncertainties in the efficiency of the neutron detector (about 4%) and in the n-p differential cross section to which the $np\gamma$ was normalized (about 5%) make only small contributions. Systematic errors are difficult to assess and are believed to be considerably smaller than the random errors quoted.

Corrections for the finite size of the detectors have not been made. It was stated previously[1] that certain corrections for counter heights could be made based on the ϕ dependence, essentially as determined from noncoplanar $pp\gamma$ data. However, recent theoretical calculations[3] indicate that instead of decreasing with ϕ, as do the $pp\gamma$ cross sections, the $np\gamma$ increase slightly as ϕ increases towards the kinematic cutoff. On this basis the quoted cross sections would then be reduced slightly (a few %) for strict coplanarity.

DISCUSSION

Comparisons with several theoretical calculations can be made. Baier, Kühnelt, Urban[3] have performed a fully relativistic and gauge-invariant calculation of $pp\gamma$ and $np\gamma$. They use the framework of the one-boson-exchange (OBE) model.

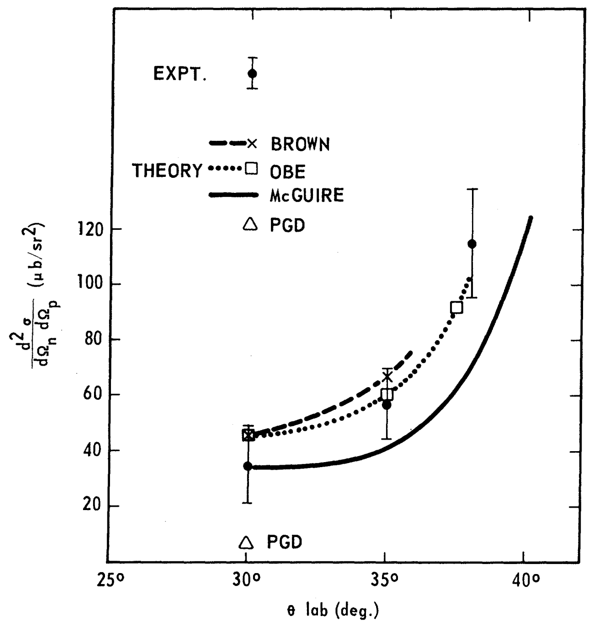

FIG. 1. Comparison of $np\gamma$ experiment with theory for coplanar symmetric angles (near 200 MeV). OBE refers to Ref. 3, McGuire to Ref. 4, Brown to Ref. 5, and PGD to Ref. 6.

McGuire[4] has calculated $np\gamma$ including the pole terms to all orders in the photon momentum K, and the internal terms to order K^0 by using the low-energy theorem. The off-shell extrapolation of the elastic phase parameters is provided by the one-pion-exchange potential.

The calculations of Brown[5] use the Bryan-Scott and Hamada-Johnston potentials and include the double-scattering terms. The difference between the predictions of the two potentials is small, about 7% at 30°, and may or may not be due to off-shell differences. In addition, the calculations are not completely gauge invariant. The predictions of the two potentials are averaged in Fig. 1.

TABLE I. The $np\gamma$ cross sections are given with random errors.

(θ_n, θ_p)	$\sigma_{np\gamma}$ μb/sr^2	OBE predictions (Ref. a)
30, 30	35 ± 14	46
35, 35	57 ± 13	60
38, 38	116 ± 20	92
40, 30	114 ± 44	52
45, 30	132 ± 53	67

[a]See Ref. 3

It is interesting that calculations of Brown[5] using only the single-scattering or pole terms give cross sections about one third of those which include the double scattering. This would explain the low value of the cross section obtained in early calculations by Pearce, Gale, and Duck.[6] Figure 1 compares the coplanar-symmetric-angle results of this experiment with the calculations. Qualitative agreement with the three recent ones is obtained. The experimental cross sections and OBE predictions[3] are given in the table.

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