$+\frac{1}{2})^{1/2}$. The sum is only over the 8 (of the 12) neutron orbitals of Clement and Baranger[8] that are above the proton Fermi sea. Using the values of $u_j v_j$ of Ref. 7, and the nuclear force mentioned above, we obtain a width of 1.1 keV. This large value arises because of pairing enhancement as well as reduced Coulomb and angular momentum barriers.

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Observation of Polarization Transfer in the Reaction ^{56}Fe$(d,p)^{57}$Fe* Using the Mössbauer Effect

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Transfer of polarization to the residual nucleus in a nuclear reaction has been observed by combining the use of a vector-polarized deuteron beam with Mössbauer measurements of magnetic sublevel populations. A large transfer of polarization was seen in the reaction ^{56}Fe$(d,p)^{57}$Fe* terminating in the 14.4-keV state of ^{57}Fe, consistent with a simple polarization-transfer mechanism. The method is applicable to a number of reactions leading to Mössbauer final states.

Simple arguments suggest that in (d,p) stripping reactions induced by vector-polarized deuterons, a large fraction of the deuteron polarization ought to be transferred to the final state of the reaction. This polarization transfer might be reduced by spin-flip processes and also by the D-state admixture of the deuteron.

Measurements of polarization-transfer parameters by direct methods are equivalent in principle to triple-scattering experiments which present formidable difficulties even with the polarized beam intensities available today. The only measurement of the polarization transfer in stripping on a complex nucleus is the result of Brown *et al.*[1] for the reaction ^{28}Si$(d,p)^{29}$Si at a proton angle of 0°. This gave a value of 1.0 ± 0.1 for the ratio of the outgoing proton polarization to the incoming deuteron polarization, compatible with a simple picture treating the proton as a spectator in the reaction. This simple model of the reaction appears to be approximately valid for few-body systems as well. In experiments carried out at The University of Birmingham[2] and at Los Alamos Scientific Laboratory,[3] large values of polarization transfer were observed in every case studied to date including the reactions ^{1}H$(d,n)2p$, ^{2}H$(d,n)^{3}$He, ^{3}H$(d,n)^{4}$He, and ^{3}He$(d,p)^{4}$He.

The present paper reports the first observation of polarization transfer to the 14.4-keV level of ^{57}Fe populated by a (d,p) reaction. The polarization of the 14.4-keV level ($I^{\pi}=\frac{3}{2}^{-}$) was determined directly by measuring the relative populations of the $m_I=+\frac{3}{2}$ and $m_I=-\frac{3}{2}$ sublevels using the Mössbauer effect.

Previous work[4-6] has established that the recoilless fraction and the effective internal field at which most of the ^{57}Fe nuclei from the reaction ^{56}Fe$(d,p)^{57}$Fe* find themselves are the same as those for ^{57}Fe produced in the decay of ^{57}Co at normal lattice sites.

In the present experiment the vector-polarized deuteron beam from the University of Birmingham radial ridge cyclotron was used, the energy being $E_d=12.3$ MeV at a beam current not exceed-

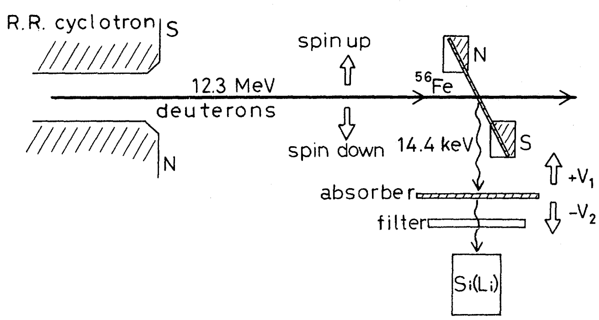

FIG. 1. Schematic diagram of the experimental arrangement.

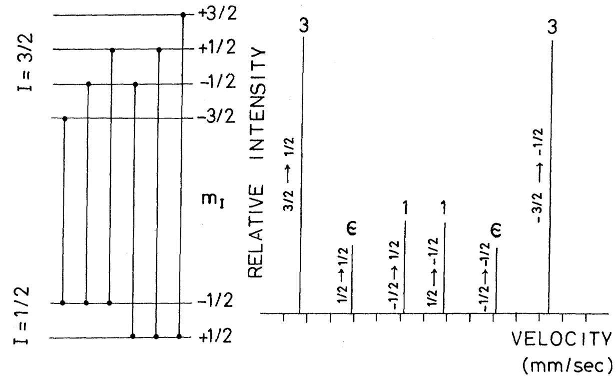

FIG. 2. Energy-level diagram and magnetic hyperfine spectrum of the Mössbauer transitions in ^{57}Fe. The energy levels are drawn for an isolated iron nucleus in an external field. The relative intensity indicated by ϵ depends on the orientation of the field.

ing 0.5 nA. A schematic diagram of the arrangement is shown in Fig. 1. The beam was focused onto a 5-mg/cm^2-thick ^{56}Fe target held near room temperature.[7] The normal to the plane of the target foil was tilted in a vertical plane by an angle $\varphi = 17°$ with respect to the incident beam. Small permanent magnets were used to magnetize the foil in its plane. The magnetizing field was approximately antiparallel to the field of the main cyclotron magnet, which defines the direction of the deuteron-beam polarization vector. It should be noted that the internal field of iron as experienced by the nucleus lies in the opposite direction to the magnetizing field. In this experiment, therefore, the cyclotron field and the field experienced by the iron nuclei are approximately parallel. All calculations are referred to a coordinate system in which the z axis is parallel to these two fields.

The vector polarization[8] of the beam, p_B, was monitored continuously throughout the run by a polarimeter using the reaction ^{12}C$(d,p)^{13}$C, whose vector analyzing power is well known.[9] In the present experiment the average beam polarization was $p_B = 0.46$. This polarization was reversed in sign at a frequency of 6 Hz. Photons from the iron target traveling vertically downwards escaped from the vacuum chamber through a Mylar window. The radiation passed through a resonant absorber and a Lucite filter, 3 mm thick, into a 10-mm-diam high-resolution Si(Li) detector. The resonant absorber was a disk of epoxy resin containing ^{57}Fe in the form of 14.8 mg/cm^2 of lithium ammonium fluoroferrate and was made by the process described by Housley, Erickson, and Dash.[10] This "single-line" absorber had a nuclear attenuation $1 - e^{-\mu d} = 0.78$ for narrow recoilless lines, and it had a linewidth of approximately 1.6 mm/sec. It was moved alternately at constant positive (v_1) and negative (v_2) velocities relative to the target using an electromechanical motion device. The values of v_1 and v_2 required for selection of the hyperfine transition were determined in a subsidiary calibration experiment using a ^{57}Co source in an iron lattice. The velocities $v_1 = +5.5$ and $v_2 = -4.9$ mm/sec were chosen to sample alternately the intensities of the outermost lines of the Mössbauer spectrum corresponding to the transitions $m_I = +\frac{3}{2} \rightarrow m_I = +\frac{1}{2}$ and $-\frac{3}{2} \rightarrow -\frac{1}{2}$, respectively, shown in Fig. 2.

Pulse-height spectra of the Si(Li) detector were routed into four separate parts of a 2048 channel analyzer, the memory quarter depending on the polarization state of the deuteron beam, spin up or spin down, and the direction of the velocity of the resonant absorber. The counting rate for the 14.4-keV group was 4 counts/sec of which about 1.5 counts/sec were genuine, the remainder being due to background. The solid angle subtended by the γ detector was 4×10^{-2} sr. The 14.4-keV line was prominent. For the iron K x rays of 6.40 and 7.05 keV, deliberately attenuated by the Lucite filter, the counting rate was 200 counts/sec. These groups served as a useful monitor of the product of the integrated beam current and target thickness.

Polarization transfer effects were revealed by calculating the ratio r, given by

$$r = N_{+\mathrm{up}} N_{-\mathrm{down}} / N_{+\mathrm{down}} N_{-\mathrm{up}} \qquad (1)$$

where N is the number of counts in the 14.4-keV peak, and the subscripts refer to the direction of the absorber motion and deuteron spin polarization, respectively. In the absence of any polarization transfer effects, $r = 1$. However, in the present experiment four separate measurements resulted in an overall mean value of $r=1.040 \pm 0.008$ without any attempt being made to subtract background. Allowing for the background contribution to the peak results in $r=1.14\pm 0.03$. An additional measurement was made with the sign of the magnetizing field on the target reversed. The value of the ratio was then $r=0.974 \pm 0.018$ before allowing for background, showing the expected reversal of the direction of the effect. In order to check for systematic errors the same ratio was calculated for the iron K–x-ray peaks. The mean result was $r=1.0003\pm 0.0012$ for the x-ray groups of the first measurement mentioned above.

In order to predict the direction of the effect, it was necessary to take into account the following aspects of the experiment: (a) orientation of the magnetizing field relative to the deuteron spin vector; (b) direction of the internal field in iron with respect to the direction of the applied magnetizing field (antiparallel); (c) the Mössbauer technique used (absorption detection method). The answer will also depend upon the assumed mechanism of the reaction. The observed direction of the effect was as expected if one assumed that the role of the proton in the reaction is that of a spectator to the capture of the neutron by the ^{56}Fe nucleus.

In order to use the measured ratios to extract a numerical value for the polarization of the ^{57}Fe* nucleus, it is necessary to correct for the recoilless fractions and for the incomplete magnetization of the target foil. It is readily shown that the observed net polarization of the $m_I=\pm\frac{3}{2}$ sublevels of the 14.4-keV level is given in terms of the measured counting rates by

$$P=\frac{N_{+3/2}-N_{-3/2}}{N_{+3/2}+N_{-3/2}}=\frac{R-1}{R+1}\,\frac{1}{M-1}, \tag{2}$$

where $R=r^{1/2}$ is the ratio of the counting rates for the outermost lines for a single state of polarization of the beam, M being the ratio of off-resonance to mean on-resonance counting rates. The above results imply $R=1.020\pm 0.004$. Subsidiary on-resonance/off-resonance measurements using the same resonant absorber gave $1/M=0.949 \pm 0.019$.

These values of $1/M$ and R, containing background contributions, lead to a value of polarization $P=0.18^{+0.12}_{-0.06}$. Using the background-corrected value of the ratio $r=1.14\pm 0.03$, we obtained a polarization value $P=0.61\pm 0.18$.

The errors quoted are purely statistical. No allowance has been made for possible systematic background subtraction uncertainties. No correction for incomplete magnetization of the target has been applied.

By taking into account the beam polarization p_B, the polarization transferred in the reaction to the final nucleus can be defined as

$$F=P/p_B, \tag{3}$$

where P in the present experiment is averaged over all reaction angles and all excitations cascading through the 14.4-keV level. Thus, the value of the polarization transferred is $F=1.33 \pm 0.39$, out of a maximum possible transfer $F_{\max}=1.5$. Finally therefore, $F/F_{\max}=0.89^{+0.11}_{-0.28}$. Any depolarizing effects due to spin relaxation are likely to decrease the final value. The spin-lattice relaxation time is of the order of 250 μsec at room temperature in regular lattice sites.[11] The significant difference in populations of the $m_I=+\frac{3}{2}$ and $m_I=-\frac{3}{2}$ sublevels observed in the present work demonstrates that the relaxation time in most of the lattice sites in which the ^{57}F* nuclei find themselves due to the (d,p) reaction is not less than the lifetime of the 14.4-keV state, i.e., 10^{-7} sec. Measurements at various temperatures may help to determine the spin-lattice relaxation time more accurately.

Tests carried out at the conclusion of the experiment showed that less than 1% of the 14.4-keV γ rays were contributed by the gradually accumulating ^{57}Co nuclei produced in the target.

The experiment was not designed to select effects resulting from direct population of the 14.4-keV level; all other processes of the $(d,p\gamma)$ type which cascade through this level were included. The transition probabilities measured were thus integrated over all angles of the outgoing protons.

Even so, the present experiment confirmed that large transfers of polarization occur in (d,p) reactions and established that the observation of the Mössbauer effect in reactions induced by polarized beams is a useful tool for study of polarization transfer phenomena in certain cases.

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$M1$ Transitions from $g_{9/2}$ Analog-to-Antianalog States in the Nuclei ^{59}Cu, ^{61}Cu, ^{63}Cu, ^{65}Ga, and ^{67}Ga

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We have found $g_{9/2}$ analog resonances in the reactions ^{58,60,62}Ni$(p,\gamma)^{69,61,63}$Cu and ^{64,66}Zn$(p,\gamma)^{65,67}$Ga with strong $M1$ transitions to the corresponding antianalog states.

The $M1$ transitions from the isobaric analog resonances (IAR) to the antianalog states (AIAS) have recently received much attention from both experimental and theoretical points of view.[1-9] It has been pointed out that these transitions are strong in the $2s$-$1d$–shell nuclei and are hindered by several orders of magnitude in the lower part of the $1f$-$2p$ shell. In a previous article[10] some preliminary results were published on the reaction ^{58}Ni$(p,\gamma)^{59}$Cu which indicated that the IAR-to-AIAS $M1$ transition strength rises to the order of the single-particle strength again. In order to collect more detailed information on the general behavior of these transitions, we have extended our investigations to (p,γ) reactions of other even-even nuclei of the upper part of the $1f$-$2p$ shell, namely, to the reactions ^{58,60,62}Ni(p,γ)-^{59,61,63}Cu and ^{64,66}Zn$(p,\gamma)^{65,67}$Ga.

The experiments were performed with the 4-MeV Van de Graaff accelerator of the Central Research Institute for Physics. The Zn targets were evaporated from natural metallic zinc, and the ^{58,60,62}Ni targets, enriched to 97.6, 95.1, and 90.6%, respectively, were electroplated onto thick gold backings. The thickness of each target was ~2 keV so the total (beam plus target) energy resolution of the system was about 3 keV in every case. A 7.5×7.5-cm^2 NaI(Tl) scintillation detector was used for the simultaneous measurement of the excitation functions for γ rays of energy

(i) $E_\gamma > E_1 - 200$ keV,

(ii) $E_\gamma > E_2 + 300$ keV,

(iii) $E_2 + 300 > E_\gamma > E_2 - 1300$ keV,

where E_1 is the energy of the first excited state of the target nucleus and E_2 is the expected energy of the IAR-AIAS transition. The excitation functions were measured in 2.5-keV steps over a region of about 150 keV around the expected position of the IAR's. The detailed γ spectra were taken with a 30-cm^3 Ge(Li) detector.

Since all the excitation functions, including those of type (iii), showed very complex structure except for that of the reaction ^{58}Ni$(p,\gamma)^{59}$Cu (see Fig. 1 of Ref. 10), it was necessary to measure the γ-ray spectra for each resonance found in the bombarding energy region covered in order to get further evidence for the identification of IAR's beyond their position. In each nucleus studied here resonances were found whose spectra were markedly different from those of all others. The difference consisted of strong transitions to the low-lying $g_{9/2}$ state, with this decay branch being the strongest primary transition in the spectrum. In each final nucleus there is only