Excitation of deep lying hole states in ^{11}C, ^{15}O, ^{27}Si, and ^{57}Ni with the (^{3}He, α) reaction at 216 MeV

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The α spectra were investigated in the discrete and continuum regions. In addition to the well known low lying levels, peaks and broad structures are observed for each nucleus at higher excitation energies. The bumps location and spreading, and their forward peaked distributions, suggest that they arise from neutron pickup in the deeper shells, i.e., $1s$ for ^{12}C and ^{16}O, $1p_{3/2}$ for ^{28}Si and $1d + (1p)$ for ^{58}Ni.

[NUCLEAR REACTIONS ^{12}C, ^{16}O, ^{28}Si, ^{58}Ni(^{3}He, α), E=216 MeV; measured $\sigma(E\alpha; \theta)$; high excitation energy observed levels and broad structure in ^{11}C, ^{15}O, ^{27}Si, and ^{57}Ni.]

For many years the study of quasielastic reactions has been the only means to localize deeply bound shells. In spite of the major improvements now achieved in this type of experiment, the much simpler pickup reaction presents attractive features as an alternative procedure. Provided the absorption of the incoming and outgoing particles is not too strong, implying rather high incident energies, both proton and neutron deep lying orbitals may be studied. Broad structures have indeed been observed in the continuum spectra of (p, d) reactions on $1p$ nuclei at 156 MeV [1] and $1p$ and $2s$-$1d$ nuclei at 185 MeV.[2] These structures have been attributed to neutron pickup from the inner shells. We present in this communication results obtained in an investigation of deep lying hole states using the (^{3}He, α) reaction at 216 MeV. A recent study[3] of the low lying discrete states in ^{12}C(^{3}He, α)^{11}C and ^{16}O(^{3}He, α)^{15}O has shown that this reaction proceeds primarily via direct pickup with rather large cross sections at forward angles. There is, however, evidence in ^{11}C that two step processes are involved in the excitation of particular states. The targets ^{12}C, ^{16}O, ^{28}Si, and ^{58}Ni were chosen in the present study as representative of $1p$, $2s$-$1d$, and $1f$-$2p$ shell nuclei. The excitation energy spectra were measured up to more than 100 MeV.

The experiment was performed with the 216 MeV ^{3}He beam from the Orsay synchrocyclotron. The outgoing particles were detected with a solid state detector telescope using a silicon surface barrier ΔE detector (2.3 mm) and a thin-window planar Ge(Li) E detector (8 mm). The thickness of the E detector was chosen to stop all α particles, but not the elastically scattered ^{3}He particles. Particle identification was performed electronically. Due to the energy definition of the incident beam, target thickness, and kinematical effects, the energy resolution was limited to 500–800 keV. In addition, small corrections had to be introduced in the final α particle spectra for ^{3}He pileup. The ^{16}O results were deduced from the measurements with both SiO_2 and Si targets.

Typical small angle spectra are shown in Fig. 1. For each nucleus, in addition to the low lying discrete states, one observes at higher excitation energies, a broad bump resting on a smooth continuum. The high excitation energy tails of these broad structures extend up to about 40 to 50 MeV, with no evidence of further structure at higher energies. On the low excitation energy side, the structure is more or less well separated from one or more peaks which can arise from the pickup of valence or inner shell neutrons. In addition, some fine structure is observed on the broad bump within the limitations of the experimental energy resolution. However, this fine structure contains only a small fraction of the cross section integrated over the structure, and is therefore not considered within the framework of this communication.

The angular dependence of these α spectra has been investigated over an angular range of 6.25° (7°) to 15° (27°) depending on the target. The broad structures are almost unobservable beyond 15°, as is shown in Fig. 2 for ^{28}Si. The other target nuclei exhibit a very similar behavior. This rapid dependence on angle compared to the general continuum is suggestive of direct neutron pickup.

The identification of the broad structure with the pickup of inner shell neutrons is extremely difficult. Experimentally one has two methods viz., the location in excitation energy and the angular distribution.

The locations and widths of the structures are summarized in Table I. For ^{11}C, ^{27}Si, and ^{57}Ni the locations of the high excitation energy peaks and the centroid of the broad structure generally agree rather well with those of the (p, d) experiment at 185 MeV and with the information from $(e, e'p)$[4,5]

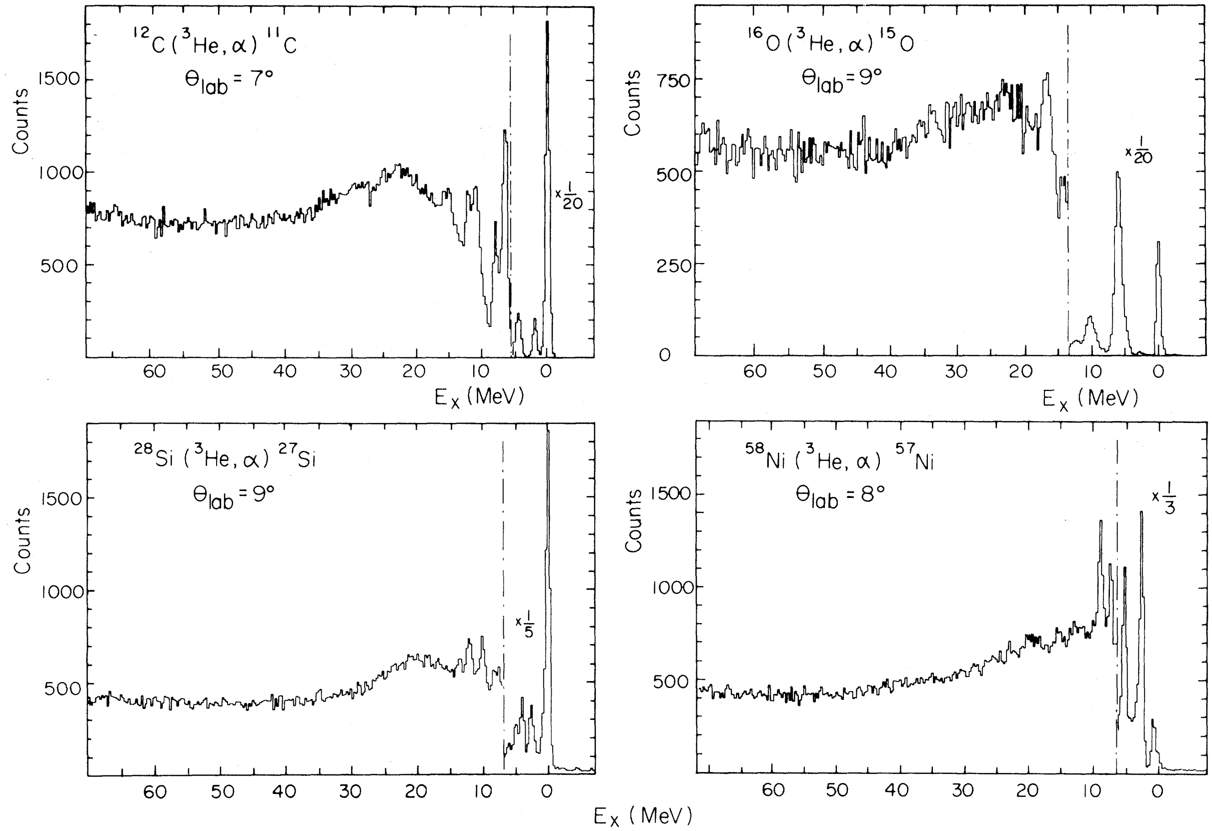

FIG. 1. Typical small angle spectra of α particles from the (^3He, α) reaction at 216 MeV on ^{12}C, ^{16}O, ^{28}Si, and ^{58}Ni targets.

and $(p, 2p)$[5] experiments on the corresponding proton hole states. In the case of ^{15}O, the statistical errors forbid any definitive conclusions; the bump maximum seems to be about 10 MeV lower in excitation energy compared to other experiments. However, two components may contribute to the bump with the main one on the low excitation energy side in the present experiment, whereas the opposite situation was observed in the (p, d) spectrum. For each nucleus, the structure widths compare relatively well with the (p, d) and $(e, e'p)$ results, whereas the $(p, 2p)$ experiment at 460 MeV [6] gives a smaller width in the ^{12}C and ^{16}O cases. Also, the observed $1p$ spin orbit splitting in ^{27}Si follows the general trend in the s-d shell.[7,8] In the case of ^{57}Ni the peaks from the $1d$ $(T_>)$ and $1p$ $(T_>)$ components are predicted near 13 and 36 MeV, respectively, based on $^{58}Ni(e, e'p)^{57}Co$ measurements. Taking into account the larger contribution from $T_<$ states and the information on $1d_{3/2}$ levels lying, for the most part, below 9 MeV [9,10] supports the conclusion that the (^3He, α) cross section above 10.8 MeV is mainly due to $1d_{5/2}$ pickup, but that the $1p$ shell may also contribute to the high excitation energy tail. The $2s$ pickup should

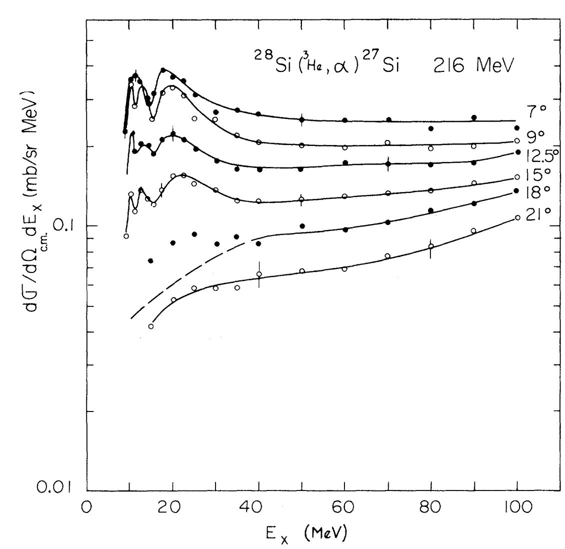

FIG. 2. Comparison of excitation energy spectra for the reaction $^{28}Si(^3He, \alpha)^{27}Si$ recorded at different laboratory angles. Each point corresponds to different excitation energy cuts integrated over ~2 MeV. Typical error bars are shown.

give a rather small cross section compared to the higher l transfers, and is mostly located below 9 MeV.[9,10]

The assignment of the broad structure to the pickup of inner shell neutrons based on the angular distribution suffers from several problems. First, the (^{3}He, α) angular distributions do not exhibit strong characteristic features depending on the neutron orbital angular momentum. These distributions are forward peaked and fall rather smoothly with angle. Secondly, the (^{3}He, α) angular distributions are not well reproduced by standard distorted wave Born approximation (DWBA) calculations; this situation may be partly due to a bad description of the distorted waves in the inner part of the nuclei at such a high incident energy. Finally, and most important, the broad structure rests on a large smooth continuum which must be subtracted in order to extract the differential cross section. It may be noticed that the structures show up above the background in the present reaction, at larger angles than in (p, d) at 185 MeV, although the (^{3}He, α) reaction involves comparatively larger momentum transfers.

The production mechanism for the background continuum is not understood. Beyond the structure, it falls significantly more slowly with angle than the broad structure resting on it (see Fig. 2) and also, the slope does not vary as much with excitation energy. In addition these α continuum cross sections are quite similar in behavior (within 50%) as a function of center of mass angle and excitation energy for all four target nuclei. Since the excitation energies of interest lie above particle emission thresholds in the residual nucleus, the background continuum could arise from direct pickup or knockout reactions occuring on a cluster of nucleons.[11] Also the continuum may contain semidirect processes as suggested by Lewis[12] for heavier nuclei.

Lacking any theoretical predictions, we have assumed that the angular distribution of the background continuum lying under the broad peak of interest is similar to that observed near 50 MeV excitation energy. The background shape could thus be obtained from the α continuum spectra at large angles. In order to extract angular distributions for the broad peaks, the backgrounds to be subtracted were normalized to the measured spectra at 50 MeV excitation energy. The resulting

TABLE I. Location of the main high-excitation energy peaks and structures observed in the present experiment. Excitation energy regions are those taken into account in the evaluation of differential cross sections (see text and Fig. 3). Comparisons with neutron and proton hole states observed in other pickup or quasifree scattering experiments on the same target nuclei are also shown.

Target nucleus	$(nlj)^{-1}$	Excitation energy region (E_{x_1}–E_{x_2}) (MeV)	E_x peak (MeV)	E_x peak (p,d) (MeV)	E_x peak proton hole (MeV)
^{12}C	(1s)	13.5 –17	15.3	15 [a,b]	(16.5) [c,d]
	1s	17.4 –45	23 } (28) }	23.5 [a,b] } (28) }	22; 19 [c,d]
^{16}O	...	15.4 –19	16.8	17 [b]	...
	1s	19 –50	23 } (32) }	(23.5) [b] } 32 }	32 [e]
^{28}Si	$1p_{1/2}$		4.14	4.14 [b]	4.05 [f]
	$1p_{1/2}$		5.24	5.24 [b]	5.15 [f]
	($1p_{3/2}$)	9 –15.4	10.3 } 12.2 }	10.5 [b] } 12.4 [b] }	
	$1p_{3/2}$	15.4 –40	19	~19 [b]	20 [c,g]
^{58}Ni	$1f_{7/2}T_<$ }	2.56– 5.23	2.56		
	$1f_{7/2}T_>$ }		5.23		g.s.
	$1f_{7/2}T_>$		7.13		1.897 [h]
	($1d_{3/2}$)$T_>$		8.84		3.56 [h]
	$1d_{5/2}$ + $1p$	10.8 –50			⟨1d⟩ ≈ 13,[c] 11 [d] (peaking at ~ 8) [c] ⟨1p⟩ ≈ 36,[c] 29 [d] (peaking at 29) [c,d]

[a] Reference 1.
[b] Reference 2.
[c] Reference 4.
[d] Reference 5.
[e] Reference 6.
[f] Reference 8.
[g] Reference 7.
[h] Reference 9.

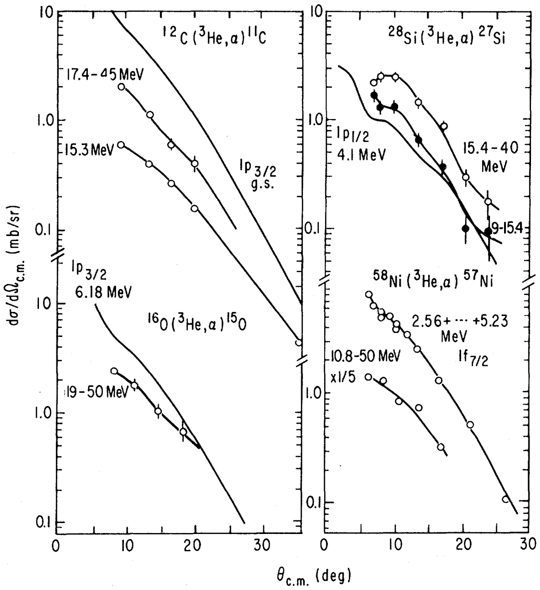

FIG. 3. Angular distributions relative to the structure regions (see Table I) observed at high-excitation energy in each nucleus. Also shown are experimental curves for a few well known discrete states in each case. Error bars (see text) are indicated when they exceed the size of the point.

spectra were then integrated over different regions of excitation energy.

The extracted angular distributions, corresponding to the excitation energy regions of Table I, are presented in Fig. 3. The error bars do not include the expected large systematic errors which arise from an improper treatment of the background continuum. In addition we present the distributions for a few well known discrete states. The resultant angular distributions for the high-excitation energy structures are quite similar to those for the discrete peaks, supporting direct pickup as the dominant mechanism.

Although the distributions are not strongly characteristic of the orbital angular momentum transfer, several suggestive observations can be made. First, the magnitude of the cross sections for the broad peaks in ^{11}C and ^{15}O are nearly the same, which is expected if both arise from the pickup of a $1s$ neutron.

Secondly, in ^{27}Si, keeping in mind[8] that nearly all the $1p_{1/2}$ strength lies in 4.14 and 5.24 MeV levels, we tentatively attribute the two structures from 9 to 15.4 MeV and 15.4 to 40 MeV, to pickup in the deep $1p_{3/2}$ neutron shell; their angular distributions compare very well with that of the 4.14 MeV level and have a summed cross section which is roughly a factor of 4 to 5 larger: this supports the $1p_{3/2}$ assignment, noting in addition that the (^{3}He, α) cross sections at 216 MeV tend to increase somewhat with excitation energy.

Finally, in the case of ^{57}Ni, where this experiment presents the first observation of high energy neutron hole states, we can say that the structure cross section above 10.8 MeV is large and consistent with a dominant contribution of the $1d_{5/2}$ strength.

In conclusion, the location and angular distributions of the broad structures observed in the present experiment support their attribution to the pickup of neutrons from inner shells. The (^{3}He, α) reaction at 216 MeV has proved useful as an alternative to the (p, d) reaction in the study of such shells in light and medium nuclei. We emphasize that the relevant momentum transfers and distortions are different in both reactions, and moreover in quasielastic reactions, which deserve further comparisons. More definite statements and quantitative information require a proper treatment (based on theory) of the background continuum and a better description of the pickup reactions at high energy.

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