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Polarization of Neutrons in n-^{12}C Scattering: A Standard for Polarization Studies in the MeV Region*

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The polarization of neutrons elastically scattered from ^{12}C at 50° has been measured as a continuous function of energy between 2 and 5 MeV using a neutron double-scattering technique. This measurement provides an absolute standard for polarization studies in this energy range. The intense pulsed yield of neutrons obtained from the first scatterer is shown to be a practicable source of polarized neutrons suitable for high-resolution experiments in the MeV region.

Despite the importance of neutron-polarization studies in furthering our knowledge of nuclear-reaction mechanisms and of nuclear structure,[1,2] no measurements of the absolute polarization of neutrons have been reported as continuous functions of energy. In previous experiments, the neutron polarization has been measured relative to the analyzing powers of other nuclei. The most notable of these is ^{4}He in which the polarization has been deduced from phase-shift analyses of the scattering data.[3] Furthermore, in those experiments[4] in which ^{12}C has been used as a neutron polarization analyzer, the analyzing powers were taken from the differing sets of phase shifts of Meier, Scherrer, and Trampy,[5] Wills *et al.*,[6] or Reynolds *et al.*[1] Hence, the need arises for an absolute calibration standard for the ^{12}C analyzing power. In this Letter, we report the results of a neutron double-scattering[7,8] experiment in which the polarization of neutrons in the reaction ^{12}C$(n,n)^{12}$C is measured absolutely throughout the energy range 2 to 5 MeV. As a refinement, the spin-precession method,[9] which we have developed recently for use with a continuous energy spectrum of neutrons,[10] is used to reduce systematic errors to negligible amounts.

The present work exploits the prolific source of neutrons available at the Yale University electron linear accelerator when operating in a mode which produces pulses of 50-MeV electrons at a rate of 300 sec^{-1}. The pulse width is 20 nsec and the peak current at the the target is 7 A. Photoneutrons are generated in a 5-cm cube of natural lead and uranium. A fraction of these neutrons is scattered from a flat plate of graphite 15 cm long × 7.5 cm wide × 1.5 cm thick (equivalent to 0.2 of a neutron mean free path at 2 MeV) placed at a reaction angle of 50° (see Fig. 1). The angular resolution of this arrangement is ± 7°. The neutrons travel along a 27-m flight path and scatter from a second graphite plate (identical to the first) into two scintillation counters which are placed at angles of ± 50° with respect to the beam axis. The counters are located 0.4 m from the center of the scatterer giving angular resolutions of ± 7°. The time-of-flight spectra are stored in an on-line PDP-7 computer; the channel widths are 6 nsec. At 2 MeV the resolution of the spectrometer is 56 keV.

A solenoid, 1.2 m long and 7.5 cm i.d., is located one quarter of the way along the flight path. The maximum axial field is 4.5 kOe, which is sufficient to give precession of the spin of a 4-MeV neutron through 180°. Since neutrons with a wide range of energies are produced in the (γ, n) target, it is necessary to determine the preces-

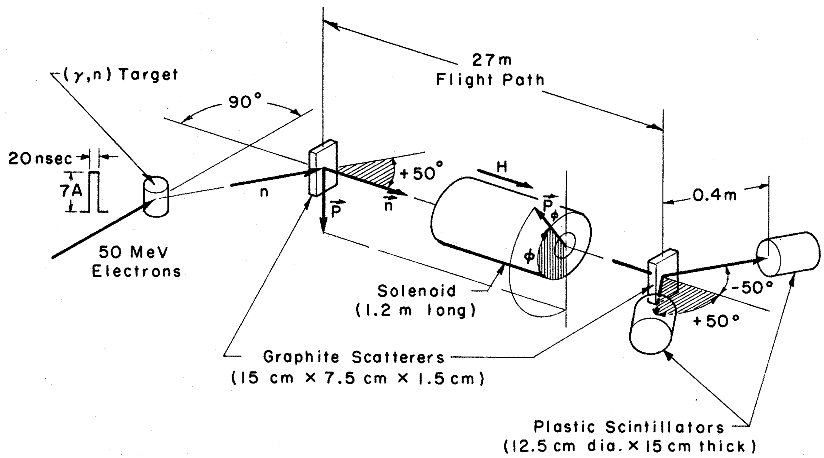

FIG. 1. Schematic diagram of the neutron double-scattering arrangement.

sional angle at each neutron energy. If E_φ is the measured energy of a neutron, whose spin precesses through φ radians when the field is set to give precession of a neutron of energy E_π through π radians, then φ is shown in Ref. 10 to be

$$\varphi = \pi(E_\pi/E_\varphi)^{1/2}. \quad (1)$$

The neutron time-of-flight spectra are recorded with and without the magnetic field. The main contribution to the background, determined with the second scatterer removed from the neutron beam, amounts to 20% of the scattered yield at energies between 2 and 5 MeV.

The conditions under which the ideal double-scattering relation $p(E) = A(E)$ can be used are determined by the energy loss ΔE of neutrons at the first scatterer and by the constancy of the polarization over the range ΔE. [Here, $p(E)$ is the polarization produced by the first scatterer and $A(E)$ is the analyzing power of the second scatterer.] These conditions are found to be well satisfied in neutron scattering from ^{12}C at energies between 2.25 and 2.40 MeV at an angle of 50° ($\Delta E = 120$ keV at 2.2 MeV). In this energy interval, the observed asymmetry in the double scattering varies slowly with energy so that the approximation

$$p(E - \Delta E/2) \approx \pm [p(E)p(E - \Delta E)]^{1/2} \quad (2)$$

can be used. Values of $p(2.25 \text{ MeV}) = -0.47$ and $p(2.3 \text{ MeV}) = -0.49$ are thereby determined where the sign is chosen to agree with that given by phase-shift analyses of the scattering data. Using these as starting values, the function $p(E)$ is deduced from the equation

$$p(E)A(E - \Delta E) = p(E)p(E - \Delta E) \quad (3)$$

by successive updating of $p(E)$ in steps of ΔE up to the sharp resonance at 2.9 MeV. In order to avoid problems associated with the effects of the finite resolution of the spectrometer in the region of this resonance, the procedure is carried out using new starting values of $p(4.8 \text{ MeV}) = +0.45$ and $p(4.9 \text{ MeV}) = +0.47$ determined from Eq. (2). The polarization $p(E)$ is then found in the range 5 to 3.1 MeV using Eq. (3) in the direction of decreasing neutron energy. The observed values of the product $p(E)p(E - \Delta E)$ are shown in Fig. 2(a): The values used in the above unfolding process are taken from the smooth curve drawn through the observed points.

In order to simplify the use of ^{12}C as a calibration standard or as a source of polarized neutrons, no corrections for finite geometry were made to the data. Fortunately, the angular distributions of the polarizations are well known[1,11] at several energies in the region of interest; averaging these polarizations in the interval of ± 10° centered at $\theta = 50°$ shows that only small corrections (≲ 2%) would be required to the present results.

The results shown in Fig. 2(b) represent the polarization of elastically scattered neutrons at 50° ± 10° (the incident neutron energy required for inelastic scattering is 4.8 MeV). Inelastic scattering in the first target is negligible compared with elastic scattering because the energy spectrum of the primary photoneutrons is Maxwellian and is such that the yield of high-energy neutrons, capable of producing inelastic events, is less than 0.1% of the yield in the energy region below 4.8 MeV.

Depolarization effects due to multiple scattering in the graphite scatterers were found to be

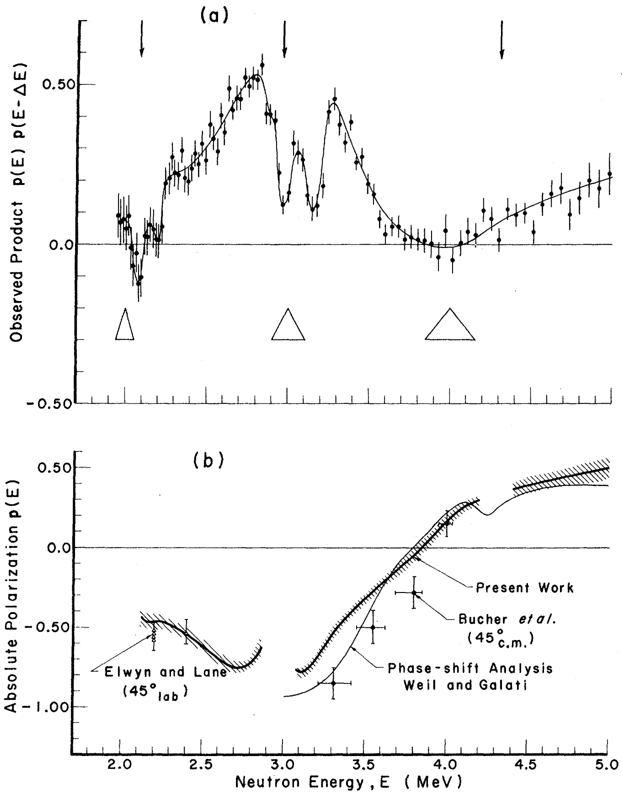

FIG. 2. (a) The observed product $p(E)p(E-\Delta E)$ as a function of incident neutron energy, with arrows indicating the positions of the 2.08-, 2.96-, and 4.3-MeV resonances, and triangles illustrating the energy resolution of the time-of-flight spectrometer. (b) The measured polarization of neutrons from the reaction $^{12}C(n,n)^{12}C$ at a laboratory angle of 50°. The cross hatching indicates the statistical errors.

small. The experiment was repeated using scatterers ranging in thickness from 0.8 cm (one eighth of a mean free path at 2.5 MeV) to 2 cm. The observed polarization did not change by more than 3% at any energy. The results shown in Fig. 2 are for the 1.5-cm-thick scatterers.

The effects of the finite energy resolution of the spectrometer ($\delta E = 56$ keV at 2 MeV and 100 keV at 3 MeV) make the analysis of the data uncertain in the regions of the sharp resonances at 2.08, 2.96, and 4.3 MeV. The values of the polarizations in the immediate vicinities of these resonances have therefore been omitted from Fig. 2(b).

Previous measurements of the polarizations, obtained by traditional mehtods, are shown for comparison.[12,13] At 2.2 and 2.4 MeV, the agreement with the results of Elwyn and Lane[13] is good. However, between 3.2 and 3.9 MeV, the present absolute values indicate significantly less polarization than those reported in Ref. 12. The phase-shift analysis of Weil and Galati,[14] which includes the results given in Ref. 12, is also shown.

Typical polarized-neutron intensities incident at the second carbon scatterer, located 27 m from the first scatterer, in units of neutrons/(100 keV)(100 cm^2)(h) vary from 1.3×10^4 at 2.3 MeV at 3×10^3 at 4.9 MeV. The polarizations are seen to be large between 2.3 and 2.9 MeV (− 50 to − 80%) and between 3.1 and 3.5 MeV (− 80 to − 40%). The total yield of polarized neutrons incident on the second scatterer between 2.1 and 5 MeV is 2.5×10^5 neutrons/(100 cm^2)(h). At this rate, the results shown in Fig. 2 were obtained in 70 h of accelerator beam time. Each datum point shown in Fig. 2(a) was therefore measured in approximately 40 min.

In conclusion, the feasibility of fast-neutron double-scattering experiments has been demonstrated in measuring the absolute polarization of neutrons elastically scattered from ^{12}C. This measurement provides a standard for polarization studies in this energy region which has a number of advantages compared with the traditionally used reaction $^4He(n,n)^4He$. Among the advantages, we note that the analyzing power of ^{12}C is now known *absolutely* in the present energy range and ^{12}C is technically more convenient to use than ^4He.

When used with the intense pulsed primary photoneutron sources available on modern high-powered electron linear accelerators or with the primary (p,n) sources available on cyclotrons, the reaction $^{12}C(n,n)^{12}C$ provides a practicable source of polarized neutrons for high-resolution experiments in the MeV region.

We wish to thank Professor E. R. Beringer for the loan of the high-field solenoid which added greatly to the success of the experiment.

*Work supported by the U. S. Atomic Energy Commission.

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α Pickup in the $A = 90$ Region

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The (^{3}He, ^{7}Be) reaction was observed for targets of ^{92}Zr and ^{93}Nb at 41 MeV. The reaction displays features expected from the pickup of an α-like fragment. The values of the cross sections agree with a prediction based on known proton spectroscopic factors. Contrary to current shell-model predictions, the trend of (^{3}He, ^{7}Be) cross sections does not require that the α spectroscopic factors change by more than 1 order of magnitude from ^{12}C to ^{93}Nb.

Whether four-nucleon transfer reactions can be described simply as an α-transfer process is a matter of current interest. Experimentally it has been shown[1] that the (^{3}He, ^{7}Be) reaction is dominated by the transfer of a $J^\pi = 0^+$ α-like fragment. This is not surprising since L-S coupling closely describes the structure of the ^{7}Be nucleus, and most of the possible configurations of the four transferred nucleons have the same quantum numbers as an α particle. However, for four-nucleon transfer reactions involving heavier projectiles which are largely j-j coupled, such a selectivity may not occur.

We have undertaken a study of the (^{3}He, ^{7}Be) reaction in the zirconium region to see if this reaction, in spite of its small cross section, could be used to investigate α structures in nuclei with large neutron excess. The reactions ^{92}Zr(^{3}He, ^{7}Be)^{88}Sr and ^{93}Nb(^{3}He, ^{7}Be)^{89}Y were induced by a 41.3-MeV ^{3}He beam from the University of Colorado cyclotron with a typical intensity on target of 1.2 μA. The experimental apparatus has been described elsewhere.[2] The ^{7}Be energy spectra are shown in Fig. 1 and the angular distributions pertinent to the following discussion appear in Fig. 2.

The strong forward peaking of the angular distributions cannot be of a statistical nature since the energy definition is larger than the coherence width of the possible compound states. It is a definite indication of the direct character of the reaction mechanism.

From ^{12}C to ^{40}Ca, (^{3}He, ^{7}Be) ground-state cross sections decreased by a factor of about 40,[1,3] but the ^{92}Zr cross section is half as large as that of ^{40}Ca and actually more than 2 times *larger* than that of ^{58}Ni.[3,4] Therefore (^{3}He, ^{7}Be) measurements remain within the limits of experimental feasibility for nuclei far heavier than calcium.

This variation of the (^{3}He, ^{7}Be) cross section has been investigated using a fixed-range approximation[2,5] for the distorted-wave Born-approximation (DWBA) factor of the cross section.[6] On the one hand, in a reaction such as (^{3}He, ^{7}Be) where absorption plays an important role, the mere increase in radius of the target nucleus reduces the cross section sharply.[1] For example, using a 3S bound-state wave function for the