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Neutron Pickup and Four-body Processes in Reactions of $^{16}O + ^{197}Au$ at 26.5 and 32.5 MeV/nucleon

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Abstract

Projectile breakup in reactions of 424-MeV and 520-MeV $^{16}O + ^{197}Au$ was studied via coincidence measurements of projectile-like fragments and light particles. The quasi-elastic breakup of the projectile was found to proceed via sequential decay. In addition, the ^{12}C-α channel showed important contributions from neutron pickup followed by successive neutron and alpha-particle emission, a mechanism generating four-body final states.

Heavy-ion reactions in the range of bombarding energies from 5-10 MeV/nucleon proceed via such "low-energy" mechanisms as nucleon transfer and compound-nucleus formation. At around 10 MeV/nucleon, however, mechanisms such as incomplete fusion and projectile breakup take on increased importance. It has been thought that at still higher energies, approaching the Fermi energy ($\approx$ 35 MeV/nucleon) and beyond, additional mechanisms would become apparent. Indeed, inclusive measurements have led to some controversy as to how rapidly phenomena associated with relativistic energies would emerge as the bombarding energy increases [1-4].

Following more recent exclusive measurements, however, it now appears that the region of bombarding energy from 10 to 100 MeV/nucleon witnesses not a sudden transition but rather a gradual evolution in mechanisms [5-7]. In particular, the competition between transfer (the capture of nucleons transferred from the reaction partner) and breakup (generic dissociation of the projectile) was found to be strong up to 40 MeV/nucleon. It is therefore of interest to determine the importance of fragmentation (prompt dissociation) processes in this intermediate-energy regime, since this would signal the onset of phenomena normally associated with high-energy collisions. In this Letter, we report on coincidence measurements of multi-body channels (with summed masses close to that of the projectile) produced in peripheral reactions of 26.5 and 32.5 MeV/nucleon ^{16}O beams on a gold target. Rather than prompt fragmentation, the results indicate that the underlying mechanism in these cases is inelastic scattering or pickup to particle-unstable states in the ejectile, followed by single or multiple decays.

The experiments were performed at the Lawrence Berkeley Laboratory's 88-Inch Cyclotron (plus ECR source). In an initial experiment, a 26.5-MeV/nucleon ^{16}O beam was incident on a 2-mg/cm^2 ^{197}Au target. Projectile-like fragments were detected in a solid-state telescope positioned at 9°, slightly forward of the classical grazing angle at 11°. Coincident light charged particles (mostly protons and alpha particles) were detected in an array of vertical strips of position-sensitive plastic phoswich detectors (similar to those described in [8]), providing high detection efficiency over a range of in-plane angles from 4° to 14°. The inelasticity of the reaction, Q_3, and the relative kinetic energy between detected fragments, E_{rel}, were determined event-by-event.

Figs. 1(a),(b) show Q_3 spectra for the ^{12}C-α and ^{13}C-α channels. Both spectra exhibit prominent quasi-elastic peaks, corresponding to reactions that have produced all three bodies in (or within a few MeV of) their ground states. The energy-angle correlations of these quasi-elastic coincidences show structures known to arise from sequential decay. This can be illustrated by the E_{rel} spectra for the two channels, shown in Fig. 2. The ^{12}C-α coincidences exhibit a peak at E_{rel} = 4.4 MeV. Similarly, an earlier high-resolution study of ^{16}O breakup at 9 MeV/nucleon by Rae et al. [9] showed a strong peak at E_{rel}= 4.31 MeV, corresponding to the 2^+ state at 11.47 MeV in ^{16}O. Note that the yield decreases rapidly for low relative energies. This is because ^{16}O does not possess any alpha-decaying states within the first 2.5 MeV above the decay threshold. (Indeed,the data points below 2.5 MeV are due to the experimental resolution.) In ^{17}O, however, the first state that alpha decays is only 0.8 MeV above threshold, and there are 14 states in the region from 0.8 to 2.5 MeV above threshold. Correspondingly, the spectrum of E_{rel} for ^{13}C-α shows relatively more yield in the first few MeV. Although the energy and position resolution attainable with phoswich detectors is not as high as with (much smaller) position-sensitive silicon detectors [9,10], the structure in the spectra of Fig. 2 and the close analogy with high-resolution results at lower energies are sufficient to show that the breakup is proceeding through excited states in $^{16}O^*$ or $^{17}O^*$.

The pickup of a nucleon followed by the decay of the recipient into two bodies (called "pickup-induced breakup") is well known. The primary fragment may decay back into the entrance channel (the process called "transfer-reemission" [11]) in which case it forms a background in inclusive measurements of inelastic scattering as in $(\alpha, ^5He^* \rightarrow n+\alpha)$ [12], $(^{16}O, ^{17}O^* \rightarrow n+^{16}O)$ [13], and similarly for ^{20}Ne [14]. This process is readily identified if coincidence measurements on the two fragments are performed [11,14]. The primary fragment may also decay into two bodies in a channel other than the one through which it was formed; e.g., as shown in [9,10]. The present work shows that these same mechanisms are present at higher bombarding energies as well.

We focus now on the prominent structure observed at large inelasticity in the Q_3 spectrum of ^{12}C-α [Fig. 1(a)]. This feature, centered at ≈40 MeV, is remarkable in light of the complete absence of such a structure in the ^{13}C-α spectrum. The yield associated with this large Q_3 is comparable to that of the quasi-elastic process, and thus represents an important mechanism at 26.5 MeV/nucleon. If indeed the primary projectile-like fragment decays into only two bodies, then the broad peak could represent, in principle, a structural feature of the ^{197}Au target at high excitation, and the excitation energy of the peak should then be independent of bombarding energy. To test this, the experiment was repeated at a higher bombarding energy.

Fig. 1(c) shows the Q_3 spectrum for ^{12}C-α obtained at $\theta(^{12}C) = 6^{\circ}$ with a 520-MeV ^{16}O beam. A careful comparison with the equivalent spectrum at 424 MeV [Fig. 1(a)] reveals that the location of the peak has shifted with bombarding energy by 5 MeV, thus ruling out any simple explanation in terms of a structural excitation in ^{197}Au.

We now show that the data can be understood in terms of neutron pickup to highly-excited states in ^{17}O followed by the nα or αn decay of the primary fragment into <u>three</u> bodies. It is clear from the observation of ^{13}C-α coincidences that neutron pickup to unbound states does occur in this reaction. Calculations (Siemens et al. [15]) of optimum Q-values for one-neutron pickup reactions predict average excitations of ≈16 and ≈22 MeV, at bombarding energies of 26.5- and 32.5-MeV/nucleon, respectively. Previous studies of projectile breakup [16] and neutron multiplicity [17] have demonstrated that most of this excitation will reside in the recipient nucleus.[§] However, in addition to single emission of a neutron, proton or alpha particle, it is energetically possible for $^{17}O^*$ to undergo sequential nα or αn decay for excitations in excess of 13.8 and 13.2 MeV, respectively.

This multiple decay results in a four-body final state. Since our detectors are insensitive to neutrons, the "lost" energy of the undetected neutron gives rise to a large apparent excitation in the ^{12}C-α spectrum. For the pickup-breakup process just described, the shift in Q-value (relative to the Q_{ggg} peak) is equal to the laboratory kinetic energy of the neutron plus the neutron separation energy of the target. We have used the calculated optimum Q-value [15] to estimate the velocity of the primary

$^{17}O^*$, and thus derive an average neutron energy. Such straight-forward considerations give rise to the predictions shown in Figs. 1(a),(c) for the centroid of this pickup-breakup peak. The agreement with experiment is excellent, with the shift in centroid correctly predicted. Moreover, the width of the bump can be reproduced in a Monte Carlo simulation of sequential decay by assuming a reasonable distribution of neutron decay energies.

Additional information is provided by the energy-angle correlations, shown in Fig. 3 for those alpha particles detected in a vertical strip located just behind the heavy-ion detector. The ring-like structures seen in the ^{12}C-α and ^{13}C-α spectra gated on the Q_{ggg} peak [Figs. 3(a),(b)] arise from the population and decay of excited states above the threshold for particle decay. Indeed, the properties of this ring can be shown to correlate with the low-lying energy level structure of the decaying parent nucleus (as was shown for the E_{rel} spectra in Fig. 2). This ring structure, though less sharp, is nevertheless unmistakable in the ^{12}C-α spectrum gated on the inelastic events in the region Q_3= -80 to -20 MeV [Fig. 3(c)]. In particular, the correlation shown in Fig. 3(c) does not show any distortions due to prompt interactions with the target nucleus, suggesting that these events are also sequential in nature. The filling-in of the ring (corresponding to coincidences at small E_{rel}) is associated with the emission of low-energy alpha particles from highly-excited states in ^{17}O (for αn emission) and kinematic recoil (for $n\alpha$ decay).

The four-body pickup-breakup peak is extremely prominent in these experiments. Why has it been less obvious or absent in other reactions? Breakup in the ^{16}O + ^{197}Au system was also studied by Bini et al. [18], at

20 MeV/nucleon. However, their ^{12}C-α and ^{13}C-α coincidence data are very similar, in contrast to data in Figs. 1(a),(b). This is explained by their lower bombarding energy, for which the most probable excitation energy generated in $^{17}O^{*}$ (≈ 9.5 MeV) is insufficient for multiple sequential decay. (The same reasoning applies to all other measurements with ^{16}O at lower bombarding energies; e.g., [9].)

The foregoing analysis illustrates why the cross sections for observing nuclei heavier than the projectile become so small as the bombarding energy is raised : the projectile acquires a high excitation energy through capturing one or more nucleons [16,17] and decays by particle emission into different channels. In those collisions in which a heavier, bound product does indeed emerge, it follows that the primary fragment must have had a very low excitation energy. This situation can occur only if the projectile captured a nucleon (or cluster of nucleons) in the target with low momentum relative to the projectile (i.e., the velocity-matching conditions discussed by Von Oertzen [19]).

In conclusion, coincidence measurements of projectile breakup in 26.5- and 32.5-MeV/nucleon ^{16}O + ^{197}Au reactions show important contributions from neutron pickup followed by successive sequential decays, leading to four-body final states. This channel is comparable in yield to quasi-elastic projectile breakup in producing ^{12}C-α coincidences. Thus, we find that a process characteristic of low-energy transfer reactions is an important mechanism for producing complex, multi-body exit channels in intermediate-energy heavy-ion reactions.

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Footnotes

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§ The very strong dependence on bombarding energy of the excitation energy induced by transfer reactions is in contrast to the much weaker dependence for inelastic scattering. This arises from the different mechanism for the generation of excitation energy in each case - mass transfer and excitation of collective states, respectively [11].

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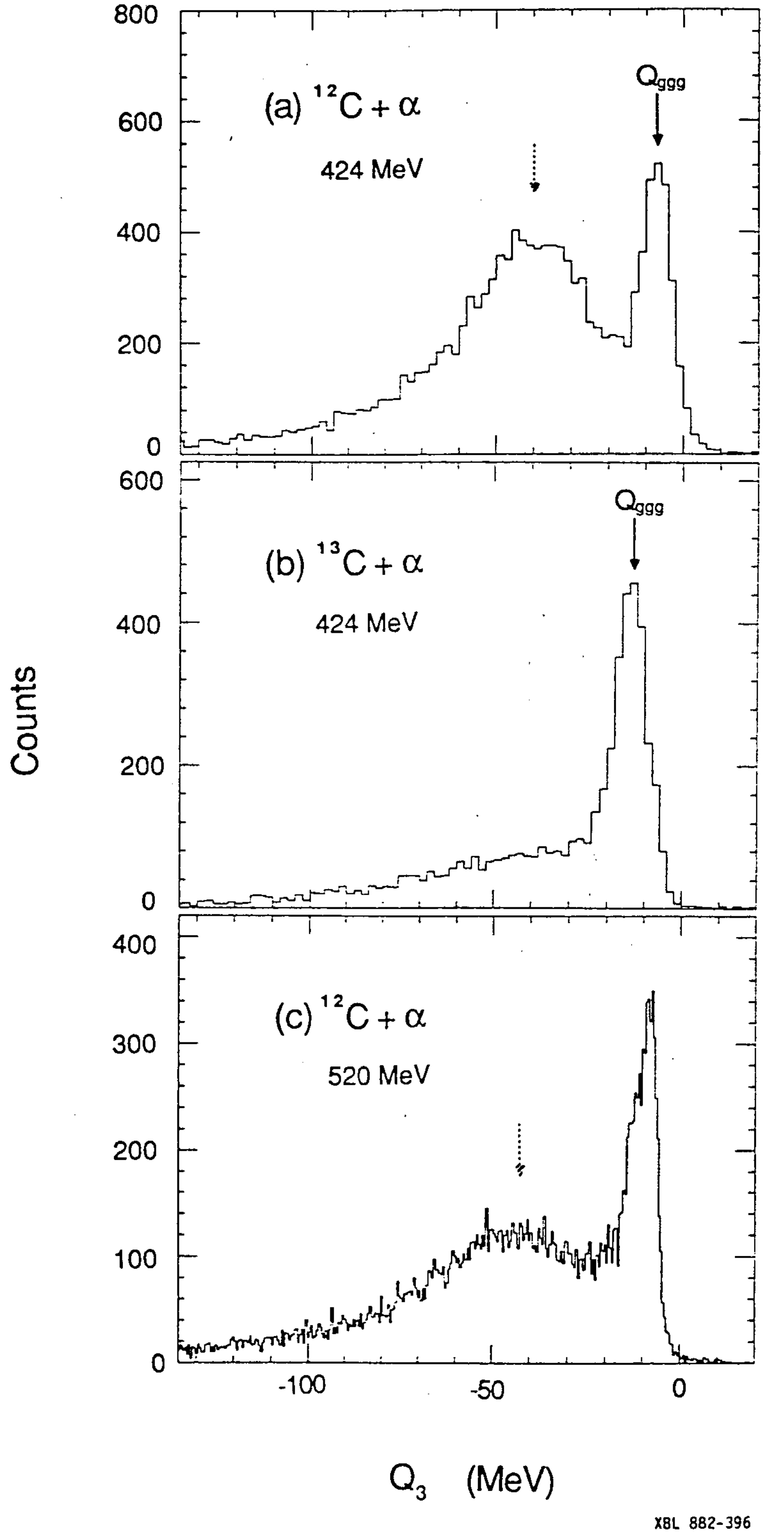
Figure Captions

1) Q_3 spectra are shown for the (a) ^{12}C-α and (b) ^{13}C-α channels produced in 424-MeV ^{16}O + ^{197}Au breakup reactions. The projectile-like fragment was detected at 9°, in coincidence with alpha particles detected with high efficiency by a phoswich array. A Q_3 spectrum for the ^{12}C-α channel at 520-MeV bombarding energy is shown in (c), for ejectiles detected at 6°.

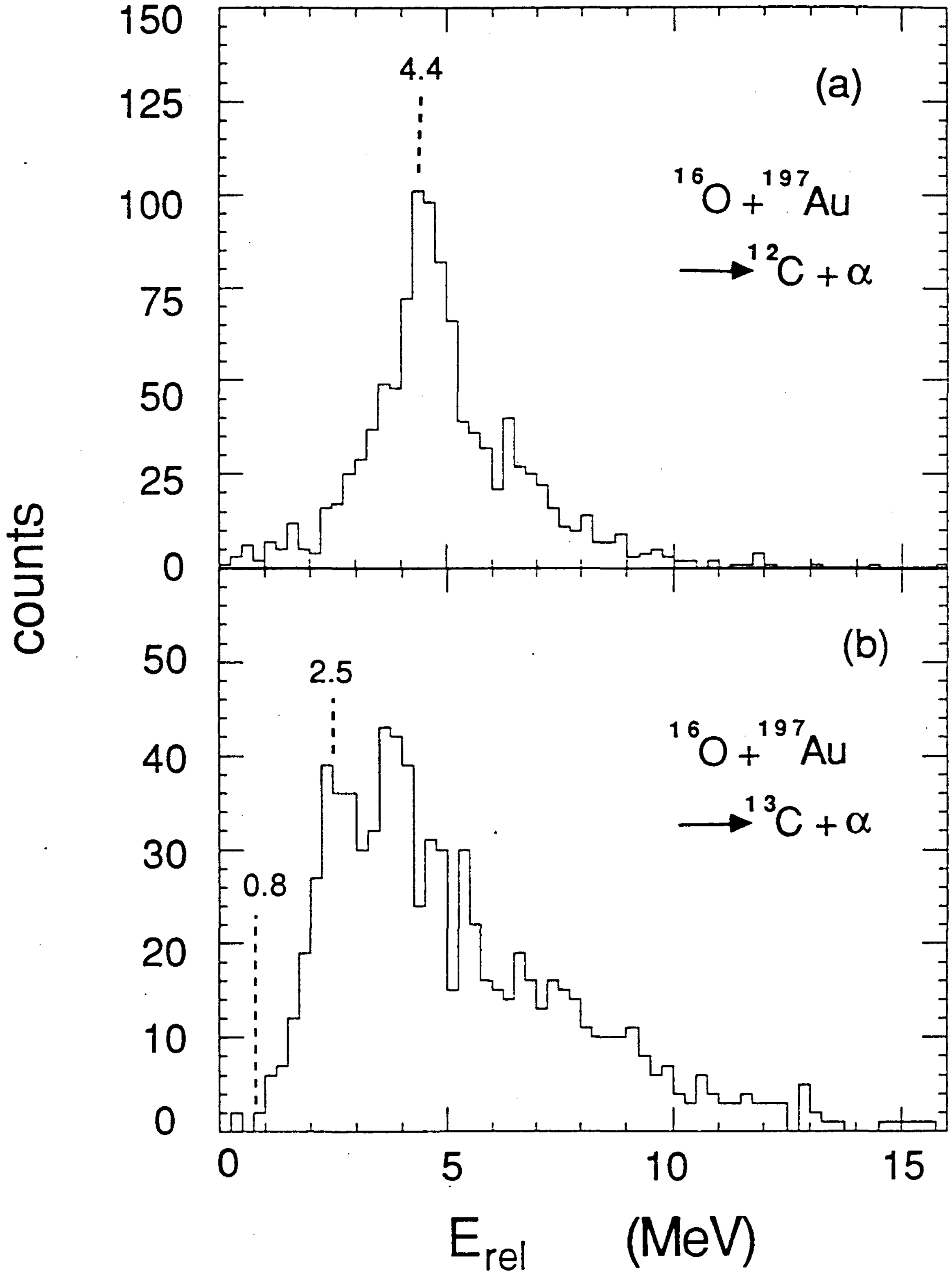
2) Relative-energy spectra for (a) ^{12}C-α and (b) ^{13}C-α coincidence channels are shown for 424-MeV ^{16}O + ^{197}Au reactions. The data are gated on the quasi-elastic peaks indicated in Figs. 1(a),(b).

3) Energy-position correlations are shown for alpha particles emitted in a vertical plane containing the coincident heavy ion (detected at 9° in-plane). Data are shown at 424 MeV for (a) ^{12}C-α and (b) 13-α coincidences gated on a quasi-elastic peak in the associated Q_3 spectrum in Fig. 1, and (c) ^{12}C-α coincidences gated on the region of high inelasticity. (The correlations exhibit shadowing caused by the heavy-ion telescope.)



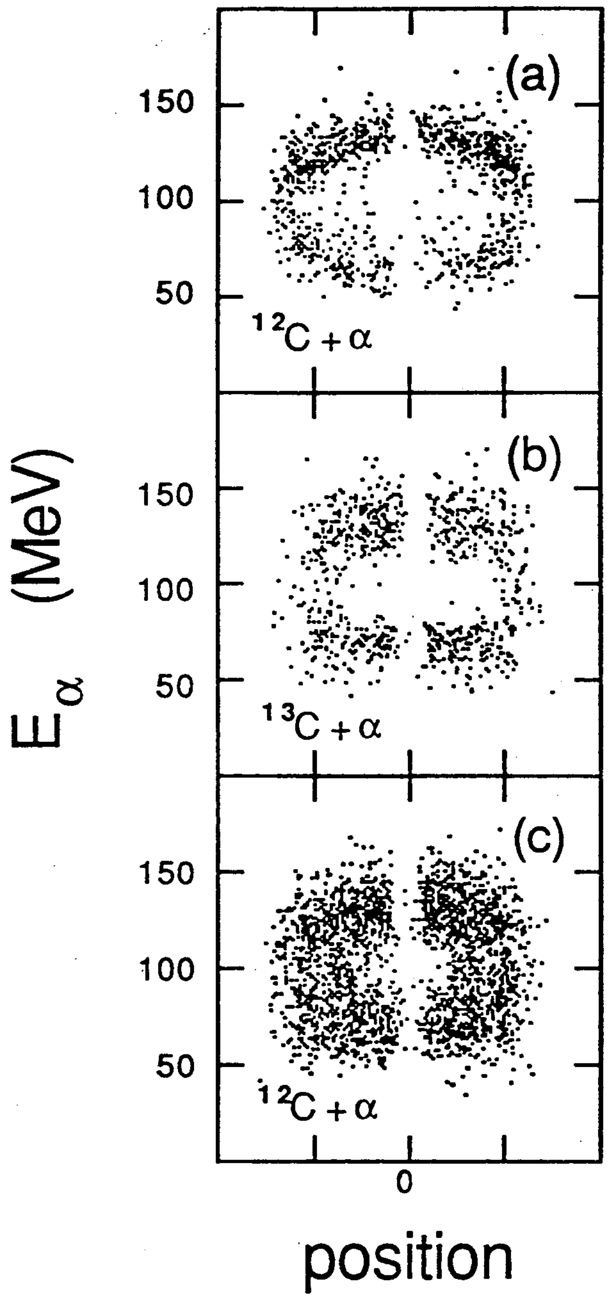
800
600
400
200
0
(a) $^{12}C + \alpha$
424 MeV
Q_{ggg}
600
400
200
0
(b) $^{13}C + \alpha$
424 MeV
Q_{ggg}
400
300
200
100
0
(c) $^{12}C + \alpha$
520 MeV
-100
-50
0
Counts
Q_3 (MeV)
XBL 882-396

Fig. 1



XBL 882-397

Fig. 2



XBL 882-398

Fig. 3

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