SPIN FLIP IN THE INELASTIC SCATTERING OF 30- AND 40-MeV PROTONS BY ^{29}Si[†]

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Proton spin flip in excitation of the first 2^+ state in ^{28}Si has been determined at 29.7 and 40.0 MeV by measuring the correlation between inelastically scattered protons and gamma rays emitted normal to the scattering plane. The data are well described by the distorted-wave Born-approximation collective model when the deformed spin-dependent potential has the full Thomas form.

The distorted-wave Born-approximation (DWBA) collective-model description of inelastic scattering from low-lying 2^+ states has been enormously successful.[1,2] Once the optical-model parameters have been fixed by fitting elastic-scattering and polarization data, the model successfully predicts, with no additional parameters, the inelastic cross section and the asymmetry at 30 and 40 MeV. It was our intention to test the model further, by measuring the spin-flip probability at these energies. Sherif and Blair[3] have recently obtained improved agreement for forward-angle asymmetry data by using the full Thomas form for the deformed spin-dependent potential. They also noted a marked sensitivity of spin-flip predictions to the form of this potential.

We have previously measured[4] spin flip in the excitation of the first 2^+ state in ^{12}C by 40-MeV protons. The analysis of these data is inconclusive due to the well-known difficulty[5,6] in obtaining good optical-model parameters to fit the elastic scattering of protons by ^{12}C. In this paper we report recent measurements of the spin-flip probability for the excitation of the first 2^+ state in ^{28}Si at proton energies of 29.7 and 40.0 MeV. For ^{28}Si at these energies satisfactory optical-model parameters describing the elastic scattering are available.[1,7]

The spin-flip was measured using the $p,p'\gamma$ method[8] in which inelastically scattered protons which excite the first 2^+ state were detected in coincidence with de-excitation gamma rays emitted perpendicular to the proton scattering plane. The proton beam from the Oak Ridge isochronous cyclotron was focused on a 23-mg/cm^2-thick natural silicon target.[9] The scattered protons were detected using an array of 12 NaI(Tl) detectors and the gamma rays were detected by a 2-in. ×3-in.-diam NaI(Tl) detector shielded by 2 in. of lead. A 2-in.-diam aperture in the lead shield defined an acceptance angle of ±10°.

The signals from the 12 proton counters were routed into different sections of a Victoreen 20 000-channel multiparameter analyzer. The digitized proton pulses from each counter were further separated into those in coincidence with gamma rays of the appropriate energy and those not in coincidence. The coincident rate, typically about 1 count/min, was less than 10^{-3} times the noncoincident rate, and thus the latter was used for the proton singles rate. The inelastic events in accidental coincidence were found by multiplying the number of noncoincident inelastic events by the ratio of coincident elastic events (which are all accidental) to noncoincident elastic events. Since this accidental ratio was the same for all counters, it was determined more accurately by taking a weighted average of all 12 counters. The net coincident rate per inelastic scattering was obtained by subtracting the accidental inelastic events from those in coincidence, and dividing by the noncoincident events. This final ratio, which was independent of dead time in the proton-pulse electronics, was normalized by the gamma-ray detection efficiency to yield the experimental correlation. The gamma-ray efficiency was determined by using a 1.84-MeV gamma ray from a calibrated ^{88}Y source and applying a slight energy correction.

Except for a small correction for finite acceptance angles, the correlation for gamma rays emitted normal to the proton scattering plane is (for 2^+ states) proportional to the probability that the incident proton undergoes spin flip along this direction. The double-differential cross section is given by

$$\frac{d^2\sigma}{d\Omega_\gamma d\Omega_p} = \frac{5}{8\pi} S \frac{d\sigma}{d\Omega_p},$$

where $d\sigma/d\Omega_p$ is the proton differential cross section and, in the limit of zero acceptance angles, the correlation function S is equal to the spin-flip probability.

The measured correlations are shown in Figs. 1 and 2 along with DWBA collective-model calcu-

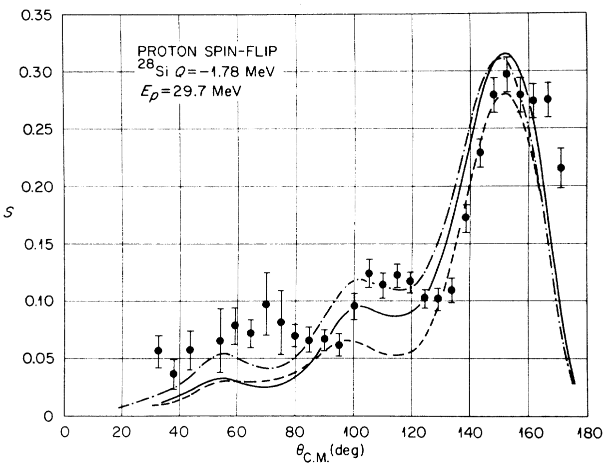

FIG. 1. Proton spin-flip probability for the excitation of the first 2^+ state in ^{28}Si by 29.7-MeV protons. The curves are DWBA collective-model calculations of Sherif and Blair. The dashed curve is for a simplified spin-dependent potential with $\beta_2^{SO} = 1.5\beta_2$. The other two curves are for the full Thomas term, for the solid curve $\beta_2^{SO} = \beta_2$ and for the dash-dot curve $\beta_2^{SO} = 1.5\beta_2$.

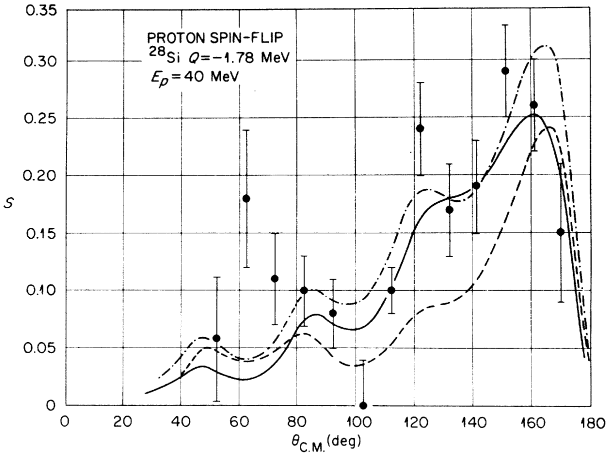

FIG. 2. Proton spin-flip probability for the excitation of the first 2^+ state in ^{28}Si by 40-MeV protons. The curves are DWBA collective-model calculations (see caption for Fig. 1).

lations carried out by Sherif and Blair. The optical-model parameters used at 40 MeV were taken from Table II in Ref. 1, and at 30 MeV, set four in Table III of Ref. 7 was used. Both sets of parameters give a good account of the elastic and inelastic cross-section and asymmetry data. These spin-flip calculations have not been corrected for finite acceptance angles. Experience with similar calculations performed at Oak Ridge indicates that the effect of a gamma-ray angular acceptance of ±10° is to increase the calculated value of S by an additive amount (about 0.02) which is approximately independent of proton scattering angle. The effect of our proton angular acceptance is negligible for proton scattering angles less than 160°. Only relative errors are shown with the data. In addition to these there is an overall uncertainty in normalization of about ±10%.

The three curves shown with the data result from different forms and strengths for the spin-dependent part of the deformed potential. A simplified deformed spin-orbit term [Eq. (5.1) of Ref. 3], which is similar to the one used to describe inelastic asymmetries,[1] was used for the dashed curve. The deformation parameter for the spin-dependent part, β_2^{SO}, was 1.5 times that for the spin-independent part, β_2. For the other two curves the full Thomas form of the deformed spin-dependent potential was used.[3] For the solid curve $\beta_2^{SO} = \beta_2$ and for the dash-dot curve $\beta_2^{SO} = 1.5\beta_2$.

The use of the complete deformed spin-orbit term improves the agreement with experiment at both energies. In addition, the 30-MeV data seem to show a slight preference for the stronger spin-orbit term, in agreement with the asymmetry results.[3]

All the calculations shown seem to underestimate the spin-flip probability for proton-scattering angles near 70°. These calculations consider only a spin transfer of zero to the target nucleus, $s = 0$. Calculations at Oak Ridge[10] using the simplified distorted spin-dependent potential indicate that the spin-flip probability in this region may be enhanced by including contributions of the allowed spin transfer $s = 1$, and $l = 2$. Detailed measurements of this type may thus provide information on the spin-spin interaction for these transitions, information which is very difficult to obtain by any other means.

We conclude that the DWBA collective-model treatment gives a good account of the present spin-flip data when the deformed spin-dependent potential has the full Thomas form and a strength perhaps slightly greater than the spin-independent part.

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PERTURBED ANGULAR CORRELATION OF NUCLEI COHERENTLY EXCITED BY PULSED-BEAM TECHNIQUES

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A new resonance method is discussed which is suited for the investigations of hyperfine interactions of excited nuclear states with lifetimes longer than 1 μsec. A first experiment was performed on a 4-μsec state of ^{69}Ge. The g factor was determined as $g = -0.222 \pm 0.001$.

We have developed a new method for studying hyperfine interactions of excited nuclear states. An excited nuclear state is produced by a pulsed particle beam with a repetition time shorter than the lifetime of the nuclear state. Then the method depends on the observation of a resonance behavior of the perturbed γ-ray angular distribution. The resonance occurs if the Larmor frequency of the excited nuclei in an external magnetic field is equal to a multiple of half the pulse frequency.[1] The width of the resonance is limited by the natural linewidth of the nuclear state. Corresponding to Freeman's method of the differential measurement of the Larmor precession,[2] a nuclear reaction excites and aligns the nuclei using a pulsed particle beam. If the emitted γ radiation has an anisotropic angular distribution and if the magnetic field H_0 is perpendicular with respect to beam and detector direction, the intensity observed at a fixed angle is modulated with the Larmor frequency ω_L. This method can be applied as long as the lifetime τ of the excited state is shorter than the pulse repetition time T_0 and the pulse length is $\Delta T \ll 1/\omega_L$.

In our experiment many beam pulses occur within the lifetime of the state, i.e., $\tau > T_0$. In the case of resonance, $T_0 = n\pi/\omega_L$ $(n = 1, 2, \cdots)$ (Fig. 1), all nuclei originating from different pulses precess with a constant phase with respect to the beam pulses, i.e., one gets a coherent superposition of the intensity modulation produced by the perturbed angular correlation. Off resonance, Larmor frequency and excitation frequency are out of phase which results in an attenuation of the modulation amplitude.

The intensity of the γ radiation at a time t (0

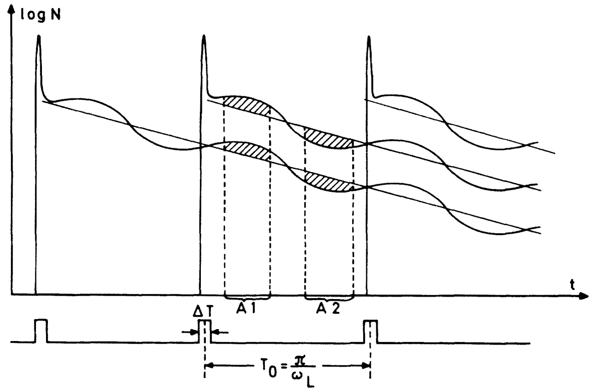

FIG. 1. Schematic illustration of the principle of synchronous Larmor precession. In the resonance, shown here, the counting rates A_1, A_2 are sensitive to the anisotropy of the perturbed angular correlation.