Neutron Spin-Flip in the Reaction $^{12}C(n,n')^{12}C^*(4.44\ MeV)$ at 15.0 MeV

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The spin-flip probability $S(\Theta)$ in the inelastic scattering of unpolarized 15.0-MeV neutrons to the first 2^+ state in ^{12}C has been determined at $\Theta=140^\circ$ (lab.) by measuring the scattered neutrons in coincidence with the subsequent 4.44-MeV deexcitation γ-rays emitted normal to the scattering plane. Time-of-flight technique with carbon recoil detection in a plastic scintillator has been used. The neutron spin-flip probability is $S=0.21\pm0.06$.

Introduction

In the last few years there has been a considerable amount of research carried out in order to investigate the reaction mechanism and the spin dependence of the interaction in inelastic scattering of nucleons from nuclei. There are various types of measurements possible. The differential cross section $d\sigma(\Theta)/d\Omega$, the polarization $p(\Theta)$, the analyzing power $A(\Theta)$ and in special cases the nucleon spin-flip probability $S(\Theta)$ may all be measured; they are sensitive to spin-dependent forces in different ways. The present paper reports on measurements of the latter type.

For the excitation of a 2^+ state from a 0^+ ground state, the spin-flip probability (SFP) can be determined by measuring the angular correlation between the inelastically scattered nucleons and the E2 deexcitation γ-rays emitted perpendicular to the scattering plane [1]. Choosing the quantization axis (z-axis) along the normal of the scattering plane, it can be shown from a very general and model-independent reaction-plane symmetry theorem given by Bohr [2], that the $M=\pm1$ magnetic substates of the 2^+ level can only be populated by the scattering, if the scattered nucleon undergoes spin-flip relative to the z-axis. On the other hand deexcitation γ-rays can be emitted along the z-axis only from these $M=\pm1$ substates, as can be seen from the polar diagrams of E2 radiation intensities. Therefore the flux of deexcitation γ-rays along the z-axis is directly related to the SFP of the scattered nucleons. Except for a small correction for finite acceptance angles, the SFP is given by the expression [3]

$$S=\frac{8\pi}{5}\left[\frac{d^2\sigma}{d\Omega_\gamma\, d\Omega}\right]\Big/\frac{d\sigma}{d\Omega},$$

where $d^2\sigma/d\Omega_\gamma\, d\Omega$ is the double differential cross section for the nucleon-gamma correlation in the spin-flip geometry, and $d\sigma/d\Omega$ is the differential inelastic cross section.

A lot of SFP measurements have been done in inelastic proton scattering from lowest 2^+ excited states of several doubly even nuclei with mass numbers ranging from 12 to 152 and at incident proton energies ranging from 5 to 40 MeV (see e. g. [4] and references given there). A comparison of inelastic scattering of protons and neutrons having corresponding energies supplies additional information about the mechanism of the process. But because of the well-known experimental difficulties involved, neutron SFP measurements are very scarce. They mostly have been performed in inelastic scattering to the first excited state (2^+, $Q=-4.44$ MeV) in ^{12}C [5–7].

The angular distribution of the SFP in inelastic proton scattering from ^{12}C at $E_p=17.35$ MeV published by Wilson and Schecter [8] and the comparable (considering the Coulomb barrier) neutron SFP angular distribution at $E_n=15.0$ MeV measured by Spaargaren and Jonker [6] both exhibit a characteristic peak at backward angles and a smaller peak at forward angles, but there are differences in the location of the minimum between these peaks and in their relative magnitude. Comparing the proton data of Wilson and Schecter [8] at $E_p=15.9$ MeV with the measurement of the relative neutron SFP angular distribution of Braley et al. [7] at a primary neutron energy of about $E_n=14$ MeV similar discrepancies can be observed. In order to clarify the energy dependence of $S(\Theta)$ and to decide, whether the observed differences are true or if they come from experimental difficulties in neutron measurements, we have set up an experimental arrangement to measure angular distributions of the SFP in the inelastic scattering of d-t neutrons by ^{12}C. Here we present a first measurement at $E_n=15.0$ MeV and $\Theta=140^\circ$ (lab.).

Experimental Procedure

The experimental method, briefly reported in [9], is based on neutron time-of-flight technique using carbon recoil detection in a plastic scintillator and n-γ coincidence technique in the spin-flip geometry. Neutrons are produced by the $^3H(d,n)^4He$ reaction at $E_d=400$ keV. The neutrons which are emitted at 0° relative to the incident deuteron beam have a mean energy of $E_n=15.0$ MeV and are totally unpolarized, even for higher deuteron energies. They hit the carbon scatterer at a distance of 60 cm from the target. The scatterer is a cylindrical plastic scin-

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tillator NE 102 A (3.8 cm in diameter, 10.2 cm high) coupled to a 56 DVP photomultiplier, which is chosen for its low noise and high quantum efficiency. Scattering from the hydrogen nuclei of the scatterer can be discriminated. The neutrons scattered from carbon nuclei are detected in a NE 213 liquid scintillator (9.3 cm in diameter, 48.8 cm high) viewed by a XP 1041 photomultiplier. A n-γ pulse-shape discrimination system is used to eliminate counts produced in this detector by γ-rays. The axes of the scatterer and of the neutron detector are perpendicular to the scattering plane. The neutron detector is shielded by lead against γ-rays from the surroundings and by a large shadow bar of iron and paraffin against the neutron source. The apparatus allows the measurement of angular distributions of $S(\Theta)$ in the range of $30°$ to $160°$. First measurements were made with the neutron detector fixed at $140°$ (lab.). The mean flight path of neutrons from the scatterer to the detector was 200 cm, which is sufficient to separate elastically and inelastically ($Q = -4.44$ MeV) scattered neutrons. Deexcitation γ-rays are detected by a NaI(Tl) scintillator (10.2 cm in diameter, 15.2 cm long) mounted on a XP 1041 photomultiplier, both being enclosed in a cylindrical shield of lead (8.5 cm thick). An additional cylindrical shield provides a conical acceptance aperture through 11.5 cm of lead. The entire assembly is placed below the carbon scatterer and accurately centered along the z-axis. The surface of the NaI(Tl) crystal is at 30 cm from the center of the scatterer, and the half-angle subtended by the conical entrance aperture is $6.7°$. An iron pyramid shields the γ-ray detector from the neutron source.

The start signals for a time-to-amplitude converter (TAC) are derived from the neutron detector, the stop signals from the carbon recoil pulses of the scatterer. By means of an external coincidence and a gating circuit the TAC is only started, if the start pulse is followed by a stop signal within the TAC range. In this way all ineffective start and stop pulses are suppressed and the number of accepted start pulses is reduced to a minimum in spite of the very high counting rates of the scatterer and the neutron detector. Stop pulses, which are not discarded, and the pulses of the γ-ray detector are fed into a fast coincidence, the output pulses of which serve to route the TAC signals into the upper memory halve of a multichannel-analyzer, whereas all other TAC signals are stored in the lower memory halve. This method of separating the neutron time-of-flight spectrum into a non-$\gamma_{\perp}$-correlated and a $\gamma_{\perp}$-correlated spectrum (spectrum A resp. B) has the advantage, that accidental coincidences can be easily identified and subtracted. The time resolution of the spectrometer is about 4 ns (FWHM).

Data were taken during 50 separate runs of 2 hours each. The counting rate of true (n,γ)-coincidences was extremely low: about 2 cph. The summed time-of-flight spectra are shown in Figure 1. Neutrons which have experienced spin-flip in the inelastic scattering are contained in the peak of the

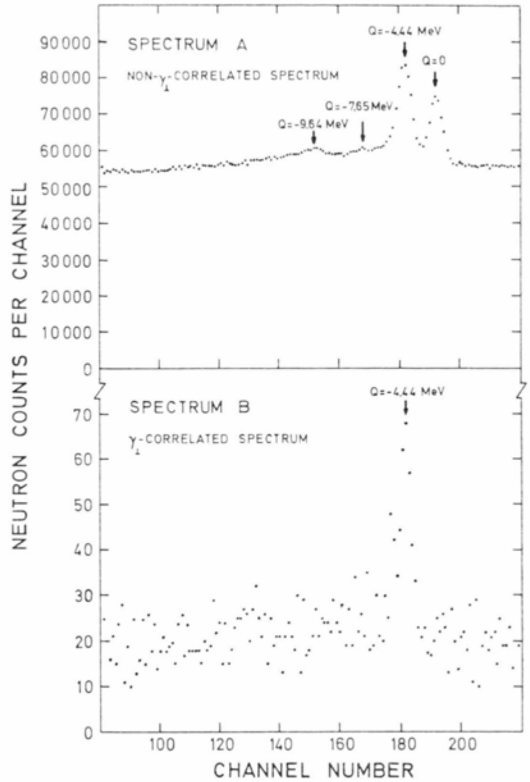

Fig. 1. Non-$\gamma_{\perp}$-correlated and $\gamma_{\perp}$-correlated time-of-flight spectra for scattering of 15.0-MeV neutrons from ^{12}C at a scattering angle of $\Theta = 140°$ (lab.). The time scale goes from right to left, the resolution is 1 ns/channel. The arrows indicate the calculated positions of peaks corresponding to known states of ^{12}C.

$\gamma_{\perp}$-correlated spectrum B. The non-$\gamma_{\perp}$-correlated spectrum A shows elastically and first-level ($Q = -4.44$ MeV) inelastically scattered neutrons clearly resolved. The hump at the left of the first-level inelastic scattering peak is due to a low-energy tail caused by multiple scattering and to inelastic scattering from higher excited state in ^{12}C ("3α" associated events in the plastic scintillator [10]). In order to separate the peaks completely the output pulses of the TAC and the pulse height spectrum of the scintillating scatterer were fed into a second multichannel-analyzer giving two-dimensional information on time-of-flight and pulse height of each scattering event during the entire measurement.

Data Reduction and Corrections

In order to determine the absolute SFP the knowledge of the absolute efficiency of the γ-ray detector for 4.44-MeV gammas is needed. The efficiency-solid-angle product including the finite volume of the scatterer was calculated to be $\varepsilon_\gamma \cdot \Omega_\gamma = (0.028 \pm 0.004)$ sr. Because of the simultaneous storage of non-$\gamma\perp$-correlated and $\gamma\perp$-correlated time-of-flight spectra it is possible to correct for chance coincidences in the peak of the $\gamma\perp$-correlated spectrum. The inelastic events in accidental coincidence were calculated by multiplying the number of noncoincident inelastic events (spectrum A) by a factor which can be deduced from those regions in the time-of-flight spectra where there are no true coincidences. The net coincidence rate per inelastic scattering was obtained by deviding the corrected peak area of spectrum B by the area of the inelastic peak of spectrum A. The influence of multiple scattering on the calculated SFP can be made negligible by an appropriate choice of the integrating limits in the time-of-flight spectra.

Coincidence losses due to pile-up and dead-time effects in the γ-ray detector system were measured to be 5%. The corresponding correction has been applied to the SFP. A further essential correction is the geometrical correction. Some of the deexcitation γ-rays from the $M = 0$ and $M = \pm 2$ substates of the excited nuclei give false contributions to the spin-flip coincidence rate because of the finite geometry. The geometrical correction of about 5% takes into account the finite acceptance angles of the γ-ray detector and of the neutron detector and the finite volume of the scatterer.

Result

The SFP in the inelastic scattering of unpolarized 15-MeV neutrons from the 4.44-MeV state of ^{12}C at $\Theta = 140^\circ$ (lab.) was measured to be

$$S = 0.21 \pm 0.06 .$$

The given error is the overall error which includes the statistical uncertainty in the number of real coincidence events, the uncertainty in the determination of the number of inelastically scattered neutrons, the uncertainties in the corrections for counting losses and for geometrical effects and the uncertainty in the absolute γ-ray detector efficiency, which is the major source of error. Within the experimental uncertainties the present result is in agreement with the results of Wilson and Schecter [8] respectively Spaargaren and Jonker [6]. In order to draw conclusions concerning the observed discrepancies at other scattering angles the entire SFP angular distribution must be measured. This measurement will be carried out in the near future.

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