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Evidence of a Direct Process in the (^4He,^8He) Reaction

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The transfer mechanism for the exotic (^4He,^8He) reaction has been investigated by measuring the angular distribution for the reaction $^{64}Ni(^4He,^8He)^{60}Ni$. The structure in the angular distribution is reproduced by a direct four-neutron–cluster transfer. In addition, the relative (^4He,^8He) cross sections from ^{64}Ni and ^{58}Ni are predicted correctly if collective effects are included in the spectroscopic factors.

In the past few years there has been considerable interest in multinucleon-cluster transfer reactions. A number of four-nucleon (two-neutron, two-proton) pickup and stripping reactions have been characterized as α-particle–cluster transfers.[1] Also three-nucleon–cluster transfer models successfully account for transitions such as (^{10}B,^7Be) and (^{10}B,^7Li).[2] In addition, Delic and Kurath[3] have described the three-neutron transfer $^{13}C(^3He,^6He)^{10}C$ by a cluster model. In this Letter we present the first evidence on the (^4He, ^8He) four-neutron–transfer mechanism and demonstrate that the transition can be characterized as a direct, one-step, four-neutron–cluster transfer. We further show that the reaction cross section is sensitive to collective effects in the nuclear wave functions.

We have measured the differential cross section for the reaction $^{64}Ni(^4He,^8He)^{60}Ni$ ($E_x = 0.0$) for c.m. angles between 4 and 60 deg using an 80-MeV α beam from the Texas A & M University 88-in. cyclotron. Data were obtained using an Engle split-pole magnetic spectrograph with a focal-plane detector which consisted of a 10-cm single-wire gas proportional counter backed by a 5 cm $\times$1 cm$\times$600 μm Si solid-state detector. This detection system has previously demonstrated particle discrimination to levels less than 100 pb/sr$\cdot$MeV for targets with $A \sim 60$, when the ^8He's are stopped by the Si detector.[4] The experimental setup was optimized for extremely low cross sections by operating with 2–3-μA beam currents, a 2.9-mg/cm^2 ^{64}Ni foil (98% ^{64}Ni), and a 2.1-msr solid angle corresponding to a 3° integration in θ. Absolute cross sections have been determined to an accuracy of 20% due to uncertainties in charge integration, target thickness, and vertical efficiency in the focal-plane detector. In addition to the ^8He angular distribution, data were obtained simultaneously for the reactions $^{64}Ni(^4He,^6He)^{62}Ni$ [ground state (0^+) and 1.17 MeV (2^+)].

The ^{64}Ni to ^{60}Ni[ground state (g.s.)] transition is particularly simple for theoretical analysis. The spins and parities of the projectile, target, reaction product, and final state are all 0^+. Thus in a cluster model, the most likely four-neutron cluster would be a relative ($s = 0$, $l = 0$, $T = 2$) configuration and the transfer would proceed by the L value $L = 0$. This cluster corresponds to an L-S–coupling [22] spatial symmetry and thus, because of the Pauli principle for the $4n$ system, requires one node in the relative $^4He + (4n)$ wave function. The two-neutron transfer in (^4He,^6He) is considered to be identical to that of the (p,t) reaction. Thus the two neutrons are assumed to be transferred in an ($s = 0$, $l = 0$, $T = 1$) cluster with a spatial symmetry [2]. This symmetry is equivalent to a 0s two-neutron cluster and hence a node in the relative $^4He + (2n)$ wave function.

TABLE I. Optical parameters used in DWBA and two-step calculations.

	V_R (MeV)	r_R (fm)	a_R (fm)	W_I (MeV)	r_I (fm)	a_I (fm)	Ref.
$\alpha + {}^{64}Ni$	169.68	1.273	0.669	27.77	1.423	0.793	5
${}^{6}He + {}^{62}Ni$	200.0	1.229	0.75	27.86	1.375	0.566	6
${}^{8}He + {}^{60}Ni$	300.0	1.419	0.547	23.63	1.66	0.285	7

The aim of the present DWBA (distorted-wave Born approximation) analysis is to predict the shapes of the ${}^{6}He$ and ${}^{8}He$ angular distributions. In addition, the relative cross section for the ${}^{62}N$ 0^+ and 2^+ states should be reproduced, and as a further test the relative cross sections for ${}^{58}Ni({}^{4}He,{}^{8}He){}^{54}Ni$ and ${}^{64}Ni({}^{4}He,{}^{8}He,{}^{8}He){}^{60}Ni$ are considered. Optical parameters, obtained from Ni + ${}^{4}He$ elastic scattering at the same MeV/nucleon as the entrance- or exit-channel projectile, are given in Table I. The ${}^{6}He$ parameters were modified from those of Fernandez and Blair[6] to produce slightly better fits to the angular distributions. The real well depth for the ${}^{8}He$ parameter (Alekseev *et al.*[7]) was increased to 300 MeV to reflect the addition of four neutrons to ${}^{4}He$. Spectroscopic amplitudes for the various transitions are given in Table II. The S factors correspond to the G_{NLSJT} (but without Ω_n) as defined by Glendenning[10] for the two-neutron transfer, and the $A(a_i, NL)$ defined by Arima *et al.*[11] for the four-neutron transfer. Only the highest component of the node number N was considered here. Spectroscopic amplitudes are quoted for both single-shell-model configurations and realistic wave functions. The collective four-neutron spectroscopic amplitudes were obtained based on two-quasiparticle-pair transfer,[12] with the restriction of no quasiparticle for the intermediate state. Effects of collective enhancement can be seen by simply comparing the two results.

For the pickup reaction $A(a,b)B$ with a single J transfer, the experimental cross section is related to zero-range DWBA according to

$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm exp} = \frac{\sigma_{DW} S_1^2 S_2^2 D_0^2}{(2J+1)},$$

where the spectroscopic factors S_1 and S_2 are for the $b = a + x$ and $A = B + x$ system. The zero-range DWBA cross section has been calculated with the code DWUCK4.[13] Radial form factors were generated by the separation energy method using a Woods-Saxon (WS) well. Matching the number of nodes to the oscillator quanta should be reliable if the calculation is not sensitive to the interior region where the wave function generated by the WS geometry is likely to be overestimated. Tests with lower radial cutoffs in the range from 0–5 fm indicated that the shape of the calculated angular distribution was somewhat sensitive to the interior while the magnitude was not. In order to reduce this sensitivity, the cluster wave func-

TABLE II. Spectroscopic amplitudes.

		Single-shell-model configuration	Nodes	S_2 (Single-shell model)	S_2 (Collective)
${}^{62}Ni + (2n)$	0^+	$(f_{5/2}{}^4)$	3	0.19	0.64 [a]
	0^+				0.62 [b]
	2^+	$(f_{5/2}{}^4)$	2	0.11	0.58 [a]
	2^+				0.73 [b]
${}^{60}Ni + (4n)$	0^+	$(f_{5/2}{}^4)$	5	0.0014	0.049 [a]
${}^{54}Ni + (4n)$	0^+	$(p_{3/2}{}^2 f_{7/2}{}^2)$	5	0.0097	0.011 [a]
			S_1(LS scheme)		
${}^{4}He + (2n)$	0^+	1.06			
${}^{4}He + (4n)$	0^+	0.30			

[a]BCS-model calculation. The U and V factors are from Ref. 8.

[b]Shell-model calculation. Wave functions are the $D3$ set in Ref. 9.

tion was multiplied by a WS damping factor of the form $\{1-[1+\exp((r-R)/a)]^{-1}\}$ and then renormalized. R was chosen to be 2.4 fm $[\sim\frac{1}{2}(1.2)A^{1/3}]$ and a was set to 0.6. The (^{4}He,^{6}He) angular distributions were found to be much less sensitive to the damping factor due to the smaller number of nodes in the two-neutron–cluster wave function.

The results of the calculations, appropriately angle averaged, are compared to the data in Fig. 1 where the results obtained without damping the form factor are also shown for the (^{4}He,^{8}He) case. The DWBA prediction for the (^{4}He,^{8}He) transition, Fig. 1(a), reproduces the structure quite well. The structure in the ^{62}Ni 0^+ and 2^+ transitions is reasonably well reproduced as indicated in Figs. 1(b) and 1(c), but the fits are not as good as in the corresponding (p,t) transitions.[10] The DWBA cross sections, coupled with the collective spectroscopic amplitudes, reproduce the experimental 0^+ to 2^+ cross section to within 50%, which is consistent with the (p,t) results. This agreement is quite satisfactory since the spectroscopic amplitude for the 2^+ transition is rather sensitive to the parameters used for the calculation.[14]

The c.m. cross section for ^{58}Ni(^{4}He,^{8}He)^{54}Ni has been measured to be 0.4–0.2 nb/sr at $\theta_{\text{c.m.}} = 5.7°$ and $E = 110$ MeV.[4] In order to compare this with the ^{64}Ni to ^{60}Ni transition, the DWBA prediction for the reaction ^{58}Ni(^{4}He,^{8}He)^{54}Ni at $E = 110$ MeV was calculated in the same manner as the ^{64}Ni(^{4}He,^{8}He)^{60}Ni result and also with the same entrance- and exit-channel optical parameters. At the upper portion of Fig. 2 the relative DWBA predictions for the two reactions are shown, angle averaged for a 3° horizontal acceptance and normalized to the experimental ^{64}Ni cross section. Combining the relative DWBA cross sections and the spectroscopic factors gives a predicted cross-section ratio of 40:1 for ^{64}Ni($\theta_{\text{c.m.}} = 5.6°$):^{58}Ni($\theta_{\text{c.m.}} = 5.7°$). The experimental cross-section ratio at these c.m. angles is (100 ± 50):1, which is in relatively good agreement with the predicted ratio. We note from the spectroscopic

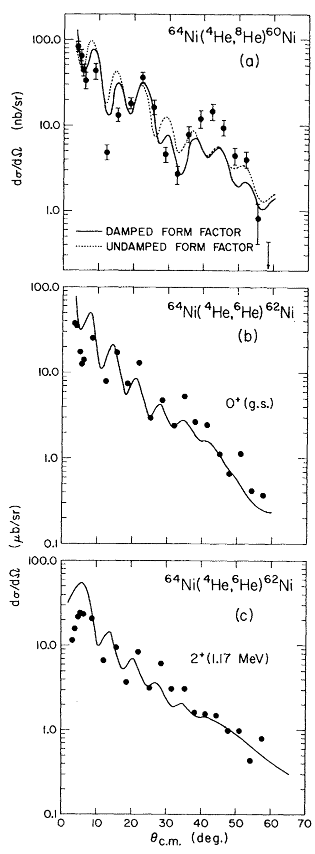

FIG. 1. Comparison of angular distributions to DWBA predictions showing the effects of radially damping the WS form factor.

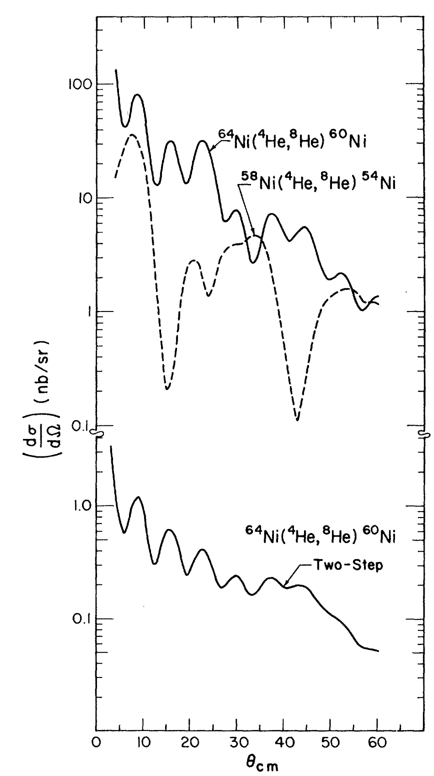

FIG. 2. Relative (^{4}He,^{8}He) cross sections from ^{64}Ni, ^{58}Ni, and a sequential two-step prediction for the ^{64}Ni(^{4}He,^{8}He)^{60}Ni transition.

amplitude given in Table II that the difference in the two cross sections is primarily due to the collective enhancement of the ^{64}Ni(^{4}He, ^{8}He)^{60}Ni transition.

Exact finite-range DWBA calculations would be expected to provide a better description of the four-neutron transfer than the zero-range results. Such calculations were attempted with the code Saturn-Mars[15] using the optical parameters of Table I. The form factors were generated by binding four neutrons to ^{4}He and ^{60}Ni with a WS geometry in the prior form representation. Unfortunately, both the magnitude and shape of the angular distribution were found to be quite sensitive to the choice of the radius in the $^4\mathrm{He}+(4n)$ form factor thus making the results of the calculation somewhat uncertain. In Ref. 3, finite-range effects were found to be important for comparing relative cross sections to 0^+ and 2^+ final states populated via three-neutron transfer since several internal cluster symmetries contributed to the transitions. However, in the present analysis, the transitions from ^{64}Ni and ^{58}Ni are essentially identical and thus we expect the zero-range results to account for the reaction Q dependence.

The sequential two-neutron pickup (^{4}He, ^{6}He) (^{6}He, ^{8}He), through intermediate states in ^{62}Ni, was considered to be a dominant two-step reaction mechanism. Estimates of this transition have been determined via the multistep code CHUCK[16] with the optical parameters of Table I. In order to simplify the calculation, only the transition to the ^{62}Ni ground state was included as an intermediate state. This restriction is not unreasonable since collective effects are most important for the (^{4}He, ^{6}He) ground-state transition. The two-step calculation was not sensitive to the form-factor damping which is consistent with the standard (^{4}He, ^{6}He) results. The predicted cross section is given in Fig. 2. The shape does not reproduce the data as well as the direct-transfer result. In addition, if the channel normalizations are chosen so that the intermediate-state cross section is the correct magnitude (both transfers are given the *same* normalization), the predicted cross section is ~ 60 times smaller than is observed.

In conclusion, the reaction cross section for ^{64}Ni(^{4}He, ^{8}He)^{60}Ni is described by a simple four-neutron–cluster transfer, thus suggesting that the reaction mechanism has a strong one-step component, though the results should be confirmed with detailed exact finite-range calculations. Two-step contributions have not been ruled out but do not appear to dominate the transition. The relative (^{4}He, ^{8}He) cross sections from ^{64}Ni and ^{58}Ni are in good agreement with the DWBA predictions when the collective enhancement is included in the relative spectroscopic factors.

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