Study of the Reaction ^{56}Fe$(p,n)^{56}$Co to the Antianalog State*

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(Received 14 January 1974)

The reaction ^{56}Fe$(p,n)^{56}$Co was studied at $E_p = 22.8$ MeV for both the isobaric-analog-state (IAS) and antianolog-state (AAS) transitions. The difference in the observed angular distributions for these two $L = 0$ transitions is not as striking as in (^{3}He,t) measurements. The strong cancelation expected for the AAS case was observed. The shapes of the angular distributions for both the IAS and AAS were improved by inclusion of a coherent two-step $(p,d)(d,n)$ process.

Nuclear reactions such as (p,n), (^{3}He, t), and (π^+, π^0) can proceed through a simple charge-exchange mechanism. This mechanism explains the strong population of the isobaric analog state (IAS) which is observed for (p,n) and (^{3}He, t) reactions on target nuclei with more neutrons than protons. The IAS has the same spin and space wave function as the target ground state, differing only in the z projection of the nuclear isospin. In the case that the excess neutrons occupy several neutron orbitals their contribution to the IAS cross section is coherent and constructive for a charge-exchange reaction.

When the excess neutrons occupy more than one shell in the lowest-order shell model, one can construct states in the residual nucleus with the same J and π as for the IAS but with isospin one unit smaller.[1] These states are called antianalog states (AAS). In the event that the charge-exchange transition amplitudes associated with various neutron orbitals are similar, strong cancelation should occur so that charge-exchange reaction cross sections to the AAS should be weak relative to those for the IAS.[1] Because of the strong cancelation, the AAS cross section should be quite sensitive to details of the target-nucleon configuration. It is of more than usual interest, then, to study charge-exchange reactions leading to AAS.

Identification of AAS of even-even targets has generally been made by finding a single 0^+ level below the IAS. A variety of reactions have been used to make such assignments including the low-energy ^{40}Ar$(p,n)^{40}$K study by Twin, Olsen, and Wong.[2] In that study, however, the reaction was completely dominated by the compound-nucleus mechanism rather than a charge-exchange mechanism. When AAS were studied by the (^{3}He, t) reaction by Hinrichs *et al.*[3] it was found that the observed angular distributions were roughly out of phase with those of the IAS and could not be explained by a one-step charge-exchange mechanism.

A suggestion was made by Schaeffer and Bertsch[4] that an out-of-phase shape could be obtained by contributions from the (^{3}He, α)(α, t) reaction. Their suggestion led to a detailed calculation by Coker, Udagawa, and Wolter[5] who showed that the cancelation of the coherent one- and two-step amplitudes gave an out-of-phase angular distribution.

It remained to be seen whether the (p,n) reaction at a higher energy where the compound-nucleus effects are smaller would exhibit AAS angular distributions which were markedly different from those of the IAS, and whether a similar two-step process could successfully describe (p,n) AAS data. In this Letter we report the first reasonably complete angular-distribution data for a (p,n) reaction to an AAS with a bombarding energy clearly in the direct-reaction regime. These data were acquired with a unique new experimental facility which allows the use of heavily shielded long-flight-path detectors while still retaining the ability to take angular distributions over a wide range of angles.

We have chosen to study the (p,n) reaction to AAS for two reasons. First, the nucleon-nucleus optical potential is well founded in comparison to that for complex projectiles, making analysis more straightforward. Second, the (p,n) reaction is more sensitive to interior portions of the

nuclear wave function while the (^{3}He, t) reaction is mainly influenced by the nuclear surface because of strong absorption of complex projectiles, thus making the predicted one-step cancelation for AAS with (p, n) reactions more striking than in the (^{3}He, t) reaction. The (p, n) reaction study is, of course, experimentally more difficult; however, these difficulties are partially offset by larger cross sections and by the use of thicker targets than those that can be used in (^{3}He, t) studies.

We chose the reaction ^{56}Fe(p, n)^{56}Co for our first study. The measurements were made with the University of Colorado rotating-beam neutron time-of-flight spectrometer[6] at a proton energy of 22.8 MeV. This new system employs neutron detectors at fixed, well-shielded positions and varies the angle of incidence of the beam upon the target to obtain an angular distribution. Initial data were obtained at 9 m flight path where Gaussian unfolding procedures were necessary to extract the area of the AAS peak at 1.45 MeV from that of the neighboring 1.72-MeV level. These data were verified and extended by subsequent measurements at a flight path of 29 m. Two 2.54-cm × 20-cm NE-224 liquid scintillation detectors were placed side by side in an earthen-shielded bunker for these longer-flight-path measurements. The 9-m measurements utilized three similar detectors in concrete shields arranged so that data for three angles were obtained simultaneously. Neutron-γ discrimination was employed to reduce background. A time-of-flight spectrum is shown in Fig. 1 with shorter flight times and hence higher neutron energies to the right and a time per channel of 0.3 nsec. The known doublet character[7] of the IAS in ^{56}Co was evidenced by the increased width seen for this peak compared to adjacent peaks.

The incident proton beam was varied in angle to obtain data between 10 and 120° lab angles. The target was 6-mg/cm^2 natural iron. The ^{54}Fe component of natural iron cannot produce neutrons with energies above those of the IAS group in Fig. 1. The ^{57}Fe and ^{58}Fe components can. Spectra taken with an ^{57}Fe target indicated no sharp levels near the ^{56}Co AAS. The 0.33% ^{58}Fe component cannot produce a detectable neutron group except possibly for its IAS transition which would lie beside the ^{56}Fe IAS group.

The angular distributions for the ^{56}Fe IAS and AAS transitions are shown in Fig. 2. The strong cancelation predicted for an AAS is quite evident in the data. The clear-cut difference in phase of the angular distributions seen in (^{3}He, t) measurements is not nearly so evident in the (p, n) data although there are substantial differences in the two $L=0$ transitions of Fig. 2.

The solid curves in Fig. 2 are distorted-wave Born approximation (DWBA) calculations for a one-step charge-exchange process with a 1-fm-range Yukawa interaction between the projectile and target nucleons. The dashed curves are the calculations for the (p, d)(d, n) process[8] from a

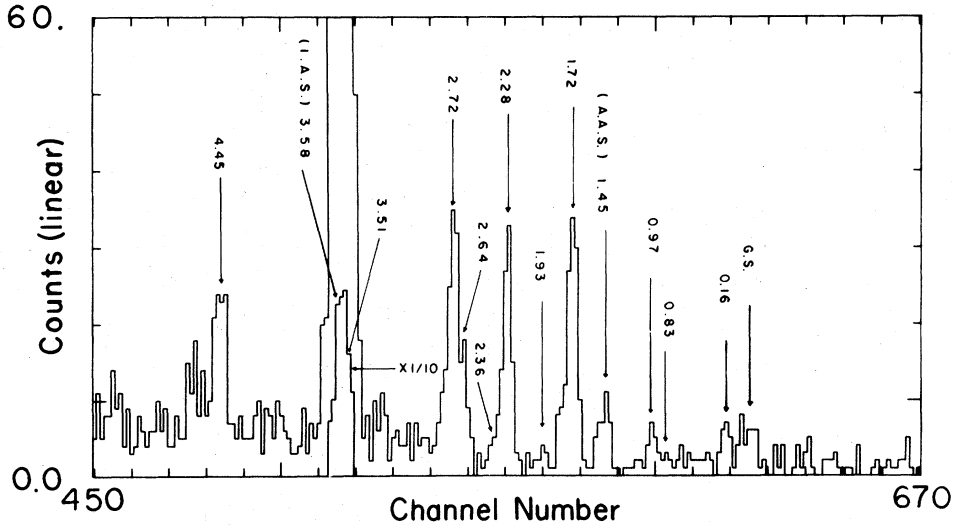

FIG. 1. Time-of-flight spectrum for ^{56}Fe(p, n)^{56}Co taken with one 1-in. × 8-in. detector at the 29-m station at an angle of 10°. Time per channel is 0.3 nsec. The AAS level is at 1.45 MeV excitation.

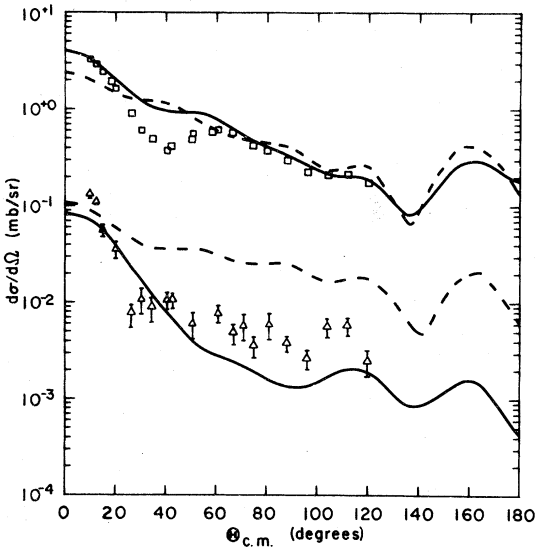

FIG. 2. IAS (squares) and AAS (triangles) angular distributions obtained for ^{56}Fe(p,n) at $E_p = 22.8$ MeV. Solid curves result from DWBA (charge-exchange only) calculations normalized to IAS. Dashed curves are absolute $(p,d)(d,n)$ two-step calculations using experimental (p,d) spectroscopic factors.

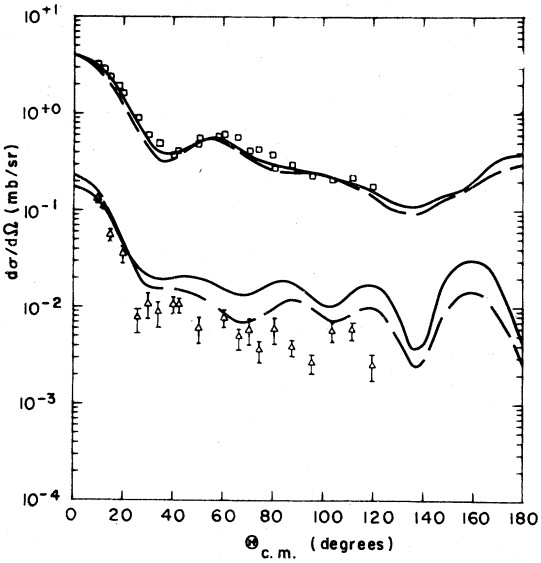

FIG. 3. Second-order DWBA calculations for IAS (squares) and AAS (triangles) angular distributions. Calculations include $(p,d)(d,n)$ two-step process and charge exchange. Solid curves give results due to experimental spectroscopic factors for the (p,d) reaction, and dashed curves result from arbitrarily modified spectroscopic factors and show the relative sensitivity of the AAS prediction to details of the ^{56}Fe wave function. Charge-exchange strength, 33 MeV.

differential-equation solution for the second-order DWBA term. The intermediate states in the deuteron channel include the first six states of ^{55}Fe.

The charge-exchange calculation is normalized to the IAS cross section with the one free parameter, $V_T = 22$ MeV. Optical-model potentials for the projectiles are given in Table I. No reasonable variation in the range of the interaction, optical potentials, or nuclear wave function was found which could substantially improve the shape of the calculated angular distributions. The $(p, d)(d, n)$ calculation uses the experimental spectroscopic amplitudes and hence has no free parameters.

The coherent addition of the charge exchange and $(p, d)(d, n)$ amplitudes gives the angular distributions in Fig. 3. The charge-exchange strength must be increased to $V_T = 33$ MeV because of the destructive interference between the one- and two-step amplitudes for the IAS state. This strength is the same as found previously in analysis[8] of (p, n) reactions in neighboring nuclei. The resulting shape of the angular distributions is improved for both the IAS and the AAS. Variations of the Yukawa range in the one-step component between $0.7 < \mu < 1.2$ did not greatly alter the AAS/IAS ratio but did slightly worsen the IAS fit.

The calculations for the solid curves in Fig. 3 have been made with published values[9] of the spectroscopic factors:

$$S_{5/2} = 0.87, \quad S_{3/2} = 1.00, \quad S_{1/2} = 0.42.$$

TABLE I. Optical-model potentials.

	V_R (MeV)	r_R (fm)	a_I (fm)	W_V (MeV)	W_D (MeV)	R_I (fm)	a_I (fm)	V_{SO} (MeV)	r_{SO} (fm)	a_{SO} (fm)
$p + {}^{56}$Fe	51.1	1.17	0.75	2.34	6.93	1.32	0.56	6.0	1.01	0.75
$n + {}^{56}$Co	$53.1 - 0.3E_n$	1.17	0.75	$0.22E_n - 2.7$	$11.4 - 0.25E_n$	1.32	0.56	6.0	1.01	0.75
$d + {}^{55}$Fe	$110.7 - 0.32E_d$	1.17	0.779	0	$24.5 - 0.25E_d$	1.32	0.593	12.0	1.01	0.75

An indication of the sensitivity to the details of the nuclear wave functions is given in a second set of calculations made with

$$S_{5/2}=0.47, \quad S_{3/2}=1.40, \quad S_{1/2}=0.42.$$

The IAS prediction is virtually unchanged. The AAS prediction was changed, however, with the results shown in the lower dashed curve of Fig. 3. Thus, even though two-step processes may significantly affect the (p,n) reactions as well as (^{3}He, t) reactions, the expected sensitivities to nuclear wave-function details for the AAS transitions remain in the (p,n) calculations. It should be further noted that the two-step processes in (p,n) reactions appear to be less important than in (^{3}He, t) reactions where the two-step process alone can fully account for the IAS and AAS cross sections.[5]

The present calculations are fairly crude. For example, we have not explicitly included the knock-on exchange[10] but have accounted for it implicitly in renormalization of the charge-exchange strength; thus we have assumed it has the same effect for the AAS transition as for the IAS. Furthermore, the charge-exchange interaction was taken to be of Yukawa form which may be somewhat too simple to provide a satisfactory monopole form factor.[11] Finally, we have not included other possibly important two-step processes. We have calculated multistep contributions through inelastic channels and found them to be of negligible importance for both the IAS and AAS transitions. We cannot, however, rule out the possible importance of other $(p,X)(X,n)$ processes where X is a cluster more complicated than dinucleons.

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

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Isospin-Forbidden Proton Partial Width in ^{41}Sc and Similar $A = 4n + 1$ Nuclei*

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(Received 2 November 1973; revised manuscript received 3 June 1974)

The lowest $T=\frac{3}{2}$ level in ^{41}Sc is observed as an isospin-forbidden resonance in ^{40}Ca$(p, p_0)^{40}$Ca at $E_{p,\mathrm{lab}}=4.978$ MeV with proton partial width $\Gamma_p=55\pm5$ eV, which is about 50 times smaller than that previously assigned and 6 times smaller than theoretical width estimates. The trend of the proton reduced widths for $T=\frac{3}{2}$ isospin-forbidden resonances obtained from Γ_p values for target nuclei with $4\leq Z\leq 20$ is shown to be consistent with a Z^2 dependence.

Nuclear levels can be characterized by the isospin quantum number T which would be unique for each level if electromagnetic (predominantly Coulomb) and charge-dependent nucleon-nucleon interactions were absent.[1] However, there is ample experimental evidence for isospin mixing[2-5] by which small admixtures of other T values arise. Isospin mixing is generally believed to increase rapidly with nuclear charge Z for $Z\leq 20$, perhaps as $Z^{8/3}$ for $T=0$ ground states,[6] and then to decrease steadily with Z for heavier nuclei.[2,4,6] One effect of the mixing is the small but nonzero