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Systematics of the double isobaric analog state cross section at 50 MeV

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Double charge exchange cross sections for 50 MeV pions to double isobaric analog states in ^{44}Ca, ^{56}Fe, and ^{93}Nb were measured. The results indicate that the effective double charge exchange operator at this energy has a strong short-range component. In addition, evidence is presented tending to implicate isospin mixing as the mechanism for excitation of the analog of the antianalog in ^{93}Nb.

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I. INTRODUCTION

Recent high-statistics data taken at the EPICS channel of the Clinton P. Anderson Meson Physics Facility (LAMPF) have revealed a feature of the reaction ^{93}Nb(π^+, π^-)^{93}Tc at 295 MeV [1]. This is the selective excitation of a state below the double isobaric analog state [DIAS (IAS$\otimes$IAS)] in ^{93}Tc which can tentatively be identified as the analog of the antianalog state in ^{93}Mo IAS$\otimes\overline{\text{IAS}}$ (or vice versa), where the parent is the ground state of ^{93}Nb, the target nucleus. This tentative identification is made on the basis of the angular distribution of the cross section compared with that of the DIAS, and the Q value of this state compared with that of the DIAS over a range of nuclei.

The IAS$\otimes\overline{\text{IAS}}$ state has isospin $T-1$ and is orthogonal to the double isobaric analog state (DIAS) and, if distortions are negected, should not be excited. Possible excitation mechanisms[1] include the following: (a) Coulomb mixing between the analog and antianalog states, (b) distortion effects due to the fact that at certain energies pion scattering may not be described by plane waves, and (c) double spin flip, which arises from the $\sigma \cdot \tau_-$ operator acting twice on the target ground state wave function.

A simple experimental method for distinguishing among these possibilities arises from the relatively weak pion-nucleus interaction at 50 MeV. This method is based on the approximation that pion scattering near 50 MeV may be described by plane waves. A number of experiments support this approximation (although some evidence can be found in recent work which does not). For example, the ratio of the peak cross section for the 0_1^+ state (7.56 MeV) and the 2_1^+ state (4.44 MeV) in ^{12}C is 0.90 [2] at 180 MeV and 0.072 [3] at 50 MeV. In the plane wave approximation, the cross section for the 0_1^+ state is zero because of orthogonality in the radial parts of the wave functions.

If the excitation of the antianalog resonance is due to isospin mixing, the ratio of its cross section to that of the DIAS should be independent of energy. If, however it is due to non-plane-wave effects, then this ratio should be energy dependent, and should decrease dramatically (as in the 0^+ and 2^+ comparison above). However, if the new state is dominated by a double spin-flip mechanism, then it should increase substantially at the lower beam energies as expected from recent calculations by Gibbs and Kaufmann [4].

The measurements of the DIAS cross sections in ^{93}Nb made in this work, together with those measured previously, make it possible to draw conclusions about the nature of the effective transition operator for pion energies of $T = 50$ MeV. The $(N-Z)$ dependence of the cross sections provides us with clues concerning the range and/or spin dependence of the DCX effective operator. In the pure configuration limit, when the $(N-Z)$ neutrons occupy a single orbit j, the DCX cross section to the DIAS is given by Ref. [5]:

$$\sigma = (N-Z)(N-Z-1)\left|\alpha + \frac{\beta}{(N-Z-1)}\right|^2 . \quad (1)$$

The two amplitudes α and β are independent of $(N-Z)$, and the relative size depends on the range and spin structure of the double charge exchange (DCX) operator. For short-range transition operators, the ratio β/α is large, and it is infinite for a δ-type operator. This ratio is also

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infinite for identical nucleons if the DCX operator has the form $\sigma_1 \cdot \sigma_2$ [6].

If the transition operator is of short range the DCX cross section should have the following form:

$$\sigma = \frac{N-Z}{N-Z-1}\,|\beta|^2\,. \tag{2}$$

However, if the DCX operator is of long range (as when the mean field part of the nuclear wave function dominates over the correlation part), the cross section will behave as

$$\sigma = (N-Z)(N-Z-1)\,|\alpha|^2\,. \tag{3}$$

These distinctly different behaviors of the cross sections as a function of $(N-Z)$ provide a clear indication about the range of the effective DCX operator. We should mention here that the range of this operator is determined by two factors: the range of the pion-nucleus interaction and the correlations in the nuclear wave function [6]. In a recent theoretical study [6] it was shown that these features of the DCX process apply not only in the case of a pure configuration but also in instances when configuration mixing is strong. Therefore the $(N-Z)$ behavior of the cross sections is a more general indication of the range of the transition operator.

In the case of short range operators (when α is small) the $N-Z=2$ ($T=1$) nuclei play a special role by having their cross sections almost a factor of 2 larger than the nuclei with $N-Z>2$, which all vary only slightly with $(N-Z)$. The special role of $T=1$ nuclei in low energy ($T=35$ to 50 MeV) DCX experiments was noticed in the past [5–7].

In this work, we report measurements of 50 MeV pion DCX cross sections made at the Clinton P. Anderson Meson Physics Facility (LAMPF) using the reactions ^{44}Ca(π^+,π^-), ^{56}Fe(π^+,π^-), and ^{93}Nb(π^+,π^-) (see Table I). We draw conclusions about the nature of the effective transition operator at 50 MeV to the DIAS. We also discuss possible excitation mechanisms for exciting the analog of the antianalog in pion DCX in heavy nuclei, which has recently been revealed at 295 MeV [1], and which should not be excited if distortions are neglected.

II. EXPERIMENT

The data were taken at the low energy pion (LEP) channel [8] of LAMPF using the Clamshell spectrometer, described previously [9–12]. The Scruncher [13], a superconducting radio frequency cavity, was used to compress the longitudinal momentum spread of the beam immediately before the target. This gave a factor of roughly four more flux at the target for a given momentum spread. Spectra were obtained at 50 MeV as shown in Table I. Absolute normalization of the cross sections was based on measurements of elastic scattering cross sections for ^{12}C at laboratory scattering angles of 30° and 40°, and normalizing those results to the ^{12}C cross sections from Ref. [14]. The momentum spread $\Delta p/p$ before the Scruncher was 2%. Target thicknesses were 600, 600, and 435 mg/cm^2 for ^{44}Ca, ^{56}Fe, and ^{93}Nb, respectively.

III. DISCUSSION OF THE DATA

Due to the small cross sections and resulting low counting statistics for the states of interest, the 50 MeV cross sections were extracted by simply counting the events in the histograms involved [Fig. 1(a) and Fig. 2], performing the absolute normalization, and applying corrections for pion survival, spectrometer acceptance, and background.

These cross sections are presented in Table I in the column "Present work." Figure 2(a) shows the spectrum obained in the present work for the reaction ^{93}Nb$(\pi^+,\pi^-)^{93}$Tc at 50 MeV and 25°. Figure 2(b) shows the spectrum obtained in the present work for the reaction ^{56}Fe$(\pi^+,\pi^-)^{56}$Ni at 50 MeV and 20°. This spectrum may be compared to one obtained earlier [15] at the same beam energy. Both present transitions to the ground state (g.s.) of ^{56}Ni around $Q=-6$ MeV, a stronger transition to the DIAS around $Q=-16$ MeV, and weak transitions in the $Q=-9$ to -12 MeV range. Our cross section measurements are compared with those of this earlier work in Table I. Figure 2(c) shows data from the current work for the reaction ^{44}Ca$(\pi^+,\pi^-)^{44}$Ti at 50 MeV. This spectrum may be compared to one taken earlier [16] also at the LEP channel of LAMPF with the

TABLE I. Cross sections and Q values for (π^+,π^-) at 50 MeV extracted from spectra of the present work, and comparison with previous work.

Target	Scattering angle (laboratory)	State	Q (MeV)	Cross section (μb/sr) Present work	Cross section (μb/sr) Previous work
^{44}Ca	25°	g.s.	−4.9	2.6 ± 0.5	1.7 ± 0.3[a]
^{44}Ca	25°	DIAS	−14.5	2.5 ± 0.4	1.4 ± 0.3[a]
^{56}Fe	20°	g.s.	−5.3	0.56 ± 0.19	0.31[b]
^{56}Fe	20°	DIAS	−16.0	0.62 ± 0.17	0.8[b]
^{93}Nb	25°	IAS$\otimes\overline{\text{IAS}}$	−17.0	0.54 ± 0.14	
^{93}Nb	25°	DIAS	−21.3	2.43 ± 0.29	

[a]Taken at center of mass scattering angle 25.1°[16].
[b]Reference [15].

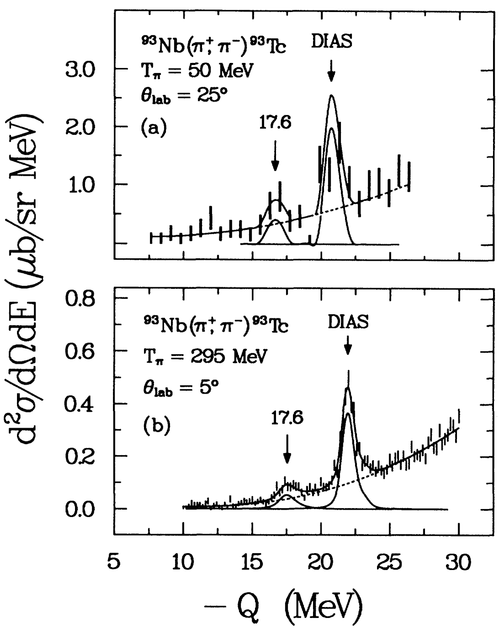

FIG. 1. (a) Data and fit from the present work for ^{93}Nb(π^+, π^-)^{93}Tc at 50 MeV and laboratory scattering angle 25°. The curves are merely to guide the eye. (b) Data and fit from Ref. [1] for the same reaction at 295 MeV and laboratory scattering angle 5°.

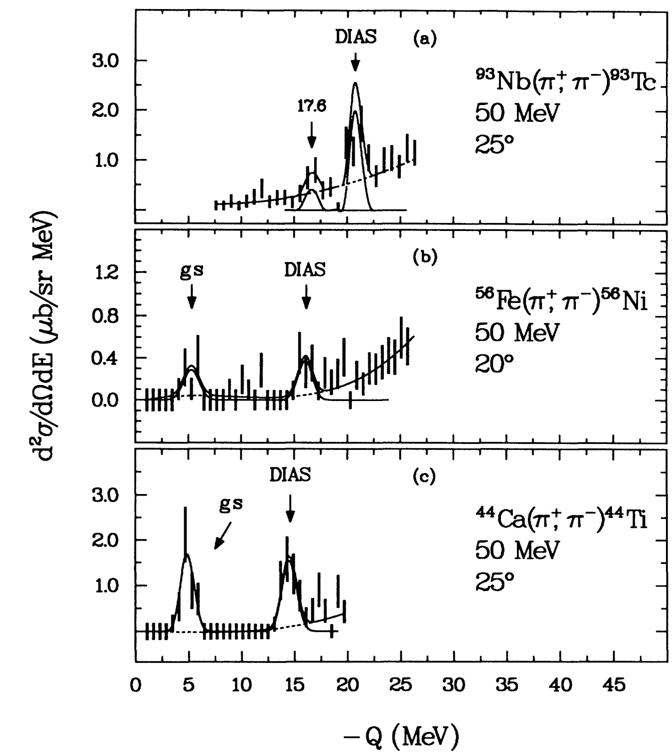

FIG. 2. The data in this figure were obtained in the present work. The curves are merely to guide the eye. (a) Data and fit from the present work for ^{93}Nb(π^+, π^-)^{93}Tc at 50 MeV and laboratory scattering angle 25°. This is the same as Fig. 1(a). (b) Data and fit from the present work for ^{56}Fe(π^+, π^-)^{56}Ni at 50 MeV and laboratory scattering angle 20°. (c) Data and fit from the present work for ^{44}Ca(π^+, π^-)^{44}Ti at 50 MeV and laboratory scattering angle 25°.

Clamshell spectrometer. Both spectra present transitions to the g.s. and DIAS in ^{44}Ti. Our cross section measurements are compared to those of this earlier work in Table I.

IV. SYSTEMATICS OF THE DIAS CROSS SECTION AT 50 MeV

Figure 3 shows DIAS cross sections at 50 MeV [9, 15–20] divided by $(N-Z)/(N-Z-1)$ plotted as a function of A. The cross sections are approximately constant, strongly indicating that the effective pion DCX operator at this energy has a short range.

This low-energy trend should be contrasted with the DCX cross sections measured for $T = 295$ MeV. Here the cross sections show a scaling which is closer to the $(N-Z)(N-Z-1)$ behavior [see Fig. 4, which shows DIAS cross sections at 295 MeV [21–34] divided by $(N-Z)(N-Z-1)$]. Thus the transition operator for this energy is of long range. This behavior of the DCX transition operator as a function of the pion energy was noticed and discussed in previous theoretical papers [5–7] and previous experimental works.

It is interesting to note that the low energy (50 MeV) cross sections when divided by the factor $(N-Z)/(N-Z-1)$ show a weak A dependence while the high energy (295 MeV) cross sections divided by $(N-Z)(N-Z-1)$ factor show a strong A dependence: $A^{-3.352}$ (Fig. 4). This indicates that the amplitude β in the above equation has a weak A dependence while the amplitude α varies significantly with A. This observation seems reasonable,

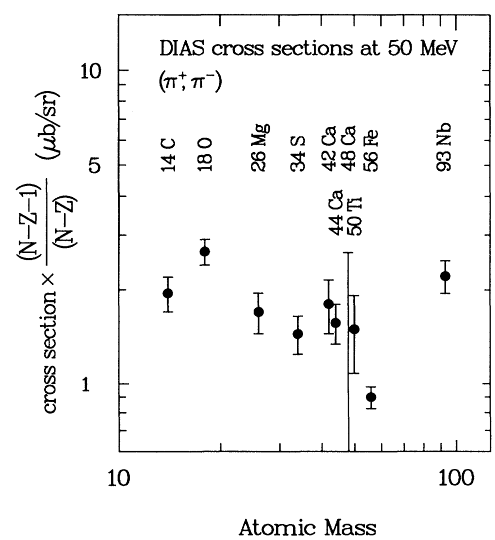

FIG. 3. Cross sections to the DIAS at 50 MeV divided by $(N-Z)/(N-Z-1)$. The data for ^{44}Ca are the average of the values in Table I.

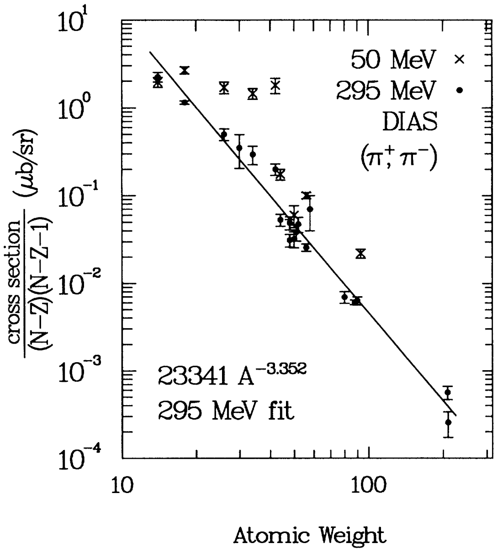

FIG. 4. Cross sections to the DIAS at 295 MeV divided by $(N-Z)(N-Z-1)$. The data for ^{44}Ca are the average of the values in Table I.

since the amplitude β reflects the presence of two-body correlations in the nuclear wave function and the short range part of the basic pion-nucleon operator. Thus, this amplitude should not depend very strongly on the size of the nucleus except for distortion effects. On the other hand, the amplitude α represents the mean field part of the wave function and the long range part of the pion-nucleon interaction; thus, the size of the nucleus will play a stronger role in that amplitude.

V. EXCITATION MECHANISM FOR THE ANALOG OF THE ANTIANALOG

The ratio of the ^{93}Nb cross sections for the $Q=-17.0$ MeV resonance IAS$\otimes\overline{\text{IAS}}$ and the $Q=-21.3$ MeV resonance IAS$\otimes$IAS at 50 MeV may be extracted from Table I, yielding 0.22 ± 0.06.

The 295 MeV cross sections were extracted by fitting the data [1] [Fig. 1(b)] with peaks of equal widths using the program NEWFIT. The ratio of the cross sections for the peak at $Q=-17.6$ and the DIAS peak is 0.21 ± 0.03. This number may be compared to the ratio for 50 MeV. The near equality suggests Coulomb mixing as the predominant excitation mechanism for the excitation of the IAS$\otimes\overline{\text{IAS}}$.

However, arguments may be advanced against Coulomb mixing as the sole agent. Consider the case when the excess neutrons in $^{93}_{42}$Mo occupy two orbits j and j'. The one-body Coulomb matrix element mixing the $|\text{IAS}\rangle$ (which has isospin $T_>$) with the antianalog which has isospin $T_<$ may be simply derived by writing the $|\text{IAS}\rangle$ as $\alpha|n\ell j\rangle+\beta|n'\ell' j'\rangle$ and the antianalog as $\beta|n\ell j\rangle-\alpha|n'\ell' j'\rangle$; using the fact that the operator $V_C^{(1)}$ is the isovector (one-body) part of the Coulomb interaction, and being a function of r does not connect the two states:

$$\langle\text{IAS}|V_C^{(1)}|\overline{\text{IAS}}\rangle = \alpha\beta\left[\langle n\ell j|V_C^{(1)}|n\ell j\rangle-\langle n'\ell' j'|V_C^{(1)}|n'\ell' j'\rangle\right] . \quad (4)$$

For the case of $^{93}_{42}$Mo, $\alpha\beta=\sqrt{1/2T}\sqrt{(2T-1)/2T}$ from shell model considerations of the neutron occupancy of the valence orbitals. The expression in the parentheses is the difference in one-body Coulomb matrix elements evaluated for orbits $(n\ell j)$ and $(n'\ell' j')$. If $n\ell j$ and $n'\ell' j'$ are in the same major shell (i.e., $n=n'$) then the difference in the radial matrix elements is very small for a long-range force such as the Coulomb force. In fact, using a Wood-Saxon wave function with the proper asymptotic behavior adjusted to reproduce the separation energies of nucleons in orbits j and j', the matrix element is nonzero but small. In light and medium-heavy nuclei these matrix elements [35] in Eq. (4) range between 100 and 200 keV. In the case of $n\ell j$ and $n'\ell' j'$ orbits belonging to different major shells this matrix element [36] is of the order 200–400 keV. As $(N-Z)$ increases in heavier nuclei the matrix element in Eq. (4) scales [37] approximately as $\sqrt{1/(N-Z)}Z/A^{1/3}$.

The mixing between the $|\text{IAS}\otimes\text{IAS}\rangle$ and $|\text{IAS}\otimes\overline{\text{IAS}}\rangle$ is estimated by

$$\beta'=\frac{\langle\text{IAS}\otimes\text{IAS}|V_C^{(1)}|\text{IAS}\otimes\overline{\text{IAS}}\rangle}{E_{|\text{IAS}\rangle}-E_{|\overline{\text{IAS}}\rangle}} , \quad (5)$$

with $E_{|\text{IAS}\rangle}-E_{|\overline{\text{IAS}}\rangle}\simeq V_1(N-Z)/A$ given by the symmetry energy. Using the Wigner-Eckart theorem one may write

$$\beta'\approx\frac{\begin{pmatrix} T & 1 & T-1\\ T-2 & 0 & T-2\end{pmatrix}}{\begin{pmatrix} T & 1 & T-1\\ T-1 & 0 & T-1\end{pmatrix}}\beta=\sqrt{\frac{2(2T-2)}{2T-1}}\beta\approx\sqrt{2}\beta , \quad (6)$$

where

$$\beta\equiv\frac{\langle\text{IAS}|V_C^{(1)}|\overline{\text{IAS}}\rangle}{\text{E}_{|\text{IAS}\rangle}-\text{E}_{|\overline{\text{IAS}}\rangle}} . \quad (7)$$

This result actually applies to any $T-1$ state $|\alpha\rangle$ and $|\text{IAS}\otimes\alpha\rangle$. Using a matrix element $\simeq$ 300 keV and the measured energy difference of 4.5 MeV yields an admixture $\beta^2\simeq0.44\%$ in ^{93}Nb. Allowing for the two coherent paths shown in Fig. 5 one expects the cross section to be

$$\sigma_{|\text{IAS}\otimes\overline{\text{IAS}}\rangle}=(\beta+\sqrt{2}\beta)^2\sigma_{|\text{IAS}\otimes\text{IAS}\rangle}\simeq0.026\,\sigma_{|\text{IAS}\otimes\text{IAS}\rangle} , \quad (8)$$

i.e., almost an order of magnitude too small.

Thus, for this Coulomb mixing mechanism to explain the current data, the charge-dependent matrix element needs to be a factor of 2.8 larger than that obtained from our simple estimates. A matrix element of 800–900 keV, which would be needed to explain the measured ratio, seems unusually large. It thus appears unlikely that

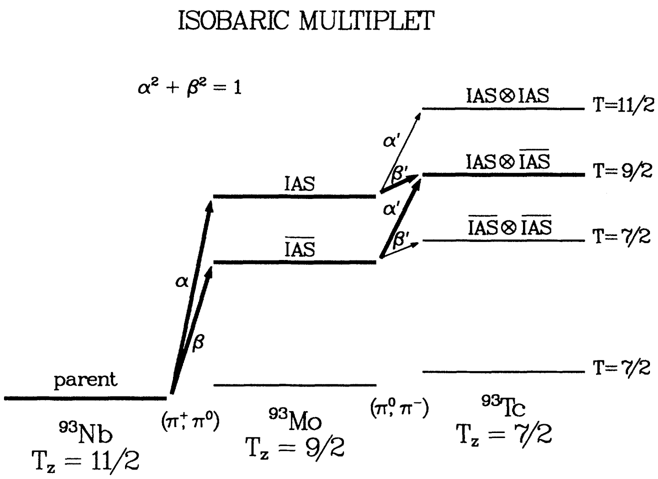

FIG. 5. Level diagram showing reactions paths to the IAS⊗$\overline{\text{IAS}}$.

Coulomb mixing is the only source of such a peak in the spectrum.

Alternative mechanisms are possible. The pion DCX transition operator contains components which are not necessarily proportional to the total isospin operator $\mathbf{T}_N$. Such components may induce transitions to states in the final nucleus that are not the $|\text{IAS} \otimes \text{IAS}\rangle$, and the final isospin may be different from the initial isospin, T. Double spin flip is a possible mechanism for exciting the $|\text{IAS} \otimes \overline{\text{IAS}}\rangle$, but calculations [4] suggest that double spin flip is strong at lower energies and should be negligible at $T_\pi = 295$ MeV, as mentioned above. Correlations in the shell-model wave functions allow transitions that do not proceed through the intermediate analog state [7]. At 300 MeV, these are known to significantly affect the A dependence of the cross sections for DCX on $f_{7/2}$ shell nuclei [7, 38], and they could lead to the population of other $\Delta J = 0$ states. However, this mechanism is expected to populate all of the $\Delta J = 0$ states in the final nucleus that can be reached via recoupling the two participant neutrons to $\Delta J = 0$ and should not selectively excite the $|\text{IAS} \otimes \overline{\text{IAS}}\rangle$. Of course, in a pure $f_{7/2}$ shell, there is no $|\text{IAS} \otimes \overline{\text{IAS}}\rangle$.

It would be interesting to extend the 50 MeV ^{93}Nb IAS⊗$\overline{\text{IAS}}$ data with angular distribution measurements for further comparison with higher energy data to see if the ratio of ≈ 0.21 holds across a range of angles, which would tend to strengthen the identification of the lower energy state as the analog of the antianalog. Another interesting prospect is studying the possible role of charge dependent effects which are not driven by a Coulomb mixing mechanism.

VI. CONCLUSION

The data reported here indicate that the effective double charge exchange operator at 50 MeV has a strong short-range component. This may be contrasted with the behavior at 295 MeV, where the mechanism appears to have a strong long-range component. These conclusions were drawn based on the A and $(N - Z)$ dependence of the double isobaric analog state cross sections at the two energies. In addition, the constancy between 50 and 295 MeV of the cross section ratio between the IAS⊗$\overline{\text{IAS}}$ and the (IAS⊗IAS) tends to implicate isospin mixing as the mechanism for excitation of the analog of the anti-analog in ^{93}Nb, although Coulomb mixing appears too weak to explain the effect.

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