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NEUTRON SPECTROMETRY FROM 1 MEV TO 1 GEV

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Revised Abstract

There is a need for an instrument to measure the fluxes and spectra of neutrons from 1 MeV to about 1 GeV. We have developed a self-contained time-of-flight spectrometer for neutrons and have measured neutron spectra in the region from 1 to 500 MeV. The spectrometer consists basically of two scintillation counters. The principle of the spectrometer requires an incident neutron to scatter elastically from a proton in the first scintillator, travel over a known flight path, and interact in the second scintillator. The time interval between these scintillation pulses is the time-of-flight of the scattered neutron. Kinematically, the kinetic energy of the incident neutron is specified in terms of the scattering angle, the flight path, and the flight-time of the scattered neutron.

A typical spectrometer configuration for neutrons above about 15 MeV consists of a $2\frac{1}{2}$ in. diam. by $2\frac{1}{2}$ in. high first detector and a 9 in. diam. by 8 in. thick second detector spaced 4 m from the first detector and at an angle of 40° with respect to the direction of the incident neutrons. For this configuration, the energy resolution varies from 7 to 20 percent and the spectrometer efficiency varies from 2×10^{-5} to 8×10^{-7} over the range of energies from 10 to 500 MeV. In measurements made thus far, the count rate of real events was typically 1 count/sec.

A modified version of the spectrometer has been designed to extend the range of the spectrometer upward to about 1 GeV. In the modified version, a telescope of two scintillation counters detects the recoil proton in coincidence with the scattered neutron. The quadruple coincidence requirement reduces the background from chance coincidences and from competing inelastic reactions of neutrons with carbon and hydrogen in the first scintillator; however, since the recoil proton must escape the first detector, this technique becomes increasingly inefficient below about 200 MeV.

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1. INTRODUCTION

We have developed a self-contained time-of-flight spectrometer for neutrons and have measured neutron spectra in the region from 1 to 500 MeV; more recently, we have modified the spectrometer to extend the range upward to about 1 GeV and have measured neutron spectra to about 725 MeV. For clarity, we shall use the term "two-fold coincidence spectrometer" to refer to the spectrometer for neutrons from 1 to 500 MeV, and the term "four-fold coincidence spectrometer" to refer to the modified version. Before describing the four-fold spectrometer in section 3, we summarize in section 2 the two-fold spectrometer which is detailed elsewhere [1].

2. THE TWO-FOLD COINCIDENCE SPECTROMETER

2.1. Principle

The two-fold coincidence spectrometer consists basically of two scintillation counters D1 and D2, which are shown schematically in Fig. 1. The principle of the spectrometer requires an incident neutron to scatter elastically from a hydrogen nucleus in the D1 scintillator, travel over a fixed flight path X and interact in the D2 scintillator. The time interval between these scintillation pulses is the time-of-flight t of the scattered neutron. Kinematically, the kinetic energy of the incident neutron is specified in terms of the neutron scattering angle θ , the flight path X, and the flight-time t of the scattered neutron. The purpose of the anticoincidence detectors A1 and A2 is to veto events produced by charged particles in the incident and scattered neutron beams.

The low-energy limit of the spectrometer is defined by the ability to detect recoil protons in the first detector with 100% efficiency. The high-energy limit occurs in practice when the background becomes significant from the neutron-proton (n-p) inelastic scattering reactions $n+p \rightarrow n+p+\pi^0$ and $n+p \rightarrow n+n+\pi^+$. Below 500 MeV, the cross sections for these n-p inelastic interactions are small relative to the total n-p cross section; hence, the spectrometer can be used for most applications to detect neutrons with energies up to about 500 MeV.

2.2. Background

Background events in the time-of-flight spectrum arise from accidental or random coincidences, neutron interactions with carbon nuclei in the D1 scintillator, and plural scattered neutrons. Gamma-rays are

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separated from neutrons by time-of-flight; hence, subtraction of the gamma-ray background is not required.

The most serious background arises from neutron interactions with carbon nuclei in the D1 scintillator. Neutron-carbon inelastic interactions in the D1 scintillator may produce both a detectable charged particle and a secondary neutron; such interactions are indistinguishable from the desired n-p interactions. A technique has been developed [1] to subtract the carbon background by making separate measurements of the neutron spectrum with D1 scintillators differing in their relative carbon-hydrogen composition. For this purpose, we have used NE-102 plastic¹ (CH_{1.105}) and NE-228 liquid¹ (CH_{2.11}) scintillators.

2.3. Resolution and efficiency

The time resolution of a spectrometer consisting of a 2 $\frac{1}{2}$ in. diam. by 2 $\frac{1}{2}$ in. high D1 scintillator and a .9 in. diam. by 8 in. thick D2 scintillator is 2.2 nsec (fwhm) for a 10 to 1 dynamic range of pulse heights from a ⁶⁰Co source. The energy resolution and efficiency of the spectrometer are shown in Fig. 2 for neutron energies from 10 MeV to 1 GeV and for neutron flight paths of from 1 to 5 m. These values were computed for a neutron scattering angle of 40° and a distance of 15 m between the target and the D1 detector. For a given neutron energy, the efficiency decreases with increasing flight path, whereas the energy resolution improves with increasing flight path. The spectrometer configuration for any measurement represents a compromise between count rate and resolution. As an example, for a flight path of 4 m, the efficiency varies from about 2×10^{-5} at 10 MeV to 8×10^{-7} at 500 MeV and the energy resolution varies from 7% at 10 MeV to 20% at 500 MeV.

2.4. Performance

Figure 3 shows the results of a measurement of 220 MeV neutrons produced by stripping 447 MeV deuterons on a 3/8 inch beryllium target in the 184 inch cyclotron at the Lawrence Berkeley Laboratory. The dashed curve is the resolution-broadened theoretical spectrum. Comparison of the measurement and the resolution-broadened theoretical spectrum indicates that the computed resolution (of 10% at 220 MeV) is correct. The excess of low-energy events is attributed to direct interactions of the deuterons with the beryllium nucleus.

Figure 4 shows the measured neutron spectra at 50° and 130° from 740 MeV proton bombardment of a 30 cm thick ²³⁸U target and the theoretical spectrum calculated with the Nucleon Meson Transport Code (NMTTC) [2]. The general purpose of these measurements was to test the degree of

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validity of the Monte Carlo calculations based on the internuclear cascade model. Measurements were made from 20 to 500 MeV at 50° and from 1 to 140 MeV at 130° . These results are reported in detail elsewhere[3].

3. THE FOUR-FOLD COINCIDENCE SPECTROMETER

3.1. Principle

A modified version of the spectrometer has been developed to reduce the background from chance coincidences and from competing carbon and hydrogen inelastic reactions and to extend the upper energy limit of the spectrometer to about 1 GeV. In the modified version shown schematically in Fig. 1, a counter telescope consisting of scintillation detectors D3 and D4 detects the recoil proton in coincidence with the scattered neutron. A counter telescope, instead of a single detector for the recoil proton, provides additional discrimination against background. For an event to be accepted, a D1-D2-D3-D4 coincidence is required without a veto from anti-coincidence detectors A1 and A2; hence, neutrons detected in D2 from inelastic carbon and hydrogen interactions in D1 are not accepted unless a charged particle is detected also in D3 and D4.

For neutron-proton elastic scattering events, the angle ψ between the recoil proton and the scattered neutron is 90° for non-relativistic energies. For relativistic energies, the angle ψ decreases slowly with increasing energy. For a neutron scattering angle $\theta=50^\circ$, the angle ψ varies from 88.5° for 100 MeV incident neutrons to 78.7° for 1 GeV incident neutrons.

3.2. Energy resolution and efficiency

The energy resolution and the efficiency (above about 200 MeV) of the four-fold spectrometer is equivalent to that shown in Fig. 2 for the two-fold spectrometer with the same D1 and D2 detectors. Below about 200 MeV corrections must be made to the spectrometer efficiency for the loss of recoil protons with insufficient energy to reach the D4 detector. Losses resulting from multiple scattering of the recoil protons can be made negligibly small by choosing the solid angle subtended by the recoil proton telescope sufficiently large to encompass nearly all multiply-scattered protons.

3.3. Background

Background in the time-of-flight spectrum is expected mainly from neutron interactions with carbon nuclei in the D1 scintillator. According to cross section data above 100 MeV compiled by Kurz [4], the total neutron carbon (n-C) cross section is typically 7 times greater, and the total n-C inelastic cross section is typically 3 times greater, than the total neutron proton (n-p) elastic cross section. Neutrons scattered quasi-elastically from protons in the carbon nucleus can satisfy the D1-D2-D3-D4 coin-

cidence requirement because such reactions are kinematically similar to n-p elastic scattering. Some background from n-C inelastic interactions may be expected also because of the relatively large cross section.

Background is expected to be negligible from the inelastic n-p reactions $n+p \rightarrow n+n+\pi^0$ and $n+p \rightarrow n+p+\pi^+$. The reasons for this expectation are two-fold: (1) the events must satisfy the kinematic and coplanarity requirements for n-p elastic scattering; and (2) the total cross section for n-p inelastic scattering in the region from 500 MeV to 1 GeV [5] is less than one-half of the total cross section for n-p elastic scattering.

For practical purposes, background from chance coincidences and from plural scattered neutrons are eliminated by the four-fold coincidence requirement.

3.4. Performance

The performance of the four-fold coincidence spectrometer was evaluated recently by measuring the neutron spectrum at 0° from 724 MeV protons on beryllium at the Lawrence Berkeley Laboratory. In this experiment, a one-inch thick beryllium target was placed inside the 184 inch cyclotron at a radius of 80.6 inches. The neutron beam was viewed through a steel collimator 2 in. high by 1 in. wide by 4 ft. long embedded in the concrete shielding wall of the cyclotron. The exit aperture of the collimator is located 15 m from the target. A quadrupole magnet, located just beyond the collimator exit aperture, deflected the charged particles from the neutron beam. The D1 detector (2 $\frac{1}{2}$ in. diam. by 2 $\frac{1}{2}$ in. high) was centered in the neutron beam 3.8 m downstream from the exit aperture of the collimator. The D2 detector (9 in. diam. by 8 in. thick) was positioned 5 m from the D1 detector and at an angle θ of 50° with respect to the incident neutrons at the D1 detector. The D4 detector (6 in. wide by 4 in. high by $\frac{1}{4}$ in. thick) was positioned 40 cm from D1 at an angle $\phi=35^\circ$ with respect to the direction of the incident neutrons or at an angle $\psi=85^\circ$ with respect to the direction of the scattered neutrons. The D3 detector (5 in. by 5 in. by $\frac{1}{4}$ in. thick) was positioned 25 cm from D1 and also at an angle $\psi=85^\circ$. The D1 detector was biased to detect a light-output equivalent to that from a 1 MeV electron. At this bias level, edge effects are negligible. The D2 detector was biased at about 6 MeV equivalent-electron energy. At this bias level, the neutron detection efficiency is approximately 20% for all neutron energies in the spectrum.

Figure 5 shows the preliminary analysis of the neutron spectrum at 0° from 724 MeV protons on a one-inch thick beryllium target. Corrections have been made to the data for the energy dependence of the differential n-p scattering cross sections using a smooth fit to existing experimental data [6]; however, apparent discrepancies between the experimental data above 150 MeV require a more careful evaluation of the data. The laboratory differential cross section for n-p elastic scattering at 50° used in this analysis varied smoothly with values of 5.3 mb/sr at 200 MeV, 3.0 mb/sr at

400 MeV, and 1.9 mb/sr at 700 MeV. The vertical error bars in Fig. 5 denote the statistical uncertainty only. This analysis does not include the uncertainty in the n-p scattering cross sections or the uncertainty in the neutron detection efficiency of the D2 detector. The spectrum shown in Fig. 5 exhibits peaks at about 350 and 700 MeV. The position of the high-energy peak has an uncertainty of ± 20 MeV as a result of an uncertainty of ± 0.2 nsec in the time calibration of the detection system. The high-energy peak in Fig. 5 has a half-width at half-maximum of about 110 MeV on the high-energy side which indicates that the energy resolution $\Delta T/T$ is about 16%; this is in agreement with the calculated resolution of 17% for this configuration. It is expected that the energy resolution could be improved to better than 10% by increasing the flight path from 5 to 10 meters. The carbon background varied from 35% in the spectrum measured with the NE-228 D1 scintillator to 50% in the spectrum measured with the NE-102 D1 scintillator. This carbon background is typically an order of magnitude smaller than that observed with the two-fold coincidence spectrometer.

A measure of the background from n-p inelastic reactions was obtained from coincidence counting rates observed with the D3 detector (D4 was not used) in positions that kinematically exclude n-p elastic scattering events. With D3 at $\psi=25^\circ$, 120° , and at $\psi=85^\circ$ but raised 5 inches, the counting rate was 15% of that observed at $\psi=85^\circ$. Except at $\psi=25^\circ$, the measurements described above were made with both NE-102 and NE-228 D1 scintillators in order to subtract the carbon background. Based on the statistics obtained in these tests, the background from n-p inelastic reactions is less than $8 \pm 10\%$ of the total n-p scattering events. Background from n-p inelastic reactions in the spectrum shown in Fig. 5 is estimated to be less than 5%. This estimate is lower than the statistical upper limit of the measured background from n-p inelastic interactions because of the theoretical considerations given in section 3.3 and the fact that only neutrons above 500 MeV, which constitute only about 25% of the spectrum shown in Fig. 5, have a significant n-p inelastic cross section.

In comparing our measurement with the previous measurement of Kiselev et al. [7] at 680 MeV, there is an apparent discrepancy in both the magnitude and position of the quasi-elastic peak. Kiselev et al. observed the quasi-elastic peak 50 MeV below the mean proton bombarding energy; whereas in our measurement, the position of the quasi-elastic peak and the mean proton bombarding energy agree within experimental error. In the measurement of Kiselev et al., peaks approximately equal in magnitude were observed at 280 and 610 MeV; whereas in our measurement, the magnitude of the quasi-elastic peak is about 0.4 of that of the 350 MeV peak. This difference may, in part, be a result of differences in energy resolution and in the corrections made for the energy dependence of the n-p differential cross section. Bertini et al. [8] have calculated the neutron spectrum predicted by the intranuclear cascade model in the interval from 0° to 5° for 660 MeV protons on beryllium. The predictions of the intranuclear cascade calculation are in better agreement with the spectrum shown in Fig. 5 than with that reported by Kiselev et al. For comparison with the measurements

at Berkeley, the intranuclear cascade calculation for 660 MeV protons has been normalized to 700 MeV.

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Fig. 1 A schematic diagram of the four-fold coincidence time-of-flight spectrometer. In the two-fold spectrometer, the recoil proton detectors D3 and D4 are not used.

Fig. 2 The efficiency versus the energy resolution for neutron energies from 10 MeV to 1 GeV and for neutron flight paths of from 1 to 5 m.

Fig. 3 Measured spectrum of neutrons at 0° from 447 MeV deuterons on a 3/8-inch beryllium target.

Fig. 4 Experimental and calculated neutron yields at both 50° and 130° from 740 MeV proton bombardment of a 30 cm thick ^{238}U target. The histogram shows the calculated results for 800 MeV protons averaged over the angular intervals from 33.5° to 60° and from 120° to 146.5° .

Fig. 5 Preliminary spectrum of neutrons at 0° from 724 MeV protons on a one-inch thick beryllium target.