Discrepancy between proton- and alpha-induced cluster knockout reactions on ^{16}O

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Cross sections for (p,pd) and (p,pt) reactions at 101.3 MeV and $(\alpha,\alpha d)$, $(\alpha,\alpha t)$, and $(\alpha,\alpha{}^3\mathrm{He})$ reactions at 139.2 MeV have been measured for an ^{16}O target. Distorted wave impulse approximation analyses of the data yield spectroscopic factors for the proton induced reactions which are comparable to shell model estimates. However, the alpha induced reactions yield values up to two orders of magnitude larger. The relationship of these results to similar results for alpha knockout reactions is discussed.

[NUCLEAR REACTIONS $^{16}\mathrm{O}(p,pd)$, (p,pt), $E=101.3$ MeV, $(\alpha,\alpha d)$, $(\alpha,\alpha t)$, $(\alpha,\alpha{}^3\mathrm{He})$, $E=139.2$ MeV; measured $\sigma(E_1,E_2,\theta_1,\theta_2)$; DWIA analysis, deduced spectroscopic factors.]

I. INTRODUCTION

Recently, inconsistencies have been reported in studies of alpha clustering in light and medium mass nuclei using quasifree $(p,p\alpha)$ and $(\alpha,2\alpha)$ reactions.[1–5] Specifically, the $(p,p\alpha)$ studies[2,3] generally yield absolute spectroscopic factors roughly consistent with simple shell model predictions, whereas the $(\alpha,2\alpha)$ results are ~ 100 times larger.[4,5] These values are obtained in conventional distorted wave impulse approximation (DWIA) analyses[6] using cluster-core wave functions with root-mean-square (rms) radii close to the target radii deduced in electron scattering. More reasonable $(\alpha,2\alpha)$ spectroscopic factors can be obtained by introducing apparently excessive cluster-core rms radii.[5] However, alpha momentum distributions observed in the $(p,p\alpha)$ reaction,[3,7] where distortion effects are less severe than in $(\alpha,2\alpha)$, restrict the range of possible radii to values more consistent with the known nuclear radii and with conventional shell model treatments. Thus, the discrepancy remains and has been attributed to the occurrence, in the extreme part of the nuclear surface probed in the $(\alpha,2\alpha)$ reaction, of alpha clustering which is greatly enhanced over average values for the larger nuclear volume involved in the $(p,p\alpha)$ reaction.[1,4,5] Somewhat surprisingly—despite the large discrepancies in absolute values—both $(p,p\alpha)$ and $(\alpha,2\alpha)$ reactions yield relative spectroscopic factors, for ground state transitions in nuclei with $16 \leq A \leq 64$, which are fairly consistent with each other[3,8] and with $(^6\mathrm{Li},d)$ results.[9]

In order to shed further light on this problem, especially the suggestion that the surface alpha clustering is largely projectile induced in the case of $(\alpha,2\alpha)$, we have compared the (p,px) and $(\alpha,\alpha x)$ quasifree knockout reactions on ^{16}O for $x=d$, t, and ^{3}He clusters. For consistency with the previous studies of alpha knockout, the incident proton and alpha energies were chosen to be 101.3 and 139.2 MeV, respectively. Our objective was to determine the ratio of spectroscopic factors for different values of the mass of x. In addition, data were obtained simultaneously for the $(p,2p)$ and $(\alpha,\alpha p)$ reactions. These data will be discussed in detail elsewhere.

II. EXPERIMENT

The experiment was carried out using 101.3 MeV protons and 139.2 MeV alpha particles from the University of Maryland isochronous cyclotron to bombard high purity ^{16}O gas at a pressure of 1 atm in a 12 cm diameter cell. The beam spot was approximately 2 mm$\times$2 mm with an angular divergence of approximately 7 Mrad. In order to define the target thickness and to eliminate particles originating from the gas cell windows, double slit collimators were used in front of each detector telescope. For the (p,px) experiment the overall angular resolution of the two double slit systems was 3.1° and 5.0°, respectively. For the $(\alpha,\alpha x)$ experiment three telescopes were used. For α-d coincidences the angular resolutions were 0.9° and 3.1°, respectively, while for α-t and α-^{3}He coincidences the angular acceptance of the second alpha detector was increased to 3.0°. For the (p,px) experiment both telescopes consisted of 540 μm silicon surface barrier ΔE detectors followed by hyperpure intrinsic germanium detector stacks capable of stopping approximately 74 MeV and 100 MeV protons, respectively. For the $(\alpha,\alpha x)$ experiment the second germanium telescope was replaced by two identical telescopes consisting of 200 μm silicon surface barrier ΔE and 5 mm lithium drifted silicon E detectors capable of stopping 120 MeV alpha particles.

All ΔE-E coincidences were processed using fast electronics such that individual accelerator beam bursts could be resolved. Coincidences between telescopes were determined using a time to amplitude converter, thus permitting concurrent identification and accumulation of real and random coincidence events. Amplified linear signals were fed to 4096 channel analog-to-digital converters interfaced to an IBM 360/44 computer. Energy calibration, addition, and particle identification were carried out by software. Pulser signals fed simultaneously to all preamplifiers were processed along with real data, thus determining dead time corrections. More extensive details of the experimental setup have been given elsewhere.[10]

Data were taken at the angle pairs listed in Table I. Also listed are L, S, and J, the orbital, spin, and total angular momenta, respectively, for the states discussed in Sec. III. It should be noted that only for the $(\alpha,\alpha t)$ and $(\alpha,\alpha^3\text{He})$ reactions are the chosen angles close to a quasifree pair (i.e., the minimum residual nucleus recoil momentum $p_{\min}$ is zero somewhere along the kinematic locus for the transition studied). The choice of a quasifree angle pair has the advantage of ensuring exact angular momentum matching for low L transfer, which tends to alleviate the importance of distortion effects. However, in view of the conflicting requirements of the various reactions studied, data were recorded instead at quasifree angles for the $(p,2p)$ and $(\alpha,\alpha p)$ reactions which were also of major interest. As a result, the (p,pd) reaction is slightly mismatched for $L=0$ transfer (by $\lesssim 0.5\hbar$), though the $(\alpha,\alpha d)$ reaction and all three $L=1$ t and ^{3}He removal reactions are still exactly matched owing to the small values of $p_{\min}$.

Data for all five reactions are shown in Fig. 1 as a function of the energy $F_3=T_1+T_2+T_3$, where T_1 and T_2 are the detected particle kinetic energies and T_3 is the (computed) residual nucleus kinetic energy. Clearly, $F_3=T_0-B$, where T_0 is the incident energy and B the cluster-core binding energy. For the (p,pd) data we could identify two 1^+ states of ^{14}N at 0.0 and 3.95 MeV. In addition, the 2.3 MeV 0^+ level in ^{14}N is observed weakly. Excitation of this level must proceed via a multistep process or via a one step, singlet to triplet deuteron, quasifree spin-flip reaction. In the $(\alpha,\alpha d)$ data the two 1^+ states are also observed. However, the statistics are too meager to determine whether the 2.3 MeV level is excited. Note that the relative populations of the states are nearly the same in the two reactions. For the (p,pt) reaction levels were observed at 0.0 MeV $(\frac{1}{2}^-)$ and 3.5 MeV $(\frac{3}{2}^-)$ in ^{13}N. Owing to the small cross sections, these same levels are just visible in the $(\alpha,\alpha t)$ data as are their analogs at 0.0 and 3.7 MeV in ^{13}C in the $(\alpha,\alpha^3\text{He})$ data.

III. ANALYSIS

The data were analyzed using a factorized DWIA in which the cross section for a reaction $A(a,ab)B$ can be written[6]

$$\frac{d^3\sigma}{d\Omega_a d\Omega_b dE_a}=S_b F_k \frac{d\sigma}{d\Omega_{a-b}} \sum_{\Lambda} |T_L^\Lambda|^2 , \quad (1)$$

where S_b is the spectroscopic factor for cluster b, F_k is a kinematic factor, and $(d\sigma/d\Omega_{a-b})$ is a half-shell two-body cross section for $a-b$ scattering. The quantity $\sum_\Lambda |T_L^\Lambda|^2$ is a distorted momentum distribution for b in the target A where

$$T_L^\Lambda=(2L+1)^{-1/2}\int \chi_{a'}^{(-)*}(\vec{r})\chi_b^{(-)*}(\vec{r})\phi_L^\Lambda(\vec{r})\chi_a^{(+)}\left[\frac{B}{A}\vec{r}\right]d\vec{r} \,. \quad (2)$$

In Eq. (2) the χ's are distorted waves for the incident and emitted particles, and $\phi_L^\Lambda(\vec{r})$ is the relative motion wave function for b and B in the target A (or, more properly, the projection of A onto the B,b product). Calculations were carried out using the code THREEDEE written by Chant.[6]

The bound cluster wave functions were approximated by eigenfunctions of Woods-Saxon wells with energy eigenvalues equal to the $A\rightarrow B+b$ separation energies. Principal quantum numbers were chosen on the basis of conservation of oscillator shell model quanta. Assuming the ejected particles originate from the $1p$ shell, this leads to $2S$ or $1D$ wave functions for deuteron removal transitions and $2P$ wave functions for triton and helion knockout. The radius and diffuseness parameters of the

TABLE I. Details of some of the transitions observed.

This experiment	θ_1/θ_2	$p_{\min}$ MeV/c	L	S	J^π	E_x MeV	$\frac{d^2\sigma}{d\Omega_1 d\Omega_2}$ μb·sr^{-2}	S
^{16}O(p,pd)^{14}N	40.1°/−40.0°	~41	0+2	1	1^+	3.95		0.43
^{16}O(p,pt)^{13}N	40.1°/−40.0°	~51	1	$\frac{1}{2}$	$\frac{1}{2}^-$	0.0	34.5± 5.5	3.4
^{16}O(α,αd)^{14}N	9.0°/−43.99°	~4	0+2	1	1^+	3.95		55
^{16}O(α,αt)^{13}N	25.81°/−43.99°	~13	1	$\frac{1}{2}$	$\frac{1}{2}^-$	0.0	90.7±24.2	53
^{16}O(α,$\alpha\tau$)^{13}C	25.81°/−43.99°	~2	1	$\frac{1}{2}$	$\frac{1}{2}^-$	0.0	110.1±25.7	55

Woods-Saxon wells were chosen to be $R=1.41B^{1/3}$ fm and $a=0.65$ fm, respectively. These values are consistent with electron scattering and proton binding energies[11] and are thus most appropriate for proton removal. However, they suffice for present purposes since the resultant cluster wave functions have rms radii close to or slightly greater than the empirical nuclear radii.

Optical potential parameters were taken from analyses in the literature of nearby targets and energies. For the (p,px) calculations the $p+A$ and $p+B$ parameters were taken from analyses of $p+{}^{12}$C at 100 MeV and 75 MeV, respectively.[12,13] For $d+B$ the parameters were from an analysis[14] of $d+{}^{14}$N at 28 MeV. For both ^{3}He$+B$ and $t+B$ we used parameters[15] obtained by fitting ^{3}He$+{}^{13}$C at 39.6 MeV. For the (α,αx) experiment at 139.2 MeV we needed, in addition to the above, $\alpha+A$ and $\alpha+B$ parameters which were taken from analyses[16] of elastic alpha scattering on ^{12}C at 139 MeV and 104 MeV, respectively.

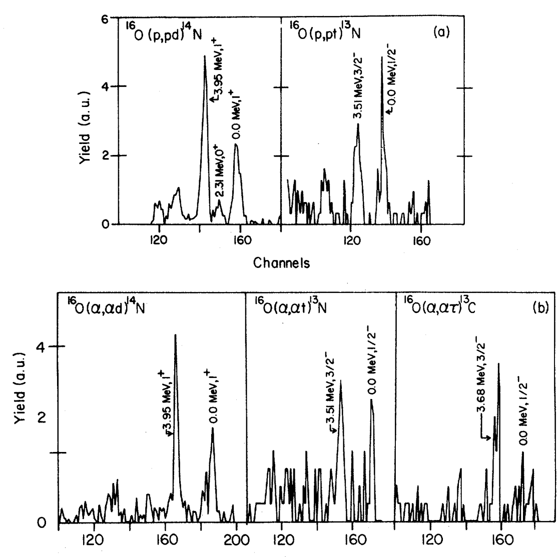

FIG. 1. Binding energy spectra ($F_3=T_1+T_2+T_3$) in arbitrary units for cluster knockout reactions on ^{16}O. (a) Proton induced reactions at $E_p=101.3$ MeV. (b) Alpha particle induced reactions at $E_\alpha=139.2$ MeV.

The two-body $a-b$ half-shell cross sections were approximated by on-shell cross sections at the final relative energy. This procedure has been shown to be an excellent approximation in (α,2α) reactions[5] at 140 MeV and involves very little error in (p,$p\alpha$) studies[2] at 100 MeV. It is adopted here without further justification. Experimental data for $p+d$ were taken from Bunker *et al.*[17]; for $p+t$ and $p+{}^3$He, cross sections were taken from Darves-Blanc *et al.*[18] and Kim *et al.*,[19] respectively. Data for $\alpha+d$ were taken from Willmes *et al.*,[20] and for $\alpha+{}^3$He from Fetscher *et al.*[21] For $\alpha+t$ scattering data were not available in the relevant energy region. Instead we used the $\alpha+{}^3$He data. The corresponding error is estimated to be less than 10%.

In Fig. 2 we show cross sections for (p,pd) and (α,αd) transitions to the 1^+ 3.95 MeV level of ^{14}N plotted as a function of emitted proton and alpha energies, respectively. This transition[22] is believed to be predominantly $L=0$ which enables us to reduce the DWIA expression for the cross section to the expression given in Eq. (1). This is a valuable simplification since deuteron knockout calculations with $L>0$ involve a complicated sum of individual spin dependent amplitudes, with the result that the free $a+b$ cross section can no longer be isolated as a simple multiplicative factor. Furthermore, in mixed L transitions the two L values enter coherently, even in the absence of spin-orbit terms in the distorted waves. The continuous curves in Fig. 2 are thus the result of DWIA calculations assuming $L=0$ only, which have been arbitrarily normalized to the data. For both reactions agreement is encouraging and suggests little need for the addition of a significant $L=2$ component. For (p,pd) a pronounced maximum near the minimum recoil momentum point is observed in both data and calculation. However, the width of the distribution is slightly overestimated. For the $(\alpha,\alpha d)$ reaction the $p_{\min}$ point is at approximately 106 MeV, where no data exist due to detector cutoffs. The calculation shows a pronounced maximum near this point and rises, in fair agreement with the data, though a more steeply rising curve would better reproduce the experiment. The spectroscopic factors obtained from normalizing theory to experiment are 0.43 and 55 from (p,pd) and $(\alpha,\alpha d)$, respectively, which is to be compared with a $1p$ shell model prediction[23] of 1.75.

For the triton and ^{3}He knockout reactions induced by both protons and alpha particles the experimental cross sections are small and our statistics are meager. Thus, it is not instructive to display energy sharing distributions of the type shown in Fig. 2. Rather we list in Table I cross sections for the ground state transitions integrated over emitted proton or alpha energy, as appropriate. These data are compared with DWIA calculations for $L=1$ transitions using Eq. (1) which, since we are ejecting a spin one half cluster, are not subject to the same complications alluded to for deuteron knockout. The resultant spectroscopic factors are 53 and 55 for the $(\alpha,\alpha t)$ and $(\alpha,\alpha{}^3\mathrm{He})$ reactions, respectively, in contrast to a value of 3.4 obtained from the $^{16}\mathrm{O}(p,pt)^{13}\mathrm{N}$ reaction. These results are to be compared with a prediction of 1.17 by Kurath and Millener.[24]

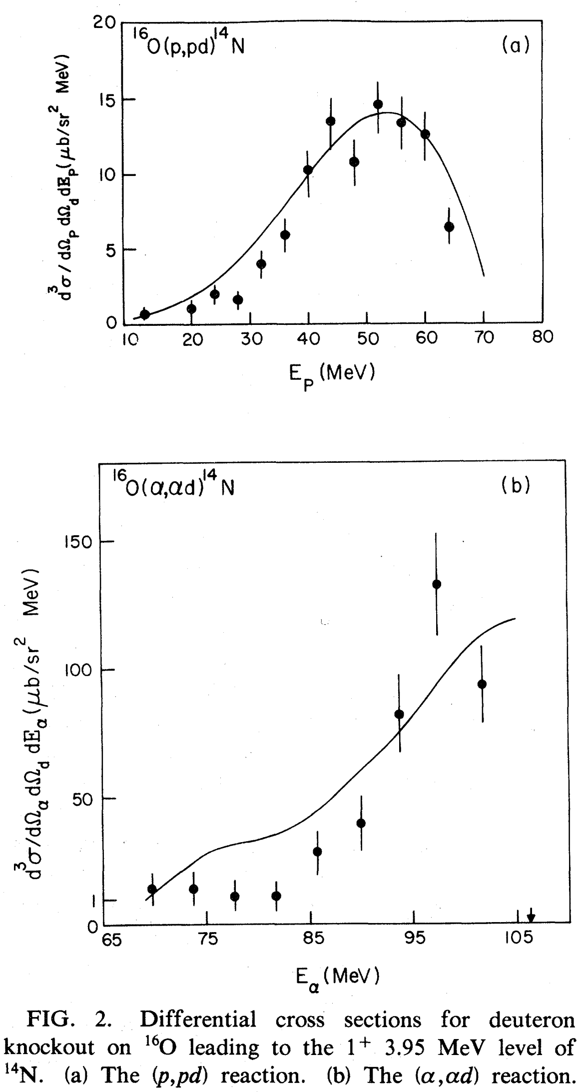

FIG. 2. Differential cross sections for deuteron knockout on ^{16}O leading to the 1^+ 3.95 MeV level of ^{14}N. (a) The (p,pd) reaction. (b) The $(\alpha,\alpha d)$ reaction. The continuous curves are $L=0$ DWIA as described in the text.

Data for $^{16}\mathrm{O}(p,p{}^3\mathrm{He})^{13}\mathrm{C}$ were not obtained in the present experiment due to the energy cutoffs of the ΔE detectors. However, the yield should be nearly identical to that of the analog reaction $^{16}\mathrm{O}(p,pt)^{13}\mathrm{N}$, independent of the reaction mechanism. Data for this reaction as well as $^{16}\mathrm{O}(p,pt)$ were previously reported by Grossiord *et al.*[22] for an incident energy of 75 MeV. In their work the authors extracted the significantly smaller spectroscopic factor of 0.08 for the ground state spectroscopic factor, mainly due to their choice of a large bound state radius parameter of 2.0 fm. A reanalysis of these 75 MeV data with the present bound state radius parameter of 1.41 fm yields a spectroscopic factor of approximately 0.6, which is in much better agreement with the present results.

IV. SUMMARY AND CONCLUSIONS

Summarizing the above results we find that agreement between the theoretical and experimental spectroscopic factors for the proton induced knockout reactions is within a factor of 3 or 4 for deuteron, triton, and ^{3}He clusters. On the other hand, for the corresponding alpha induced reactions the extracted spectroscopic factors are 1 to 2 orders of magnitude larger. In view of the quality of our data, especially for mass 3 knockout, and the uncertainties inherent in the DWIA analysis, we do not regard the differences between theory and experiment for the proton induced reactions as significant. However, for the alpha induced reactions, the observed effect is so large that there is little doubt as to the qualitative result. Namely, as is the case for alpha knockout, we obtain deuteron, triton, and ^{3}He spectroscopic factors which are comparable to theory when measured in a (p,px) reaction, whereas they are 1 to 2 orders of magnitude larger when measured in an $(\alpha,\alpha x)$ reaction.

In Ref. 4 it was argued that the large spectroscopic factors obtained in $(\alpha,2\alpha)$ studies might not correspond to preexisting alpha clustering. As an alternative it was suggested that considerable alpha clustering in the nuclear surface might be induced by the projectile. The mechanism assumed for this effect is a two-step process involving first an inelastic scattering to a level having large alpha parentage followed by quasifree knockout of an alpha cluster from the excited level. For the case of $^{16}O(\alpha,2\alpha)^{12}C$, a suitable candidate level strong in inelastic scattering and having a large alpha width is located at 6.92 MeV, close to the alpha threshold.[5] The present results, however, suggest that such multistep processes are unlikely. This follows from the large differences in the various cluster-core separation energies. Specifically the deuteron, triton, and ^{3}He separation energies from ^{16}O are $\sim$20.7 MeV, 25.0 MeV, and 22.8 MeV, respectively. All are much higher than the alpha separation energy of only $\sim$7.2 MeV, and hence the corresponding cluster-core wave functions decay much more rapidly with radius in the important surface region. Thus, if the 6.92 MeV level, or others nearby, serve as the initial stage of a two-step mechanism for the four $(\alpha,\alpha x)$ reactions considered, one would expect much less enhancement of clustering in the case of the mass 2 and 3 clusters than for the $(\alpha,2\alpha)$ reaction. We have seen that this is not the case. Rather, if multistep mechanisms are important the present data imply additional inelastic strength close to, or above, the 20 MeV region having large overlap with deuteron or mass 3 clusters coupled to the various low-lying residual states observed. While this cannot be totally excluded, it seems unlikely.

Other reaction mechanisms cannot, of course, be completely excluded. However, it is worth noting that the $(\alpha,2\alpha)$ studies of Ref. 4 report an angular dependence consistent with free $\alpha+\alpha$ scattering over nearly two orders of magnitude. This, we argue, strongly supports a one-step knockout reaction of preexisting clusters. Clearly, similar studies for the $(\alpha,\alpha x)$ reactions reported herein would be most valuable. Nevertheless, the available experimental evidence appears to support the notion of greatly enhanced alpha clustering in the extreme nuclear surface suggested in Refs. 4 and 5. That deuteron, triton, and ^{3}He clusters are also comparably enhanced is perhaps no surprise, since the four cluster-core partitions discussed are not orthogonal.

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