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Neutron-Proton Bremsstrahlung Studies using the
White Neutron Source at the LAMPF/WNR

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Abstract

Nucleon-nucleon bremsstrahlung is a few-body radiative process that provides insight into several areas of nuclear physics. It is one of the simplest systems for studying the off-shell behavior of the nucleon-nucleon potential. The physics involved in neutron-proton bremsstrahlung (NPB) is significantly different from that of proton-proton bremsstrahlung (PPB). In particular, NPB cross sections are much larger than PPB cross sections because NPB allows E1 radiation, and the contribution to the cross section from the meson exchange currents has been calculated to be as large as the contributions from external radiation.

To date there have been essentially four NPB experiments. These measurements have covered only a small part of the available phase space. A major experimental problem in performing these measurements has been the lack of a suitable intense, high-energy neutron beam.

We are planning a measurement of the NPB cross section using the white neutron source at the WNR target area at the LAMPF accelerator. We plan to implement the experiment in three phases. In the first stage, we shall measure inclusive hard-photon production using a multi-element gamma-ray telescope that is insensitive to neutrons. In the second phase, we shall measure the bremsstrahlung gamma-rays in coincidence with recoil protons. In the last phase, we shall detect the scattered neutrons in coincidence with the recoil protons and gamma rays.

Introduction

The simplest interaction between two nucleons is nucleon-nucleon elastic scattering. The next level of complexity is inelastic NN scattering involving the emission of electromagnetic radiation. The electromagnetic interaction is a nice way to probe the strong interaction because it is "understood" and "weak". When the two outgoing nucleons emerge from their interaction with small relative velocities and couple together, it is called a capture reaction. The radiative processes that occur between the kinematic regions of elastic scattering where the two particles scatter with 90° between them and the highly inelastic capture reaction (0° between the two outgoing particles) are called nucleon-nucleon bremsstrahlung (NNB).

Figure 1 shows the diagrams for NNB below the pion threshold. The diagrams in Fig. 1a-d are called external diagrams and involve emission of photons either before or after the strong interaction, from either one of the particle legs. Figure 1e is an internal diagram that involves meson exchange. Figure 1f is the diagram for rescattering. Above the pion threshold, additional diagrams that involve coupling to the delta resonance are necessary.

Diagrams for Nucleon-Nucleon Bremsstrahlung

Figure 1. Diagrams involved in nucleon-nucleon bremsstrahlung. Diagrams a-d are external diagrams, e) meson exchange diagram and f) rescattering diagram.

In the language of the Direct Semi-Direct capture model, the external diagrams are analogous to the direct matrix elements, and the internal diagrams are analogous to the semi-direct amplitudes.

The physics of NNB depends strongly on the types of nucleons involved in the collision. Because the center of mass and center of charge are coincident in the case of proton-proton bremsstrahlung (PPB), dipole radiation is not allowed. The leading term in PPB is therefore E^2 . Because PPB involves nucleons of the same charge, to first order only neutral mesons are exchanged that do not radiate. Therefore, the meson exchange term is quite small in PPB. These two differences between PPB and neutron-proton bremsstrahlung (NPB) explain why the cross section for NPB is much greater than for PPB.

The major goal in the study of NPB is to understand the nucleon-nucleon interaction by looking at its off-shell behavior with particular emphasis on the meson exchange terms. In addition, NPB data may also shed light on the source of high-energy photons that have been observed in heavy-ion reactions. Electroweak scientists are also very interested in NPB data because NPB processes are thought to produce significant backgrounds in several neutrino experiments.

Nucleon-Nucleon Physics

Figure 2 shows a calculation of the NPB cross section by V. R. Brown¹. In Fig. 2a, Hamada-Johnston and Bryan-Scott potentials are used to calculate the NPB cross section for scattered neutrons and protons at $\pm 30^\circ$ for an incident neutron energy of 200 MeV as a function of gamma-ray angle. As seen from this plot, it will be very difficult for any NPB experiment in this region of phase space to distinguish between different potentials even with excellent data. In Fig. 2b, the contributions to the cross section for the meson exchange term and the external radiation diagrams are plotted separately for the Bryan-Scott potential. As seen from the figure, the contribution of the exchange term depends on the gamma emission angle. In this calculation, the exchange term is smaller than the external term for gamma-rays emitted on the same side as the protons (positive angles) and larger than the external radiation when gamma emission occurs on the neutron side, especially at back angles.

Because this experiment will span the incident neutron energy range from 50 to 400 MeV, we shall be able to study the heavy meson contribution to the exchange term and investigate the contribution of the Δ resonance above the pion threshold.

Figure 2. Calculated NPB cross section using the Hamada-Johnston and Bryan-Scott potentials.

Heavy-Ion Physics

Since the observation of hard photon emission following heavy-ion reactions², there has been considerable recent interest in NPB cross sections. Understanding the origin of these gamma rays would give information on the early stages of the collision, where the nucleons in the two heavy ions accelerate and radiate. The interpretation of these gamma rays should be much less ambiguous than pion emission because gamma rays are not strongly absorbed. Because the NPB process allows E1 radiation, it is much larger than PPB. The dominant gamma-ray production process is therefore thought to be from NPB processes.

The gamma-ray spectra obtained² following the $^{14}\text{N} + ^{12}\text{C}$ reaction at 40, 30 and 20 MeV/nucleon are shown in Fig. 3. As seen in the figure, the gamma ray energies extend far beyond the bombarding energy per nucleon. The question is whether these high-energy gamma rays can be explained in terms of the elemental NPB process or is some collective process required. The classical NPB calculation, multiplied by 2 to roughly account for meson exchange currents, and the quantum mechanical calculations of the NPB cross section tend to agree with the data; however, these calculations have not been tested by comparing their results with measurements of the elemental NPB cross section.

Figure 3. Inclusive gamma-ray production data from ^{14}N on ^{12}C and Pb. The solid lines are calculations using semi-classical NPB cross sections. The dashed lines are calculations using quantum mechanical expressions for the NPB cross sections.

Large Cerenkov Detector Backgrounds

An experiment to measure the Weinberg angle, θ_w , has been proposed as a test of the Standard Model³. The experiment involves measuring the ratio, R , of the

neutrino-electron scattering cross sections for different neutrinos following the decay of positive pions.

$$R = \frac{\sigma(\nu_\mu, e)}{\sigma(\nu_e, e) + \sigma(\bar{\nu}_\mu, e)}$$

The pions are produced by stopping the 800 MeV proton beam from the LAMPF accelerator in a heavily shielded target cell surrounded by water. The neutrinos scatter from the electrons in the water, and the electrons produce Cerenkov light. The largest source of error in this ratio comes from gamma rays that convert into energetic electrons and mimic the electron-neutrino scattering signal. The largest source of gamma rays in the energy range of interest in this experiment (10-50 MeV) are calculated to come from NPB processes. An accurate knowledge of the NPB cross section will have significant impact on the design of this detector and the shielding of the target cell.

Past experiments

There have been very few experiments to measure the NPB cross section. Figure 5 is a plot of the off-shell parameter, ΔM^2 , as a function of gamma-ray energy divided by the projectile energy for all of the NPB experiments. The off-shell parameter is the square of the difference between the off shell mass and the proton mass, in units of the proton mass for the external diagrams. The curve labelled ref 4 is the experiment of Brady et al.⁴ at 208 MeV, the curve labelled ref 5 is the measurement by Edgington et al.⁵ at 130 MeV. Both of these experiments integrated over the gamma-ray energy. A more recent experiment by DuPont et al.⁶ at 76 MeV is shown labeled as ref 6. This experiment was similar to the preceding experiments in that it detected the proton and neutron but used a segmented detector. Also plotted in Fig. 5 is a similar curve for the region of phase space that would be obtained using the white neutron source at LAMPF with 400 MeV incident neutrons and detected outgoing nucleons at ± 20 degrees. As can be seen from the plot, this experiment probes regions significantly farther off shell than any previous experiment.

In these three past experiments the scattered neutron and the recoil proton were measured directly and

the gamma-ray energy was deduced. A recent experiment by Nifenecker and Pinston⁷ at SATURNE measured photons directly. In this experiment the inclusive gamma-ray spectrum for neutrons of 180 ± 80 MeV incident on a liquid hydrogen target was measured using a "smart" gamma-ray detector. The detector consisted of a charged-particle veto, a BaF_2 active radiator, two ΔE detectors and a large NaI calorimeter. Because the two ΔE detectors identified the converted electrons, this technique is very insensitive to neutrons.

Figure 4. Plot of the off-shell parameter ΔM^2 as a function of the gamma-ray energy for the three previous NPB experiments. The uppermost curve represents the proposed experiment at LAMPF for incident neutrons at 400 MeV and particles detected at $\pm 20^\circ$.

LAMPF/WNR Experiment

The proposed experiment will be performed at the continuous energy, white neutron source at the WNR target area at LAMPF. This source has high intensity and a neutron spectrum that extends above 400 MeV. This source has been previously described in detail.⁸ Figure 5 shows the experimental setup. The NPB measurements will proceed in three phases. The first phase will be the measurement of the inclusive gamma-ray spectrum over the incident neutron energy range from approximately 50 MeV to 400 MeV, and for gamma rays from 20 to 200 MeV. The target will consist of a liquid hydrogen cell approximately 6 cm thick and 15 cm in diameter. The

gamma-ray detector will be a multi-element gamma-ray telescope similar to that used by Nifenecker and Pinston⁷ in their inclusive experiment. The gamma-ray detector will consist of a charged-particle veto, a 1 cm thick BGO active radiator, two 5 mm thick plastic ΔE detectors, and a 40.5 x 40.5 x 40.5 NaI calorimeter. The calorimeter is segmented into 16 optically isolated 10 x 10 x 40.5 cm NaI sections. The active radiator consists of 10 pieces each 7 cm wide and 20 cm long. The efficiency of the detector was calculated to be approximately 30 percent, and the resolution is approximately 15 percent for gamma-ray energies of 150 MeV. The detectors will be located at $\pm 90^\circ$ on either side of the neutron flight path. We estimate the count rate due to NPB events to be approximately 112 events/day in a 10 MeV neutron bin and a 10 MeV gamma-ray bin. Because we shall acquire 35 pulse-height spectra in the incident neutron energy range from 50 to 400 MeV simultaneously, the total count rate should be approximately 24,000 NPB events/day. This first phase of the experiment will not be able to distinguish gamma rays from bremsstrahlung processes from gamma rays following capture or π^0 decay. The data, however, will be

NPB EXPERIMENTAL APPARATUS

Figure 5. The experimental apparatus for the neutron-proton bremsstrahlung experiment.

immediately useful to test the heavy-ion calculations and contribute to background information for the LCD experiment.

In the second phase, we shall measure the gamma rays in coincidence with the recoil protons. The proton detector will be a 200 x 60 x 1 cm thick segmented plastic array. It will be segmented into 10 cm squares and located 1.5 m downstream from the liquid hydrogen target. By measuring the recoil proton in coincidence with a gamma ray, it is possible to uniquely identify the radiation as coming from a bremsstrahlung process instead of from a capture reaction or from neutral pion decay.

Figure 6 shows the kinematics for the NPB reaction for incident neutron energies of 100, 200 and 400 MeV. In the example shown in the plot we assume that the proton is detected at 10° on the opposite side from the gamma ray. The band represents the uncertainty in the incident neutron energy which comes from the time resolution of the gamma-ray detector. As we move along the kinematic locus, the neutron angle and energy are also varying. If we set a window on a particular gamma-ray energy, we should observe two proton groups.

Figure 6. An example of the NPB kinematics for protons detected at 10° , gamma-ray detector at 90° , for incident neutrons of 100, 200 and 400 MeV.

In the final phase, we shall detect the scattered neutron. This triple coincidence experiment should allow the measurement of the NPB cross section over a wide region of phase space. Three variables (energy and two angles) for each outgoing particle will be measured, as well as the energy of the incoming neutron. Thus, the kinematics are highly overdetermined, which should allow excellent background discrimination.

We expect to mount this experiment over the next several months, with phases 1-3 taking place during the next three summer running periods.

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