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ALPHA-PARTICLE TRANSFER VIA THE ($^{12}C, ^{8}Be$) REACTION: APPLICATION TO STUDIES OF ^{16}O AND ^{20}Ne†

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Abstract:

By utilizing particle identification techniques to detect the two breakup α-particles from ^{8}Be, the $^{12}C(^{12}C, ^{8}Be)^{16}O$ and the $^{16}O(^{12}C, ^{8}Be)^{20}Ne$ reactions have been studied. The ($^{12}C, ^{8}Be$) reaction strongly populates the positive parity 4p-4h rotational band of ^{16}O based on its 6.05 MeV(0^+) state and both the positive and negative parity rotational bands of ^{20}Ne based on its ground state (0^+) and 5.80 MeV(1^-) state, respectively.

The question of whether quartet configurations play an important role in nuclear structure has prompted a great deal of experimental work on α-transfer reactions.[1,2] It has been suggested that the ($^{12}C, ^{8}Be_{g.s.}$) reaction may be among the most suitable,[2] since the parentage of $^{12}C_{g.s.}$ as $^{8}Be_{g.s.} + \alpha$ is especially large. This reaction has not previously been reported; in part this is due to the difficulty of detecting ^{8}Be, which is unstable with respect to breakup into two α-particles (by 92 keV). Herein we wish to report a simple technique for the detection of ^{8}Be, as well as results for the $^{12}C(^{12}C, ^{8}Be)^{16}O$

and the $^{16}O(^{12}C, ^{8}Be)^{20}Ne$ reactions.

Methods of identifying ^{8}Be which have been previously reported have relied on the separate detection of the two breakup α-particles: either their tracks have been observed in nuclear emulsions[3] or they have been recorded in coincidence in separate solid state detectors.[4]

Our approach for detecting ^{8}Be employs a ΔE-E telescope feeding a conventional particle identifier. If the two breakup α-particles travel together through a counter telescope, they will be identified as a ^{7}Li. This can be seen as follows: the differential energy loss of a particle with charge z and velocity v in a given absorber may be written

$$dE/dx \sim z^2 f(v^2)/v^2 ,$$

where f varies logarithmically (hence slowly) with v^2. Thus, the dE/dx for a ^{7}Li with energy E relative to that for the two simultaneous α-particles, each of which carries half this energy, is

$$\frac{dE/dx\ (^{7}Li)}{dE/dx\ (^{8}Be)} = \frac{63}{64} \frac{f(0.286\ E)}{f(0.25\ E)} \approx 1 .$$

Similarly, the two breakup α-particles will also be detectable as a ^{7}Li if an identifier of the power law type is used.[5] Fortunately, the Q-value for the $(^{12}C, ^{8}Be)$ reaction is often much more positive than that for the $(^{12}C, ^{7}Li)$ reaction on the same target (for $T_z = 0$ targets the difference is ∿ 15 MeV). Thus the $(^{12}C, ^{8}Be)$ reaction may be observed over a large range of excitation energy without contamination from the $(^{12}C, ^{7}Li)$ reaction.

We have tested this approach for detecting ^{8}Be particles with the $^{12}C(^{12}C, ^{8}Be)^{16}O$ and $^{16}O(^{12}C, ^{8}Be)^{20}Ne$ reactions. A ^{12}C-beam of 62.6 MeV from the Berkeley 88-inch cyclotron was used to irradiate a solid carbon target of 160 μg/cm^2 thickness and an oxygen gas target. Particles were detected in two four-counter telescopes each of which consisted of two ΔE-detectors (80μ and 50μ thick), an E-detector (500μ), and a reject detector (500μ). Our electronics were as described in Ref. 5, except for one important addition. Scattered ^{12}C-ions stopping in the first ΔE-detector saturated its linear amplifier, thus causing pileup problems. Saturating pulses were detected and eliminated by using an updating discriminator whose output inhibited the master gate of the identifier electronics for 4μs--the baseline recovery time of the linear amplifier.

Only a small fraction of the ^{8}Be particles emitted into the solid angle of one of our telescopes was actually detected. In the laboratory system the two breakup α-particles are confined within a cone which is centered about the velocity vector of the center of mass of ^{8}Be. This cone forms an angle γ_{max} given by

$$\gamma_{max} = 2 \arcsin \left[(Q/E_8)^{1/2} \right] ,$$

where Q is the breakup energy of the ^{8}Be and E_8 is the laboratory energy of the ^{8}Be. For our solid angle of 0.6 msr (solid target), we have calculated[6] for the ^{8}Be g.s. a detection efficiency of 2.1% for E_8 = 20 MeV, which increases about linearly to 6.4% for E_8 = 60 MeV. In contrast, our efficiency for detecting ^{8}Be*(2.9 MeV) is calculated to be only 4% of the g.s. value.

Figure 1 presents a spectrum of ^{16}O obtained from the ^{12}C(^{12}C,^{8}Be) reaction. The observed resolution was 500 keV FWHM. In order to provide further evidence that this is indeed the (^{12}C, ^{8}Be) reaction, the energies of several ^{8}Be peaks were studied as functions of the scattering angle. The result for one of these peaks is given as an insert in Fig. 1 along with two curves: i) the kinematics of the $^{12}C(^{12}C, ^{8}Be)^{16}O$ reaction populating the known ^{16}O state at 10.34 MeV, and ii) the kinematics of a hypothetical reaction $^{12}C + ^{12}C \longrightarrow$ mass 17 + mass 7 with the Q-value adjusted to match both curves at the laboratory angle of 14°. The experimental points prove that mass-8 particles are being detected.

Provided the peaks in our spectra are due to the population of single ^{16}O states, their excitation energies can be determined to ±70 keV, except for the 14.67 and 16.27 MeV states which have uncertainties of ±140 keV. Table I compares our measured excitation energies for ^{16}O states with literature values[7] and also lists the transition cross sections at θ(lab) = 14°. The c.m. cross sections are given both as the measured number $(d\sigma/d\Omega)_{observed}$ and as $(d\sigma/d\Omega)_{absolute}$; the latter includes the correction for the ^{8}Be detection efficiency. The angular distributions are found to be forward peaked and structureless. They decrease by factors of 5 to 8 between 14° and 34° in the lab system with those of the 6.92 and 11.10 MeV states being flatter than those of the 6.07 and 10.34 MeV states.

Analysis of these results indicates that (^{12}C, ^{8}Be) appears to be a "good" α-transfer reaction in that the four nucleons are transferred as a 0^{+}-cluster. This is apparent from comparing (^{12}C, ^{8}Be) spectra with those from (^{7}Li,t), a reasonably well-established example of an α-transfer reaction,[8] and with those from (^{10}B, ^{6}Li), an example of four nucleon transfer without any pronounced selectivity.[9] The (^{12}C, ^{8}Be) spectra show strong population of the rotational band based on the 6.05 MeV(0^+) state, which contains the 6.92(2^+), 10.35(4^+) and 16.30(6^+) states; these states have essentially 4p-4h character.[10] (Unfortunately the ^{16}O states at 6.05 MeV(0^+) and 6.13 MeV(3^-) could not be resolved.) In addition to this band we observe two strong states:

(i) The peak near 11.10 MeV which is probably the 11.096 MeV(4^+) and not the 11.08 MeV(3^+) state, since unnatural parity states do not seem to be populated (the 2^- states at 8.87 and 12.53 MeV were not observed). This 4^+ state also shows up strongly in the ^{14}N(α,d)^{16}O and ^{13}C(^{6}Li,t)^{16}O reactions and therefore was suggested to have predominantly 2p-2h character(see Ref. 11); the ^{14}N(^{3}He,p) reaction,[12] however, provided evidence for a more complicated structure--possibly involving ^{12}C-core-excitation.

(ii) A broad (800 keV FWHM) state or group of states at 14.67 MeV probably contains the 6^+ state at 14.81 MeV observed in elastic α-particle scattering[13] as well as in[11] ^{14}N(α,d)^{16}O. Population of the broad 5^- state at 14.6 MeV reported in Ref. 14 appears to be unlikely, since it would be a member of the odd parity, 3p-3h rotational band (containing the 9.6(1^-), 11.63(3^-), 14.6(5^-), and 20.8 MeV(7^-) states) and we do not find evidence for the first two members of this band.

All these (^{12}C,^{8}Be) results are very similar to previous data from the ^{12}C(^{7}Li,t)^{16}O reaction;[8,15] this comparison suggests that (^{12}C,^{8}Be) is a new α-transfer reaction. By contrast, the four-nucleon transfer reaction[9] ^{12}C(^{10}B,^{6}Li)^{16}O populates all the above mentioned states, as well as states of comparable intensity at 8.87(2^-), 9.85(2^+), and 13.26 MeV(3^-).

A spectrum from the ^{16}O(^{12}C,^{8}Be)^{20}Ne reaction taken at θ(lab) = 17° is shown in Fig. 2. The observed resolution is 600 keV FWHM. The excitation energies determined from this work are known to ±100 keV. As in the previous case this spectrum resembles the data obtained with the (^{7}Li,t) reaction.[15,16] Our results are consistent with the assumption that the (^{12}C,^{8}Be) reaction mainly populates two rotational bands (see Ref. 16 and references given therein):

(i) The positive parity band based on the ground state and containing the 1.63(2^+), 4.25(4^+), and 8.79 MeV(6^+) states. It has $(sd)^4$ structure.

(ii) The negative parity band containing the 5.80(1^-), 7.17(3^-), and 10.30 MeV(5^-) states. It has $(sd)^3$ $(fp)^1$ structure.

Both bands are expected to be strongly populated by an α-transfer reaction.[16]

In summary, the (^{12}C,^{8}Be) reaction appears to offer potential as an additional tool for the study of α-clustering in nuclei--along with the (^{6}Li,d), (^{7}Li,t), and (^{16}O,^{12}C) reactions. Complications due to mutual excitation processes are severely reduced by a detection method that discriminates in favor of observing ^{8}Be in its ground state. Through the use of wide area detectors, the detection efficiency of ^{8}Be's could be easily increased by a factor of ten. This technique plus the availability of ^{12}C beams of sufficient energy and intensity at many tandem and cyclotron laboratories should permit the study of the (^{12}C,^{8}Be) reaction on a wide variety of targets.

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Table Caption

Table I. Summary of the results of the present experiment. The first two columns list data on the known states in ^{16}O and ^{20}Ne according to Refs. 7 and 1, respectively. The third column gives our excitation energies. The fourth and fifth columns give the measured and absolute differential cross sections as explained in the text.

Figure Captions

Fig. 1 Energy spectrum from the $^{12}C(^{12}C,{}^{8}Be)^{16}O$ reaction. The excitation energies are determined from this experiment. See also Table I. The insert in the upper right hand corner contains a plot [E(lab) vs θ(lab)] of the kinematics of the $^{12}C(^{12}C,{}^{8}Be)^{16}O^{*}$(10.34 MeV) reaction as compared to the kinematics of a hypothetical reaction 12(12,7)17. See explanation in the text.

Fig. 2 Energy spectrum from the $^{16}O(^{12}C,{}^{8}Be)^{20}Ne$ reaction. The excitation energies are determined from this experiment. See also Table I.

Table I. Results for the Reaction (^{12}C, ^{8}Be) on ^{12}C and ^{16}O Targets.

Energies and J^{π} values of known levels (Refs. 7 and 1)		Energies (this work) (MeV)[b]	$(d\sigma/d\Omega)^{a}_{obs}$ (μb/sr)[c]	$(d\sigma/d\Omega)^{a}_{abs}$ (μb/sr)
^{16}O g.s.	0^+	-0.03	1.5	25
6.050	0^+	6.07	8.2	150
6.919	2^+	6.92	6.6	120
10.353	4^+	10.34	16.0	330
11.096	4^+	11.10	7.6	160
14.82	6^+	14.67	18.0	420
16.304[d]	6^+	16.27	13.0	320
^{20}Ne g.s.	0^+	-	0.4	10
1.63	2^+	1.62	2.5	60
4.25	4^+	4.26	6.3	170
5.80	1^-	5.78	1.5	40
7.17	3^-	7.16	3.5	100
8.79	6^+	8.79	7.0	220
10.30	5^-	10.35	11.0	350

[a] Cross sections for populating ^{16}O and ^{20}Ne final states are given in the c.m. system and are averages of several measurements at θ(lab) = 14° and 17°, respectively.

[b] Errors are quoted in the text.

[c] The cross sections could be uniformly in error as much as 50%.

[d] Reference 10.

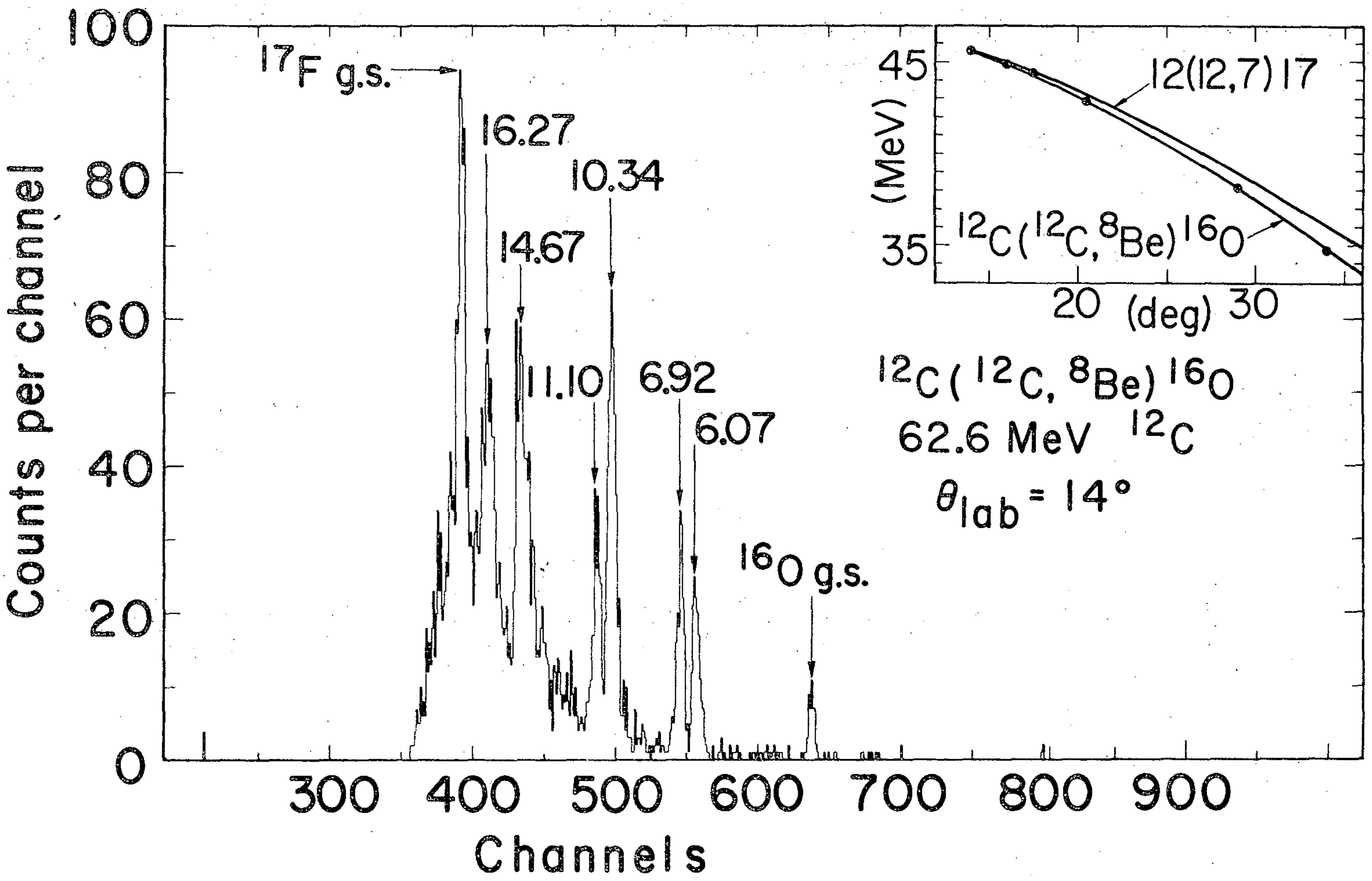

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Fig. 1

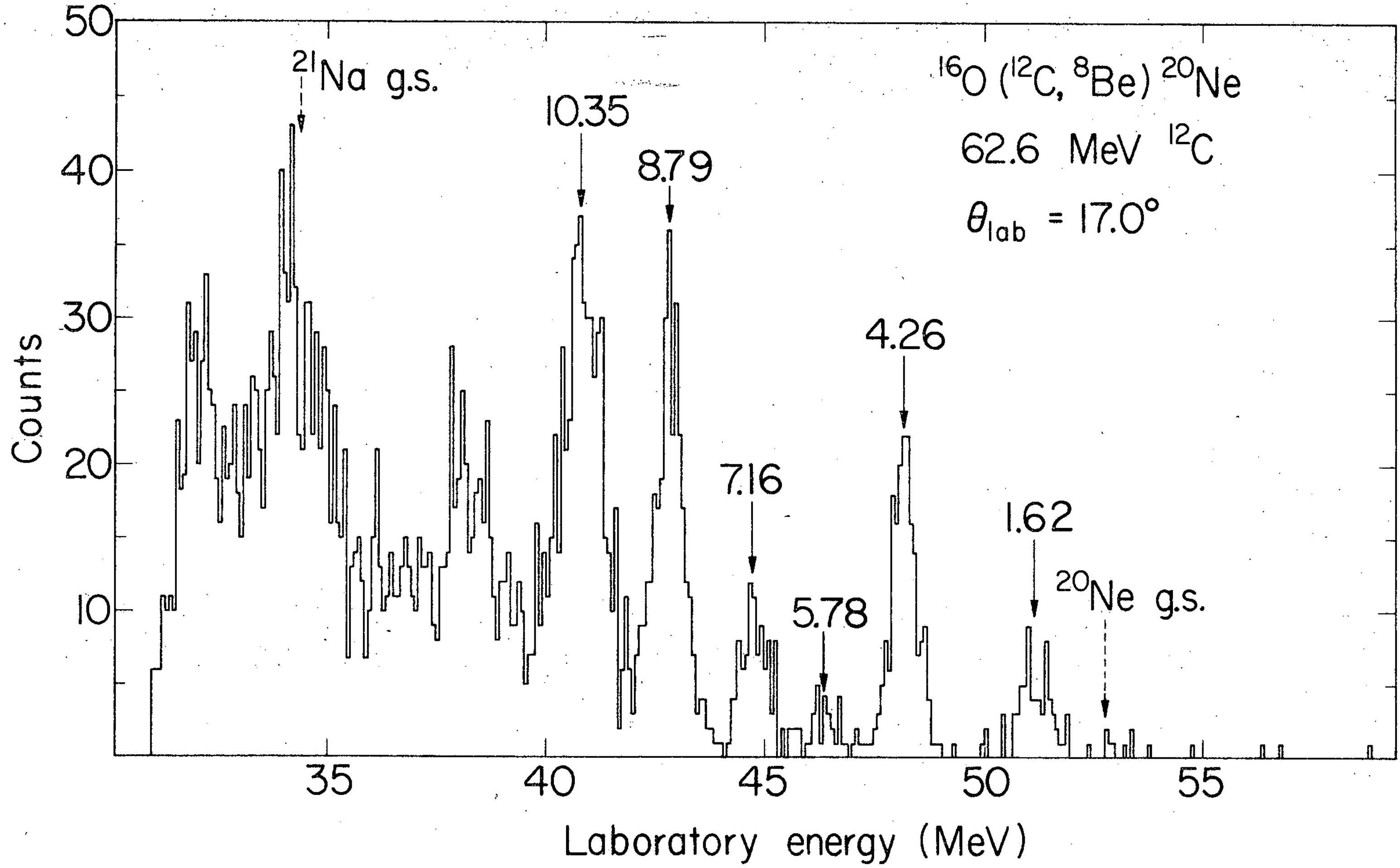

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Fig. 2

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