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Quenching of isoscalar spin-flip strength in ^{54}Fe

D. F. Geesaman, R. D. Lawson, and B. Zeidman
Argonne National Laboratory, Argonne, Illinois 60439

G. C. Morrison
University of Birmingham, Birmingham, United Kingdom

A. D. Bacher and C. Olmer
Indiana University, Bloomington, Indiana 47405

G. R. Burleson, W. B. Cottingame, and S. J. Greene
New Mexico State University, Las Cruces, New Mexico 88003

R. L. Boudrie and C. L. Morris
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

R. A. Lindgren
University of Massachusetts, Amherst, Massachusetts 01003

W. H. Kelly*
Montana State University, Bozeman, Montana 59715

R. E. Segel
Northwestern University, Evanston, Illinois 60201

L. W. Swenson
Oregon State University, Corvallis, Oregon 97331
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The inelastic scattering of 162 MeV π^+ and π^- to 8^- states in ^{54}Fe was studied. Isoscalar and isovector structure amplitudes were extracted for each state. The summed isoscalar strength corresponds to only 11% of that predicted in an $[(f_{7/2})^{-3}g_{9/2}]_{8^-}$ calculation, while 38% of the isovector strength is observed. This is similar to the quenching of strength observed in lighter nuclei and demonstrates that the strong quenching of the isoscalar spin-flip strength persists in the f-p shell.

I. INTRODUCTION

Pion inelastic scattering has proved to be a valuable tool for studying the isospin structure of nuclear excitations. As a consequence of the elementary pion-nucleon interaction near the (3,3) resonance, pions excite isoscalar states a factor of 4 more strongly than isovector states with the same internal structure. At large momentum transfer, high-spin-particle-hole states are selectively excited in pion inelastic scattering.[1] The transition amplitudes might be expected to have relatively simple structure since a one-body $1\hbar\omega$ excitation can only involve one j subshell of each major oscillator shell. This paper reports the study of pion inelastic scattering to 8^- states in ^{54}Fe. These data were analyzed in the DWIA formalism which provided a reasonable description of the angular distributions. By combining the analysis of the pion data and previously published electron data, isoscalar and isovector transition strengths were extracted for each 8^- state.

The selectivity of pion inelastic scattering for isoscalar spin-flip strength is particularly valuable since no other nuclear probe shares this selectivity. This fact makes pion scattering a natural complement to 180° electron scattering which selectively excites isovector spin-flip states. At the present time, the isoscalar spin-flip mode of the nuclear response is the least understood of the elementary modes of excitation of nuclear ground states. With the ^{54}Fe results obtained in this work, it is clear that much less isoscalar spin-flip strength has been identified in high-spin-particle-hole states than isovector spin-flip strength. This phenomenon persists from the $0p$-shell nuclei up to at least the middle of the $0f$-$1p$ shell. It is well known that the isovector spin-flip strength to such high spin states identified in electron scattering is only 30—50 % of simple single particle estimates.[2] Comparing these results with those for low spin states may permit the study of the momentum dependence of the quenching phenomena since similar quenching has been observed[3] for Gamow-Teller resonances ($L=0$, isovector spin-flip excitations) where it has been interpreted as evidence for non-nucleonic degrees of freedom, and, in particular, isobar-hole states.[4] The non-nucleonic degrees of freedom considered thus far can contribute only weakly to isoscalar excitations and are not expected to make sizable contributions in any case for high spin states. The large unexplained relative quenching of the isoscalar strength compared to the isovector strength implies that the nuclear structure input must be examined more critically for both modes of the nuclear response.

II. EXPERIMENTAL RESULTS

The experiment was carried out on the EPICS channel and spectrometer system at LAMPF. A large (10 cm$\times$20 cm) isotopically enriched target ($>97\%$ ^{54}Fe, 151 mg/cm^2) was used. Spectra with π^+ were accumulated in 10° steps from 40° to 100°; π^- spectra were accumulated at 70°, 80°, and 90°. Short runs were taken at 5° intervals to establish the elastic scattering yields. The channel and spectrometer were used in the conventional fashion[5] to provide typical energy resolution of 200 keV (FWHM). Additional muon rejection was provided by vetoing events which passed through a carbon wedge absorber, the wedge thickness and angle having been chosen to range out pions. This veto had the effect of eliminating a small number of pions from the accepted spectrum, but the absolute cross sections obtained from the appropriately normalized muon-rejected and nonrejected spectra were completely consistent. Both the π^+ and π^- data were normalized by measuring elastic pion scattering from hydrogen in a CH_2 target at an angle of 54°. The $\pi+p$ cross sections were taken from the experimental work of Bussey *et al.*[6] and from phase shift calculations.[7] The uncertainty in the absolute normalization is less than 5% which is generally smaller than the uncertainty due to counting statistics and the systematic uncertainties ($\sim$10—20%) in choosing the shape of the background in the peak fitting procedure. Yields were extracted for states up to 14 MeV in excitation using excitation energies fixed to the values deduced from electron scattering and, independently, allowing the peak positions to vary in each spectrum. A typical comparison of the π^+ and π^- spectra at 80° is given in Fig. 1. As a consequence of the significantly lower incident π^- flux ($\sim\frac{1}{5}$ the π^+ flux) the π^- spectra were not accumulated for comparable integrated flux, and while similar π^+ statistics were available at the other angles, the 70° and 90° π^- spectra contain even fewer counts. Angular distributions for three of the states identified as 8^- levels are shown in Fig. 2. In addition to the 8^- states at 8.31, 8.95, 9.97, 10.68, and 13.26 MeV identified in electron scattering, possible 8^- states were observed at 9.80$\pm$0.05 and 11.65$\pm$0.07 MeV excitation.

The experimental spectra between 9.5 and 11.0 MeV excitation energy were relatively complex, containing at least three 8^- states and several background states. The analysis of the π^+ data provided consistent angular distri-

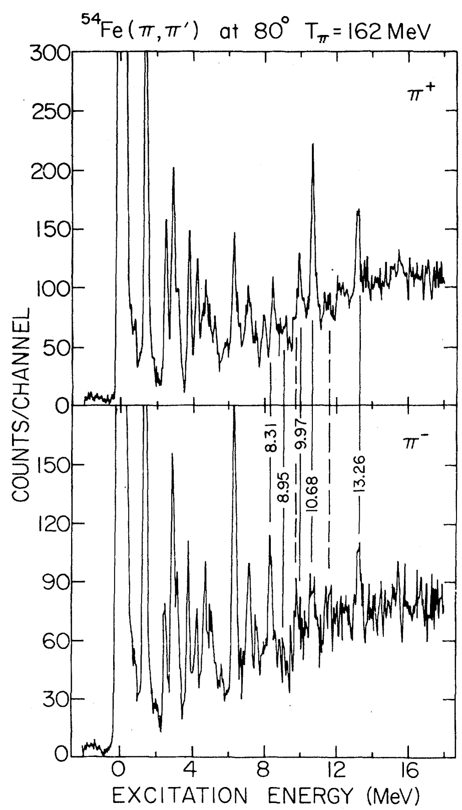

FIG. 1. Spectra for the inelastic scattering of 162-MeV pions by ^{54}Fe at 80°. The solid lines indicate $M8$ transitions observed in electron scattering. The dashed lines indicate the 8^- candidates at 9.80 and 11.65 MeV excitation identified in the present work. The errors on each point are purely statistical with the data binned in 50 keV bins. The vertical scales are normalized to be relative cross sections.

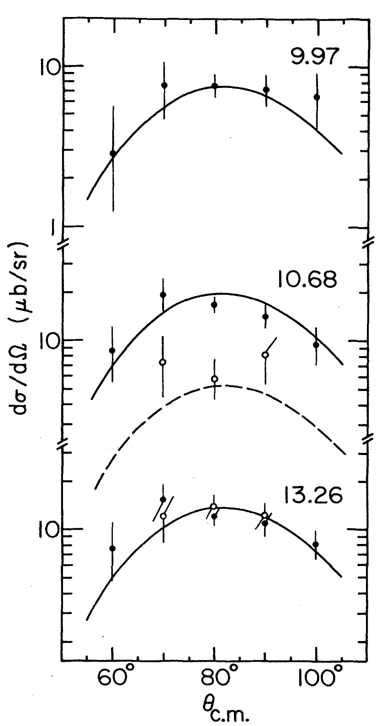

FIG. 2. Angular distributions for 8^- states from pion inelastic scattering by ^{54}Fe. The open points indicate π^- data while the solid points signify π^+ data. The curves are DWIA calculations normalized with the structure coefficients extracted for each state.

butions over a 50° range, and allowed a clear identification of the 8^- states at 9.97 and 10.68 MeV. Both of these states are more weakly excited by π^-'s and the resulting uncertainties are considerably larger. The 9.80 MeV state is seen more strongly in π^- spectra where the angular distribution is not over a wide enough range to clearly identify the spin. The 11.65 MeV state is weakly excited in both π^+ and π^- scattering. The presence of states with these general properties is suggested by the calculation discussed below. If further evidence should reveal that either is not an 8^- state, the conclusions discussed below are only strengthened.

III. ANALYSIS

As is evident in Fig. 1, the inelastic yields to the different 8^- states differ greatly for π^+ and π^-. This is the result of interference of isoscalar and isovector amplitudes, since for a transition with a pure isospin structure (either pure $\Delta T=0$ or pure $\Delta T=1$) the π^+ and π^- yields must be equal. Indeed this is the case for the purely isovector transition to the 13.26 MeV $T=2$ state. By combining the pion data with the electron inelastic scattering results,[8] it is possible to separate the isospin amplitudes for each state. The experimental cross sections and $B(M8)$ satisfy the following relations for the "ith" state:

$$\sigma^i_{\pi^-}(\theta)=[Z^i_0 M_0^{\pi^-}(\theta)+Z^i_1 M_1^{\pi^-}(\theta)]^2 ,$$

$$\sigma^i_{\pi^+}(\theta)=[Z^i_0 M_0^{\pi^-}(\theta)-Z^i_1 M_1^{\pi^-}(\theta)]^2 ,$$

$$B^i(M8)_e=(Z^i_0 M^e_0+Z^i_1 M^e_1)^2 .$$

In these equations M_0^π (M_1^π) is the square root of the cross section for exciting an isoscalar (isovector) transition to a pure one-particle—one-hole state in a closed shell nucleus by π^- inelastic scattering ($M_0^{\pi^+}=M_0^{\pi^-}$, $M_1^{\pi^+}=-M_1^{\pi^-}$). M^e_0 and M^e_1 are similar amplitudes $[\sqrt{B(M8)}]$ for electron inelastic scattering. The coefficients Z_0 and Z_1 contain the nuclear structure amplitudes for isoscalar and isovector excitation of each state. The reaction dynamics are contained in the "M" factors and these can be obtained from distorted wave impulse approximation calculations (DWIA).[9] Based on the free nucleon properties,

$$M^e_0=\left[\frac{\mu_n+\mu_p}{\mu_n-\mu_p}\right]M^e_1=-0.187M^e_1 ,$$

where μ_n and μ_p are the free neutron and proton magnetic moments, respectively. Near the (3,3) resonance,

$$M_0^{\pi^-}\approx 2M_1^{\pi^-} .$$

It should be noted that only P wave and higher partial waves of the π-N amplitudes can contribute to spin flip excitations.

For the electron scattering case, the absolute values of M^e_0 and M^e_1 can be obtained from DWIA.[8] However, the uncertainties in the reaction dynamics make the DWIA calculation of the absolute values of M_0^π and M_1^π more uncertain. To avoid this uncertainty, M_1^π can be obtained from the experimental results for the $T=2$ state since Z_1 is determined by the electron scattering data. Then only the ratio, M_0^π/M_1^π, need be extracted from the DWIA calculations. This procedure renders the results relatively insensitive to the exact choice of the radial form factor or the pion optical potential. Since the ratio of isoscalar to isovector cross sections is determined essentially by an isospin Clebsh-Gordan coefficient, it is not expected to be sensitive to the reaction dynamics. Recent calculations indicate that while medium corrections may modify the ratio of M_0^π/M_1^π for low spin states,[10,11] they have little effect for high spin states with surface localized transition densities, thereby supporting the procedure used here. It should also be noted that in the few cases where the isoscalar pion results have been checked with proton inelastic scattering, the results have agreed very well,[2] although

TABLE I. Isospin amplitudes for ^{54}Fe 8^- states.

Experiment			Theory[a]		
Excitation energy	Z_0	Z_1	Excitation energy	Z_0	Z_1
8.31	0.09 $\pm$0.03	0.22 $\pm$0.02	8.31	0.312	0.445
8.95	0.01 $\pm$0.03	0.19 $\pm$0.02			
9.80	0.15 $\pm^{0.02}_{0.03}$	0.02 $\pm$0.05	9.58	0.252	0.177
9.97	0.07 $\pm$0.03	−0.19 $\pm$0.02	9.99	0.495	−0.367
			10.50	0.181	0.213
10.68	0.21 $\pm^{0.02}_{0.03}$	−0.13 $\pm$0.03	10.71	0.381	−0.089
11.65	0.11 $\pm^{0.02}_{0.04}$	0.07 $\pm$0.04	11.44	0.297	0.072
			11.76	0.231	0.112
			12.19	0.282	0.103
13.26	0	0.44 $\pm$0.02	12.62	0	0.601
$\sum_i Z^2$	0.092$\pm$0.033	0.336$\pm$0.051		0.805	0.807
1p-3h sum rule	0.875	0.875		0.875	0.875
Fraction of 1p-3h sum	11%	38%			

[a]Only the nine states with the largest expected cross sections in pion or electron inelastic scattering are listed. See Ref. 8 for a discussion of the parameters used in the theoretical calculations.

there are considerable uncertainties in the proton reaction dynamics.[12]

The structure coefficients Z_0 and Z_1 for each 8^- state are tabulated in Table I. The angular distributions predicted with these Z coefficients are shown in Fig. 2. For the 9.97 MeV state the π^+ and e^- data require that the π^- cross sections be very small, $\lesssim 2$ μb/sr, and therefore not observable. This is consistent with the experimental spectra in this region of excitation energy. The Z coefficients obtained in an $[(f_{7/2}^{-3})\times g_{9/2}]_{8^-}$ calculation are also given in Table I.[8] In this model space, the structure coefficients satisfy a sum rule: i.e., $\sum_i (Z_0^i)^2=\frac{7}{8}$ and $\sum_i (Z_1^i)^2=\frac{7}{8}$. The isovector strength can be further subdivided into strength in $T=2$ states, $\sum_i (Z_1^i)^2=\frac{3}{8}$, and $T=1$ states, $\sum_i (Z_1^i)^2=\frac{4}{8}$. The sum of the experimental isoscalar strength is only 11% and the sum of the isovector strength is only 38% of the limits in the extreme three-hole—one-particle calculation. (If the 9.80 and 11.65 MeV states are not 8^- states, then only 7% of the isoscalar strength is observed whereas the isovector strength is essentially unchanged.) Note that to have equal isoscalar and isovector strength would require, for example, one additional pure isoscalar state with 5 times the peak $\pi^{+/-}$ cross section of the 13.26 MeV state or five additional states with $\pi^{+/-}$ cross sections equal to that of the 13.26 MeV state. In both spectra, the 13.26 MeV state is the second largest state observed at excitation energies above 8 MeV.

IV. DISCUSSION

It is significant that the quenching of the particle-hole strengths in ^{54}Fe is very similar to that obtained for high-spin-particle-hole states in other nuclei. In Fig. 3, the ratio of the summed isoscalar strength to the summed isovector strength is shown for all cases of stretched particle-hole states (a stretched state is one which has the maximum angular momentum attainable for a $1\hbar\omega$ excitation, i.e., 4^- in the $0p$ shell, 6^- in the $1s$-$0d$ shell, and 8^- in the $0f$-$1p$ shell) where information on both the isovector strength (from electron scattering) and on the isoscalar strength exists (^{14}N, Refs. 13 and 14; ^{16}O, Ref. 15; ^{24}Mg, Ref. 16; ^{28}Si, Ref. 1. A similar ratio is obtained in recent work on ^{14}C, Ref. 17. It has not been included here because the $T=2$ state was not observed in pion scattering, and so the analysis is more model dependent). Consistently, the isoscalar strength is more strongly quenched than the isovector strength. There appears to be a trend that the ratio becomes smaller as A increases. Furthermore, in the two examples where single nucleon transfer data to these high spin states exist, ^{16}O (Ref. 18) and ^{28}Si (Ref. 19), the spectroscopic factors for the $T=0$ and $T=1$ states are approximately equal.

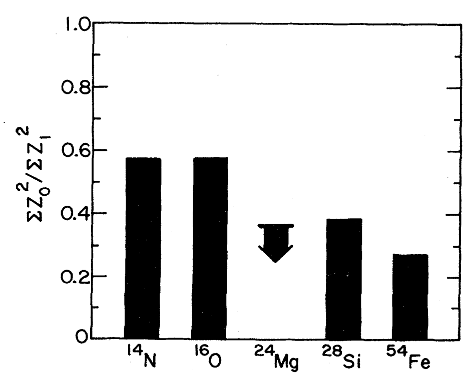

FIG. 3. Ratio of the summed isoscalar strength $\sum Z_0^2$ to the summed isovector strength $\sum Z_1^2$ for ^{14}N, Refs. 13 and 14; ^{16}O, Ref. 15; ^{24}Mg, Ref. 16; ^{28}Si, Ref. 1; and ^{54}Fe, the present work. The value reported for ^{24}Mg is an upper limit on the isoscalar strength.

The summed isovector strengths themselves are only 30—50% of the one-particle—n-hole values. The fragmentation of the isovector strength for these high spin states is quite similar in magnitude to the quenching of the Gamow-Teller strength observed in (p,n) reactions. While isobar-hole admixtures have been invoked by several authors to explain the latter effect,[4] isobar-hole effects are expected to be relatively weak for high-spin states.[20] Indeed, pion and delta non-nucleonic degrees of freedom have very small effects on the isoscalar observables and cannot account for the strong quenching of the isoscalar spin-flip strengths. This implies that nuclear structure is most likely to be responsible for the quenching. The lack of consistency between the inelastic scattering amplitudes and the transfer reaction spectroscopic factors shows conclusively that the high spin states cannot be simply a particle coupled to the ground state of the $A-1$ nucleus, nor can the ground state of the $A-1$ nucleus be a single j hole in the target A nucleus. This is easily seen by expanding the one-body inelastic scattering operator over a complete set of states in the $A-1$ nucleus,

$$\langle A,i||T||A,0\rangle \propto \langle A,i||a_{j_1}^{+}a_{j_2}||A,0\rangle$$
$$\propto \sum_n \langle A,i||a_{j_1}^{\dagger}||A-1,n\rangle$$
$$\times \langle A-1,n||a_{j_2}||A,0\rangle ,$$

where i labels the final high-spin state in the A nucleus, and n labels the states of the $A-1$ nucleus. Either of the assumptions above truncates the sum at one term involving only the ground state of the $A-1$ nucleus. This implies, for example, that the ^{28}Si 6^- states are not simply an $f_{7/2}$ proton particle coupled to the ground state of ^{27}Al, nor is the ^{27}Al ground state a $d_{5/2}$ hole in ^{28}Si. This, however, is only a symptom of the difficulties associated with the structure, and does not identify the causes of the quenching. To date, no calculation has been able simultaneously to reproduce the inelastic scattering and spectroscopic information in ^{16}O or ^{28}Si (Refs. 21 and 22).

The present data give a clear indication that the strong quenching of isoscalar spin-flip strength is a rather general phenomenon. Because of the limitations of other probes, previous examinations of isoscalar spin-flip strength have focused upon isoscalar magnetic moments, which, while very accurately measured, exhibit a weak sensitivity to the expectation value of the spin. Nevertheless, several studies have concluded that the spin contribution to isoscalar magnetic operators is quenched by

$\sim$20–50 %.[23–26] This quenching is usually attributed to the effects of two-particle–two-hole admixtures, which have been calculated in perturbation theory. Similar effects have been shown by Bertsch and Hamamoto[27] to account for much of the quenching of the Gamow-Teller strength in ^{90}Zr. For spin degrees of freedom, the tensor force is extremely important in generating the two-particle–two-hole correlations and the calculations must include very large $\hbar\omega$ excitations to converge. The calculations[23–25] do indicate that the isoscalar strength will be quenched more than the isovector strength; however, no calculations for the high-spin states are as yet available and no detailed comparison can be made. Related calculations of the influence of tensor correlations on the energy weighted sum rules for spin operators also suggest large effects.[28,29]

Another approach to quenching has been used by Blunden, Castel, and Toki.[22] These authors do RPA calculations to consider $3\hbar w$ and higher excitations. While a calculation with a boson exchange interaction does not show significant differences between isoscalar and isovector excitations, the use of a Landau-Migdal force plus π and ρ exchange gives a 25% reduction in the ratio of isoscalar to isovector strength. This is a manifestation of the momentum dependence of the interaction, where the isovector interaction is weak in the momentum region probed for the high spin states, while the short ranged isoscalar interaction ($g_0=0.7$) is strong at all momentum transfers. Certainly the strength of the isoscalar spin-dependent term is poorly understood. One interpretation of this data may be that g_0 is indeed large.

Zamick has pointed out[30] that quenching of the high spin strength arises naturally in the deformed limit and considers ^{28}Si as an example. The difference between the $\Delta T=0$ and $\Delta T=1$ strengths arises from different internal structures for these states, which are necessary to make the ratio of the inelastic transition strength to the spectroscopic factor different. This alternate approach should be pursued in light of the rather general nature of the quenching as observed in Fig. 3.

V. SUMMARY

In summary, data for pion inelastic scattering to 8^- levels in ^{54}Fe have been presented. By combining these data with previous electron scattering data, isoscalar and isovector transition amplitudes were extracted for each 8^- state. Only 11% of the simple one-particle–three-hole strength was observed for the isoscalar excitations and only 38% of the one-particle–three-hole strength was observed for the isovector excitations. This stronger quenching of the isoscalar spin-flip strength compared to the isovector strength appears to be a general feature for high-spin-particle-hole states; the present case represents the heaviest nucleus for which such an isospin decomposition has been performed. While much of the quenching of strength is due to fragmentation of the single particle strength, no calculation to date has been able to explain simultaneously the relative quenching of the isoscalar and isovector states and the associated spectroscopic factor data where it exists. The observed A dependence of the ratio of the isoscalar to isovector quenching may help identify the mechanism. From a comparison with calculations for isoscalar magnetic moments, it appears likely that two-particle–two-hole correlations may be very important in quenching the spin-flip strength. If two-particle–two-hole correlations are important, this will have very general implications and it will be necessary to critically reexamine the nuclear structure input for isovector transitions before one can conclude anything about the possible effects of non-nucleonic degrees of freedom. The isoscalar high-spin particle-hole states with their expected lack of sensitivity to non-nucleonic degrees of freedom will provide perhaps the cleanest nuclear structure test of these effects.

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*Present address: Iowa State University, Ames, IA 50011.

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