NEUTRON-PROTON BREMSSTRAHLUNG AT 208 MeV *

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Nucleon-nucleon bremsstrahlung provides a means of investigating the off-mass-shell behavior of the nucleon-nucleon interaction. Potential models, for example, must account for this behavior. This is important not only because these potentials are used in calculations of nuclear structure and nuclear matter, but also because they provide tests of the more fundamental descriptions of the N-N interaction.

Ashkin and Marshak[1] and others[2,3] in 1949 suggested nucleon-nucleon bremsstrahlung as a way of studying off-mass-shell effects. In recent years p-p bremsstrahlung ($pp\gamma$) has received considerable experimental[4-9] and theoretical[10-15] attention. However, further refinement of both experiment and calculations appears necessary to allow determination of explicit off-mass-shell behavior of the p-p interaction.

Work on n-p bremsstrahlung ($np\gamma$) is yet at a primitive stage. Calculations[1,16-18] indicate that the cross section should be several times larger than that of $pp\gamma$. No measurements of the "free" $np\gamma$ cross section have been reported except for an upper limit[19] established at the University of California at Los Angeles with 14-MeV neutrons. The experimental work of Wilson[20] and Cohen et al.[21] on proton-nucleus bremsstrahlung has recently been extended by Edgington and Rose[22] at Harwell. However, extraction of the $np\gamma$ cross section from measurements on complex nuclei is rather uncertain.[23] Edgington and Rose[22] using 140-MeV protons and a D_2O-H_2O difference method and Koehler et al.[24] at Rochester using 197-MeV protons and a liquid-deuterium target have extracted the "quasifree" $np\gamma$ total cross section. The results even when corrected for energy difference are apparently incompatible.[24]

We report here $np\gamma$ measurements using a neutron beam produced by the Lawrence Radiation Laboratory 184-in. cyclotron. The overall setup is shown in Fig. 1. A circulating beam of deuterons strikes an internal Be target and produces at the liquid-hydrogen target a collimated neutron beam 1.5 in. high by 1.2 in. wide. The peak, which comprises 90% of the beam, has a mean energy of 208 MeV, a full width at half-maximum of about 45 MeV, and a flux of $\simeq 10^7$ neutrons per second.

Most of the data were taken in the coplanar or so-called Harvard geometry in which the proton and neutron are detected at equal angles to the beam. The proton energies E_p were measured to about 1% in a NaI crystal placed behind the three plastic scintillators of the proton telescope. Neutrons were detected in a NE102 plastic scintillator 5 in. diam by 12 in. long, and their flight times t_n, relative to a proton in S_1, were measured. The efficiency of the plastic for a 4-MeV electron threshold is a nearly constant 30% over the energy range of interest, $25 < E_n < 125$ MeV. It was measured in a separate experiment.[25]

A second and identical proton telescope (not shown in Fig. 1) was used for most runs. It was placed at the same polar angle to the beam as the primary one, but above the plane so as to be outside the $np\gamma$ kinematic range. It then served to monitor noncoplanar backgrounds and was particularly useful for measuring double scattering at nearly the same geometry as did the primary telescope.

Two "start" pulses, $S_1S_2S_3$, were taken from each telescope; the second, delayed by two rf cycles, allowed simultaneous recording of random events. The neutron detector D_n pro-

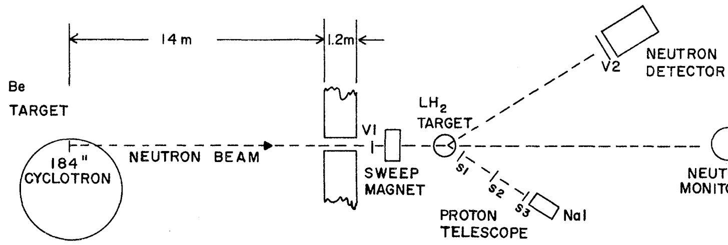

FIG. 1. Experimental setup.

vided the "stop" pulse for each of four time-to-amplitude convertors (TAC). The TAC signals were mixed as were the energy signals from the two telescopes. Each mix was sent to one side of a modified ND160 two-parameter analyzer which was routed to store four 32×32 spectra, each of the form E_p vs t_n.

For a monoenergetic beam and a given θ_p and θ_n, the $np\gamma$ events would lie on a ring in the primary spectrum of E_p vs t_n. However, due to the energy spread of the neutron beam and the finite size of the detector solid angles, the $np\gamma$ kinematic region is considerably smeared, so that careful background subtraction is necessary. In the 35° data, for example, the random background in the $np\gamma$ kinematic region constituted 12% of the raw coincidence data. Target-empty coherent events contributed 52% and double scattering 10%.

Cross sections were calculated by normalizing to those of n-p elastic scattering[26] which were monitored during each run. In Fig. 2, we plot the measured $np\gamma$ differential cross sections versus mean angle ($\theta_p = \theta_n$), both in the lab system. Statistical errors only are shown. The corresponding $pp\gamma$ cross sections measured at Rochester[7] with 204-MeV incident protons are also plotted after being multiplied by a factor of 4. Thus, in this kinematic region $\sigma_{np\gamma}{}^2/\sigma_{pp\gamma}{}^2 \simeq 4$, where $\sigma_{np\gamma}{}^2 \equiv d^2\sigma/d\Omega_p d\Omega_n$.

Corrections for the finite height of the detectors have not been made for the values plotted in Fig. 2. Making the simple assumption that the φ dependence is given by phase space, we estimate that to be coplanar the $np\gamma$ cross sections at 30, 35, and 38° should be increased by 3, 5, and 13%, respectively.

In addition to the statistical errors shown, there are uncertainties of about 5% due to those in the n-p elastic cross section.[26] At each angle, uncertainties in the double-scattering correction contribute about 3% and that due to the probable error in the neutron counter efficiency, about 5%. Other uncertainties such as those due to the broad energy spread of the beam and possible contributions from the low-energy tail are more difficult to ascertain as they require a knowledge of the energy dependence of the cross section. Those due to the tail will be small for a dependence similar to that of $pp\gamma$.

Using the $p+d$ reaction with 140-MeV protons, Edgington and Rose[22] at Harwell detected the high-energy photons and obtained a total $np\gamma$ cross section of $\simeq 8$ μb for $E_\gamma > 40$ MeV. With 197-MeV protons, the Rochester group[24] detected photons and charged particles and obtain $\sigma_{np\gamma} = 35 \pm 12$ μb for $E_\gamma > 40$ MeV. Both groups integrate the photon spectrum over energies $E_\gamma > 40$ MeV and over photon angles. From similar data on $pp\gamma$, Rochester has calculated the total $pp\gamma$ cross section, $\sigma_{pp\gamma}$, and concludes that the ratio $\sigma_{np\gamma}/\sigma_{pp\gamma} = 50 \pm 20$. [In our restricted kinematic region (Fig. 2), the ratio of differential cross sections is $\simeq 4$.]

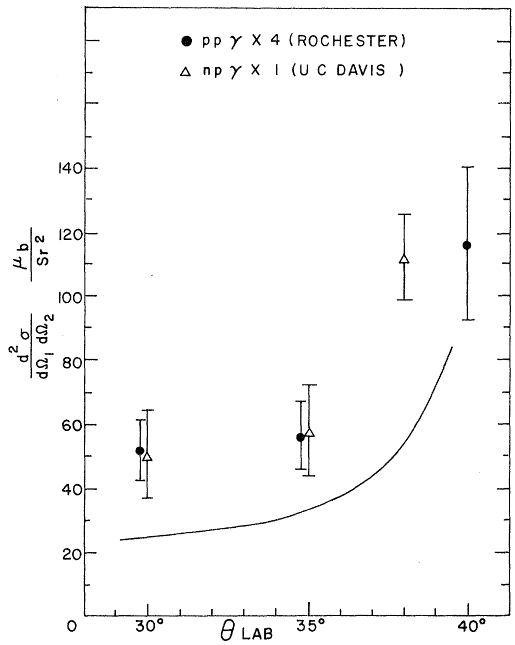

FIG. 2. Laboratory differential cross sections in Harvard geometry versus laboratory angles. Only statistical errors are shown for $np\gamma$. The curve is from the calculations of Nyman.

The curve in Fig. 2 is derived from the predictions of Nyman.[27] These are calculated using only on-shell parameters (phase shifts) and in the $pp\gamma$ case account quite well for differential cross sections in the Harvard geometry.[28] We can use Nyman's theory to compare our results with those of the Rochester group. Coresponding to the values shown in Fig. 2, Nyman gets 16.5 μb for the $np\gamma$ total cross section for $E_\gamma > 40$ MeV. Our values are about a factor of 1.8 larger than those calculated by Nyman. Assuming the same factor for all kinematic regions, we would obtain for $E_\gamma > 40$ MeV an $np\gamma$ total cross section of $\simeq 30$ μb, in agreement with Koehler et al.[24]

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STORAGE AND DIFFUSION OF COSMIC-RAY ELECTRONS IN THE GALAXY*

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In this Letter we discuss the propagation of cosmic-ray electrons in the galaxy and the effects of attendant energy loss. We show that previous discussions, based on the concept of a "leakage lifetime" T_L, are misleading and proceed to discuss briefly a more satisfactory approach.

It has been shown experimentally that the primary cosmic-ray electron component consists largely of negatively charged particles.[1-4] This provides clear evidence that electrons are accelerated within the galaxy. It is usual to suppose that the electrons propagate by a random walk through the irregular galactic magnetic field, and that the observed intensity is a quasisteady equilibrium between steady input and loss. If the steady source of particles as a function of energy E and position $\vec{r}$ is $Q(E,\vec{r})$ and if $D(\vec{r},E)$ is the diffusion coefficient, then the assumption of a steady state requires that the density $N(\vec{r},E)$ satisfy

$$Q(\vec{r},E)-\frac{\partial}{\partial E}\left(\frac{dE}{dt}N\right)+\nabla\cdot(D\nabla N)=0, \qquad (1)$$