Angular Distributions for the Reaction $^{18}O(\pi^+, \pi^-)^{18}Ne$ and Pion Double-Charge-Exchange Form Factors

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The first angular distributions for pion double charge exchange to discrete nuclear states are reported. The analog and nonanalog states are found to be equally strongly populated. The direct, surface-dominated nature of the reaction is clearly demonstrated by the angular distribution shapes. It is shown that in order to produce detailed agreement with the data, the present ideas for the pion charge-exchange form factors may need to be drastically revised.

Pion double charge exchange is a unique reaction. It has no analog in conventional nuclear reactions and is capable of probing unusually high-isopin states and exotic nuclei. It has long held out the hope of illuminating some of the most elusive aspects of nuclear structure such as two-body correlations and differences in neutron and proton distributions. However, in spite of the fact that the reaction was first discussed in the early 1960's,[1] it became possible to study double-charge-exchange (DCX) transitions to discrete nuclear states only when intense pion beams became available at the "meson factories." The first experiments of Burman and collaborators[2] at the LEP channel at Clinton P. Anderson Meson Physics Facility (LAMPF) demonstrated clear-cut ground-state transitions in several nuclei, established the general low level of cross sections for these reactions, and provided the first indications of the extreme sensitivity of these reactions to nuclear structure. However, these experiments suffered from poor energy resolution (full width at half maximum ~4 MeV) and were confined to 0°. With these limited data it has not been possible to make much progress in our understanding of the reaction mechanism of DCX, which is, of course, prerequisite to realizing any of the grander hopes about the potential of DCX in the study of nuclear structure. In this Letter, we report on the first measurements ever of angular distributions for DCX transitions to discrete nuclear states, and show how these shed light on some very characteristic aspects of the DCX reaction mechansim.

The present experiment on $^{18}O(\pi^+,\pi^-)^{18}Ne$ was performed at $T(\pi^+) = 164$ MeV at the EPICS pion spectrometer facility at LAMPF. The flux was $> 5\times 10^7$ pions/sec, and a ~0.9-gm/cm^2-thick target of ^{18}O, in the form of ice, was used. The spectrometer, the particle detection system, and the target have been described earlier.[3,4] Figure 1 illustrates a typical π^- spectrum for $\theta_{lab} = 18°$. It also shows the composite spectrum obtained by summing the spectra at all the angles at which data were taken, i.e., $\theta_{lab} = 13°$, 18°, 23°, 30°, and 45°, in order to obtain better statistics. The raw yields were corrected for chamber inefficiencies and other dead times and normalized to the primary beam-on-target (BOT) monitor and the scattered-pion-monitor telescope (the two agreed within a few percent). In order to obtain the absolute cross-section normalization, π^+ elastic-scattering yields were measured between 13° and 45°. From the absolute elastic-scattering cross sections of Iversen *et al.*[3] for $\theta \geq 18°$ an average value of the absolute normalization constant was determined. This constant was used

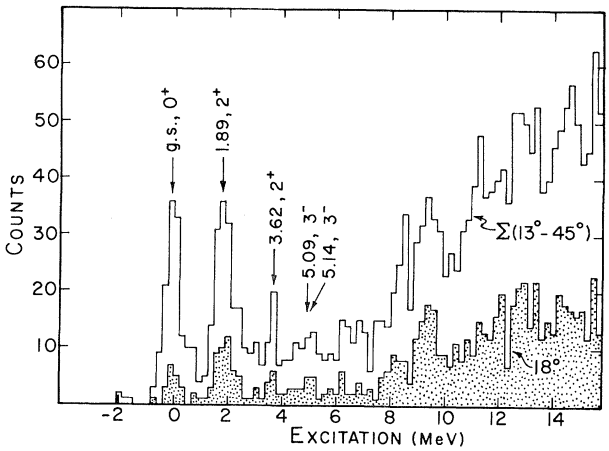

FIG. 1. π^- spectrum from the reaction $^{18}O(\pi^+,\pi^-)^{18}Ne$ at $T(\pi^+) = 164$ MeV. See text for explanation.

for normalizing all DCX yields. The correctness of using this normalization constant for DCX data at 13° was verified by applying it to elastic yields at 13° and 15°. The resulting elastic cross sections were found to be in excellent agreement with the optical-model predictions. (At $\theta \leq 15°$ the predictions are insensitive to the details of the optical model and its parameters). We believe that the absolute cross-section scale so determined is accurate to within ± 15%. The errors bars on the differential cross sections shown in Fig. 1 include this uncertainty, statistical errors, and, in case of the most-forward data points at 13°, an additional ± 30% error due to uncertainties in chamber-efficiency determination.

The spectra shown in Fig. 2 illustrate the dramatic advantage of the higher-energy resolution (full width at half maximum ≈ 600–800 keV) and better background rejection in our experiment. The transitions to the 0_1^+ ground state and the 2_1^+ state at 1.89 MeV are clearly resolved. It appears that the 3.62-MeV 2_2^+ state is also excited. Since ^{18}Ne breakup sets in at 3.9 MeV, transitions to individual states are difficult to identify at higher excitations.

Since this is the first time transitions to excited states have been identified in DCX reactions, let us examine the implications of this observation. In the early discussions of DCX, it was assumed that DCX reactions would primarily proceed via two successive analog transitions, e.g., in our case ^{18}O(g.s., $0^+, T=1$) → ^{18}F(1.04 MeV, 0^+, $T=1$) → ^{18}Ne(g.s., $0^+, T=1$). All other intermediate states in ^{18}F and final states in ^{18}Ne were expected to participate very weakly, if at all. As Fig. 2 demonstrates dramatically, this is far from the case. The integrated strength of the nonanalog transition to the 2_1^+ state is comparable to that of the ground-state transition. This should destroy definitively the myth of the preeminence of analog transitions in DCX. Serious doubts about it were already cast by the observation[2] that at 0°, the nonanalog DCX transition from ^{16}O(g.s., $T=0$) to ^{16}Ne(g.s., $T=2$) was only a factor 2.3± 0.7 weaker than the analog transition from ^{18}O(g.s., $T=1$) to ^{18}Ne(g.s., $T=1$). Our observation is more direct because both the analog and the nonanalog transitions occur to states in the same nucleus ^{18}Ne.

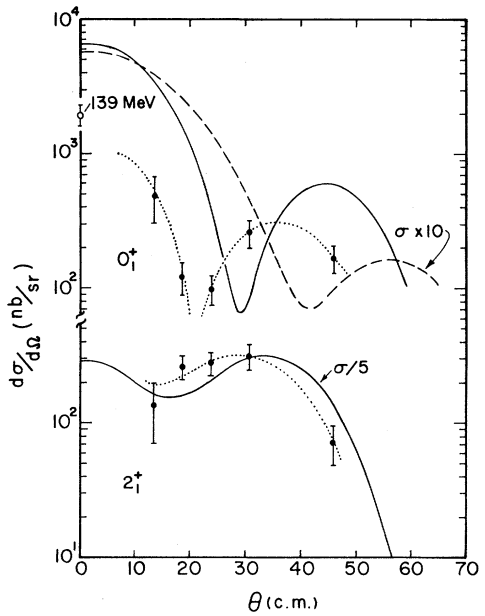

FIG. 2. Differential cross sections for DCX transitions to the 0^+ g.s. and the 2^+ state at 1.89 MeV in ^{18}Ne. The dotted line is simply to indicate the trend of the data points. The solid curves are from Oset, Strottman, and Brown (Ref. 5) and the dashed curve shows the cross sections of Miller (Ref. 6) (multiplied by 10 for the sake of clarity of the figure).

In Fig. 2, we show the differential cross sections measured in the present experiment for transitions to the ground-state 0^+ and the 1.89-MeV 2^+ state, as well as the 0° g.s. cross section measured by Burman *et al.*[2] at $T(\pi) = 139$ MeV. The summed cross sections for the excitation region 5–20 MeV are not shown in the figure; these decrease monotonically from ~ 8 μb/sr at 13° to ~ 2 μb/sr at 45°. The trend of our measured 2^+ cross sections is such that we can, with confidence, set an upper limit of ~ 200 nb/sr for its zero-degree value. This implies that even though Burman *et al.*[2] could not resolve the 2^+ state, the 2000± 340 nb/sr measured by them can indeed be ascribed to the ground-state transition. Perrin *et al.*[7] measured σ(18°) at $T(\pi^+) = 148$ and 187 MeV. Their data suffered from poor statistics and it is only meaningful to compare the sum of our 0^+ and 2^+ cross sections at 18°, $\sigma(0^+ + 2^+, 18°) = 390 \pm 65$ nb/sr, based on seventy counts, with their corresponding cross sections, 370 ± 120 nb/sr based on ten counts at $T(\pi^+) = 148$ MeV and 330± 100 nb/sr based on eleven counts at $T(\pi^+) = 187$ MeV. The errors on the cross sections of Perrin *et al.* are statistical only. The agreement, perhaps fortuitously, is excellent.

The qualitative features of the angular distributions in Fig. 2 are very instructive. The angular distributions are well structured. They show the characteristic shapes for $L=0$ and $L=2$ transfers observed in surface-dominated direct reac-

tions, and are in contrast to the washed-out angular distributions which might be expected from two completely uncorrelated steps of single charge exchange anywhere in the nuclear volume.

In Fig. 2, we also show some theoretical predictions for the angular distributions of the g.s. 0^+ and the 2_1^+ transitions.[5,6,8] The calculation of Miller[6] was done in the coupled-channels optical-model formalism with only analog transitions between pure $d_{5/2}{}^2$ states. We see in Fig. 2 that Miller's calculations underpredict the ground-state cross sections by a factor of about 2 at the forward maximum and a factor of ~ 10 at the second maximum. The calculations of Oset, Strottman, and Brown[5] were done in the Glauber-model formalism with a $d_{5/2}, s_{1/2}$ basis for the $A = 18$ wave functions. Oset, Strottman, and Brown[5] overpredict the cross sections for both ^{18}Ne(g.s.) and 2_1^+ transition by the same factor ~ 5. Quite apart from the absolute cross-section discrepancy, neither calculation succeeds in reproducing the most characteristic feature of the data, i.e., the minimum in the ground-state distribution at $\theta_{\text{c.m.}} \approx 21°$. As a matter of fact, it is found that as long as a realistic nuclear density[3] is assumed for ^{18}O and ^{18}Ne, none of the present theories of DCX are capable of producing a minimum at as small an angle as 21°.

In the optical-model calculations, the charge-exchange form factor is normally taken to be of the form $F(r) = [N\rho_N(r) - Z\rho_Z(r)]/(N-Z)$, and in absence of better information $\rho_N(r) = \rho_Z(r)$ is assumed, where $\rho_Z(r)$ is taken from electron scattering. With such a form factor, Miller and Spencer[6] find that at $T(\pi) = 164$ MeV, the minimum occurs at $\theta_{\min} = 42°$, 38°, and 41° for Kisslinger, Laplacian, and Londergan-McVoy-Moniz forms of optical potential, respectively. Sparrow and Rosenthal[8] obtain $\theta_{\min} \approx 38°$ with Kisslinger potential. Sternheim[9] has investigated the effect of the neutron radius on $\sigma(\theta)$ in a model which does not include the Coulomb potential. He obtains $\theta_{\min}$ at 45° with $r_n = r_p$. If r_n is increased by 0.15 fm the minimum moves to 34°. Another increase by 0.15 fm moves the minimum in by a smaller amount, to 30°. The general conclusion remains that in optical-model calculations with any plausible assumptions about $\rho_N(r)$ and $\rho_Z(r)$ the minimum cannot be brought to angles less than ~ 30°.

In the Glauber-model calculations of Oset, Strottman, and Brown[5] we notice that the minimum occurs at 29°, corresponding to a profile function which peaks at ~ 3.5 to 3.8 fm. In a recent, improved version of their earlier fixed-scatterer calculation, Kaufmann, Jackson, and Gibbs[10] obtain $\theta_{\min} \approx 31°$. In other words, although some of these calculations predict minima at smaller angles than the optical-model calculations, they are still far from the $\theta_{\min} \approx 21°$ observed in our data.

The geometrical problem posed by the location of the minimum becomes transparent in the strong-absorption model. It has been shown by many authors that at energies in the vicinity of the (3, 3) resonance elastic[11,12] as well as inelastic scattering[13,14] of pions can be quite successfully explained in terms of the strong-absorption diffraction model. It has been shown[13] that for ^{18}O, the data both for elastic scattering and for inelastic scattering to the 2_1^+ state can be successfully fitted with a strong-absorption radius of ~ 3.8 fm. (At this radius, the proton density is ~ 10% of its central value.) Seth[13] has recently attempted to apply the strong-absorption model to single and double charge exchange, in analogy with the Blair model for one- and two-step inelastic scattering. Blair[15] has shown that the correct diffraction-model result differs somewhat from that given by Seth[13] and $\sigma(\theta, \text{DCX})$ is proportional to $\{J_0(x) - [a/(R-a)]xJ_1(x)\}$, where $x = qr$, $q = 2p \sin(\frac{1}{2}\theta)$ is the strong-absorption radius, and a is the diffuseness. (The same expression has been obtained by Johnson[16] by a different approach.) For $R = 3.8$ fm and $a = 0.6$ fm this expression gives a minimum at $\theta = 32°$. In order to produce a minimum at $\theta = 21°$, $R = 4.8$ fm is required. Clearly such a radius is unphysical since the density at this radius is only ~ 1% of the central density.

It is obvious that in order to explain the location of the observed minimum, our ideas about the form factor for DCX have to be revised.[1,13] None of the formalisms used up to now take into account any other possible reaction mechanism except two successive steps of single charge exchange. However, many other mechanisms are possible. For example, as Miller and Spencer[6] have emphasized, DCX is expected to be extremely sensitive to short-range correlations[17] and true meson absorption. These effects would introduce $\rho^2(r)$ terms in the DCX form factor. The interference between $\rho(r)$ and $\rho^2(r)$ terms can produce minima at different angles depending on the magnitude and the phases of the two terms. As an exercise, Blair has shown that if, for example, one assumes that the two components in the form factor have the diffraction-model form, equal size (*ad hoc*), destructive phases (*ad hoc*),

and ~20% different radii (*ad hoc*), the experimental minimum at 21° is reproduced and an excellent fit to our data is obtained. This, of course, does not prove that such a calculation is correct, or that even the suggested mechanisms for interfering components in the form factor are the only, or even the most important, ones. The point that this exercise makes is that *one requires other than a $\rho(r)$ component in the form factor, and that such a component must be of comparable magnitude.*

The present experiment has dramatized the value of angular distribution data for DCX. It is clear that many more measurements of this type need to be made so that new theoretical ideas about the reaction mechanism of DCX can be developed and tested.

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