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MULTIPLE DISSOCIATION OF [SUP]16 0, [SUP]14 N, AND [SUP]12 C AT 32.5 MEvYNUCLEON

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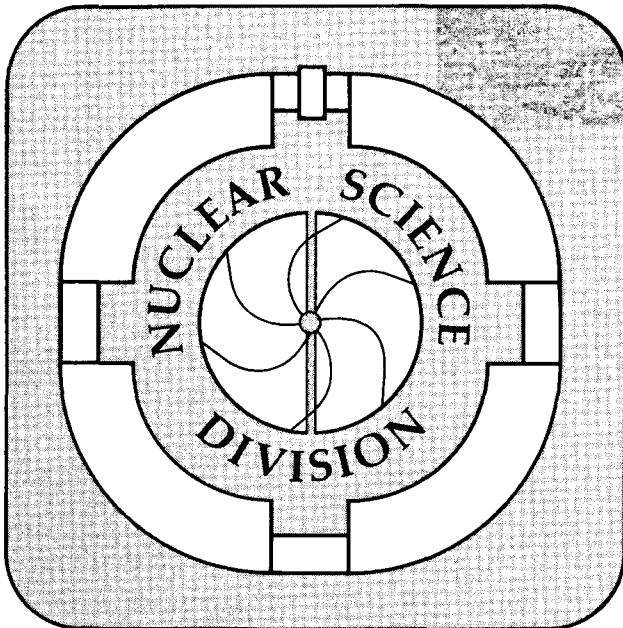
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Multiple Dissociation of ^{16}O, ^{14}N, and ^{12}C at 32.5 MeV/Nucleon

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September 1988

DISCLAIMER

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1. INTRODUCTION

The study of the breakup of a projectile into its component fragments has, with few exceptions, been based either on the inclusive detection of the fragments or on two-particle coincidence measurements (Stokstad, 1984). These types of experiments have revealed much about the breakup process at bombarding energies of 20 MeV/nucleon or less, partly because the two-body channels are quite strong, and partly because of high precision (Rae, 1981 and 1984; Bhowmik, 1982; Homeyer, 1982). It is clear, however, that at higher energies there will be an increasing probability for the projectile to break up into more than two components, i.e., for multiple dissociation, and that the study of this is best done with a detection system that can observe all or most of the breakup products. Such a study has been made by Engelage, et al., (1986) at relativistic energies. In general, exclusive measurements are necessary to:

i. determine the extent of multiple dissociation,
ii. determine the excitation energy of the primary fragment,
iii. address the question of prompt or sequential decay.

In this paper we describe experiments in which most of the projectile fragments were detected, and which provide information on the first and second items above. We are able to begin work on the third.

A word about terminology: at low bombarding energies one knows that the main mechanism of the breakup process occurs through excitation followed by sequential decay (Stokstad, 1987) There have been a number of theoretical studies indicating that a process called multifragmentation is expected to occur at intermediate to high bombarding energies (for example, Bondorf, 1985; Gross, 1988). Since the term "multifragmentation" has come to mean a prompt (as opposed to a sequential) decay, we have avoided the use of this term in referring to our experimental results for the breakup of a projectile into three or more fragments. Instead, we use the generic term "multiple dissociation", which does not imply a time scale for the decay.
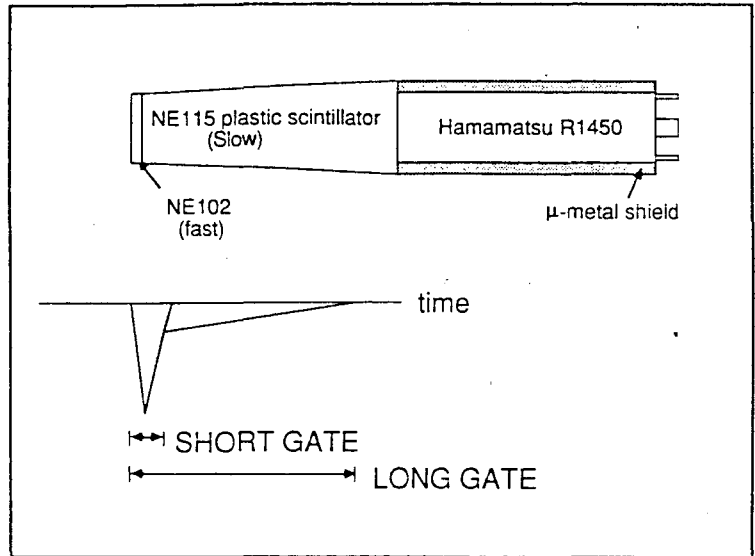
2. EXPERIMENT

2.1 Detector system

We have constructed an array of 34 fast/slow plastic phoswich scintillators. A single element of the array is shown in Fig. 1. The front edge of the detector is 17 mm long and subtends an angle of 5 deg. Each element is a truncated pyramid, which permits close packing, and consists of a 1mm thick fast scintillator (2 ns decay time) followed by 102 mm of a slow plastic (225 ns). Particles are identified by recording separately the light from a short time gate and a long time gate, as indicated. The response for heavy ions is illustrated in Fig. 2. Protons and deuterons, and elements up to the projectile, are resolved. There is also a group of particles that stands apart from the locus of Z=4. This corresponds to two alpha particles having entered the detector simultaneously. The geometry of the array for a 7x7 configuration is illustrated in Fig. 3. A 5x7 (horizontal x vertical) configuration was used in the present experiment with three vertical strips of position sensitive plastic scintillator (Schmidt 1985) on each side of the array. A complete description of the array is given by Pouliot et al. (1988).

Beams of fully-stripped ^{16}O, ^{14}N, and ^{12}C were produced in the LBL Electron Cyclotron Resonance ion source and accelerated by the 88-Inch Cyclotron to energies of 32.5 MeV/nucleon. Beam intensities were limited to a few tenths of an electrical nanoampere because of the intense scattering seen by the detectors closest (2.5 deg.) to the beam. The response of the detectors to different ions and the energy calibration were determined in a separate experiment using a variety of beams from hydrogen through oxygen. All coincidences between three or more particles were recorded. Those coincidences involving only two particles were scaled down by a factor of 128. Random coincidences for the channels presented here were negligible.

Fig.1 Schematic diagram of a single phoswich detector. The face of each detector is located 19 cm from the target. By digitizing the charge collected in the short gate and in the long gate, the atomic number of the detected particle can be determined.

NE115 plastic scintillator (Slow)

Hamamatsu R1450

NE102 (fast)

μ-metal shield

time

SHORT GATE

LONG GATE

XBL 8711-4684

Fig. 2 Sample spectrum obtained at an average laboratory angle of 5 deg.

$Z=$ 1 2 3 4 5 6 7 8

Long Gate

$^{16}O + {}^{12}C$ at 32.5 MeV/A

Short Gate
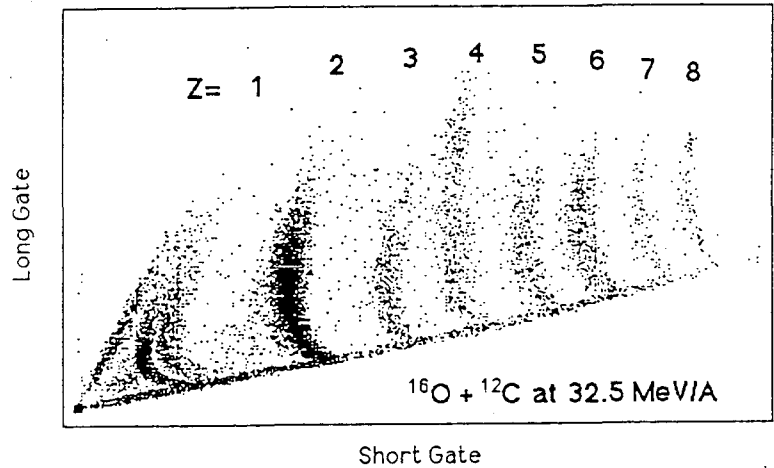
Fig. 3 A perspective schematic diagram of the array with the detectors in a 7x7 configuration.

Phototube

Fast/slow plastic phoswich

Beam
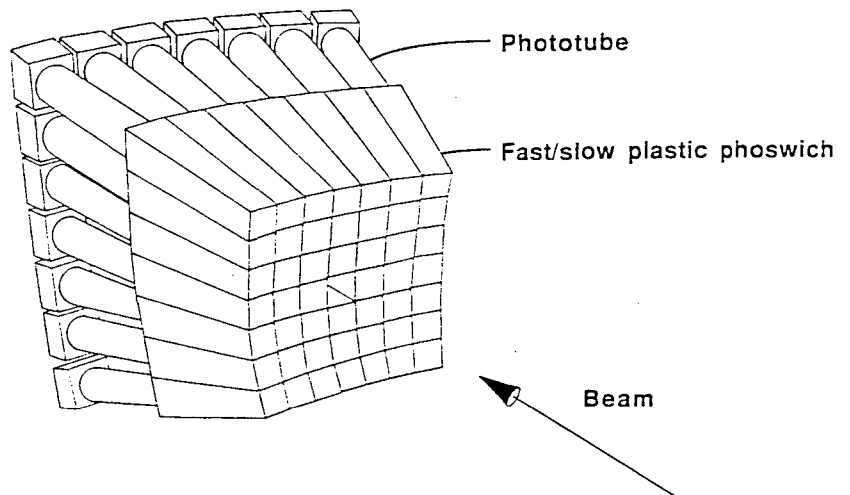
XBL 8711-4685

2.2 Identification of projectile breakup

Projectile breakup events were selected by requiring that the sum of the identified charges be equal to the charge of the projectile. The thresholds for particle identification implied by the 1 mm thick fast plastic varied from 9 MeV for protons to 19 MeV/nucleon for ^{16}O, and effectively eliminated the detection of charged particles evaporated by an excited target-like nucleus. The projectile fragments, having velocities near that of the beam, were well above this threshold.

The peripheral nature of the reaction can be tested by comparing the relative yields of the fragments obtained for different targets, since they should be independent of the target. Experiments were done on targets of ^{197}Au, ^{12}C and ^{9}Be in order to examine this. Fig. 4 shows the yields, ordered by intensity for the different channels observed when a ^{16}O beam interacts with the different targets. One sees that the yields are nearly independent of the target except for the weakest channels, which are populated more strongly in the reactions on the light targets. Since these weaker (and higher multiplicity) channels may, in the case of the light targets, be produced by more violent interactions with the target, we repeated the comparison, requiring that the detected particles have a total of at least 80% of the beam energy. This produces a closer agreement in the relative yields, although the yields of the weaker channels are preferentially attenuated by this cut on the total energy.

2.3 Detector efficiency

The close packing of the detectors in the array produces a high detection efficiency for particles incident on the array. However, even for forward-peaked projectile breakup reactions, it is possible for one of the fragments to miss the array. The spatial distribution of alpha particles in coincidence with a carbon nucleus detected at (an average of) 5 deg. is shown in Fig. 5. (Alpha particles detected in the plastic strips also were used to construct this plot.) The boundaries of the array alone are indicated, and one may see how some of the alpha particles are lost. The efficiency in this particular case is about 80%. Preliminary Monte-Carlo studies using the computer code LILITA (Gomez del Campo, 1979) suggest that channels involving protons are detected with a lower efficiency than channels involving only alpha particles or heavier ions. This is most likely associated with the protons being emitted to larger angles because of their lighter mass. Very few of the projectile fragments are lost because of insufficient energy to penetrate the 1mm of fast plastic at the front of the detectors. Since the yields of the different channels vary by several orders of magnitude it appears possible to obtain an overall view of the results before the corrections for the relative efficiency have been finalized and applied.

Channels
1 C·He
2 N·H
3 Be·He·He
4 He·He·He·He
5 B·He·H
6 C·H·H
7 Li·He·He·H
8 B·Li
9 He·He·He·H·H
10 Be·He·H·H
11 Li·Li·He
12 Be·Be
13 Be·Li·H
14 B·H·H·H
15 Li·Li·H·H
16 Li·He·H·H·H
17 Be·H·H·H·H

X – ^{16}O + Au
O – ^{16}O + ^{12}C
□ – ^{16}O + ^{9}Be
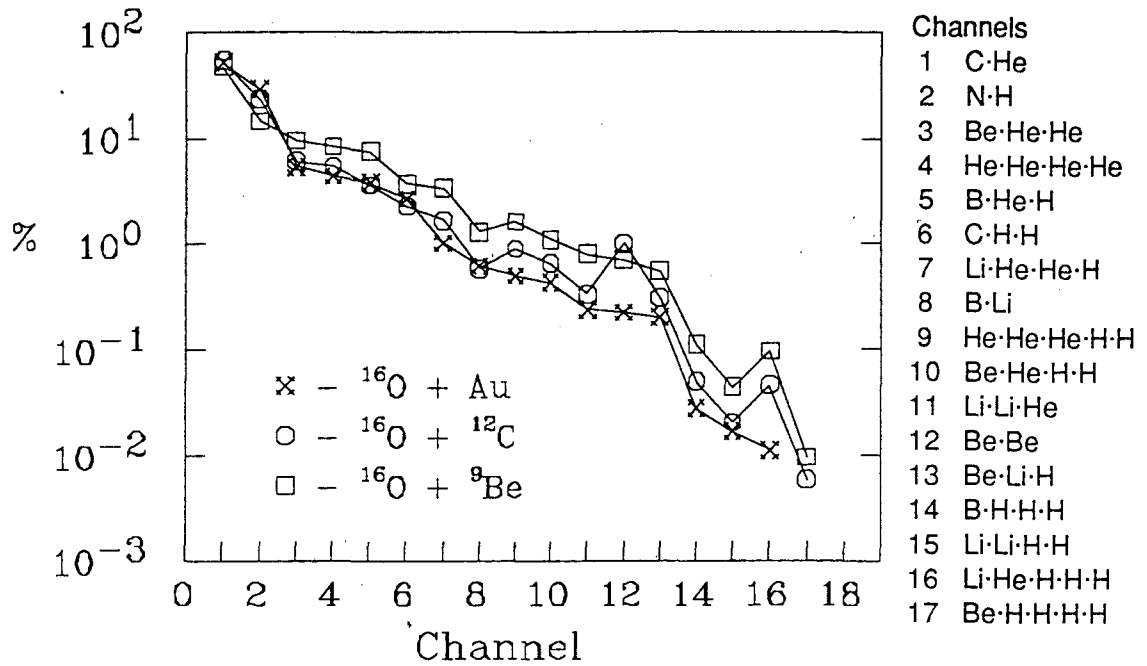
Fig. 4   The yields of different channels obtained for ^{16}O bombarding targets of ^{9}Be, ^{12}C, and ^{197}Au. The only "cut" on the data is that the sum of the charges of the identified particles total to that of the beam. Requiring that the total energy be greater than 80% of the beam energy improves the agreement for the weaker channels.

^{16}O + ^{12}C

≥N
1000
750
500
250
1

Σ = 58890

Beam ^{12}C

Θ Out plane

Θ In plane

Fig. 5   The spatial correlation of alpha particles in coincidence with carbon ions observed in a detector closest to the beam. The granularity is indicated by the indicated sizes of the hole for the beam and the detector that caught the carbon ion.

3. RESULTS

3.1 Channel yields

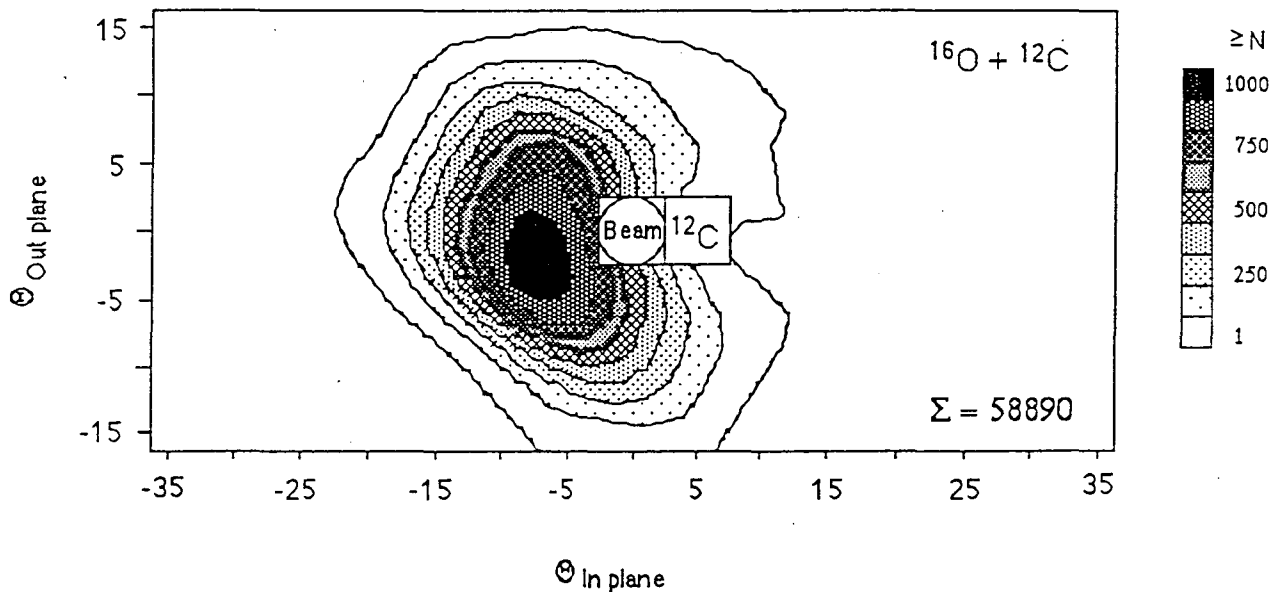The uncorrected yields of the different channels for each of the three beams on a ^{197}Au target are plotted in Fig. 6 as a function of the separation energy for that channel. No cut has been made on the total energy. The channels are distinguished only by the combination of atomic numbers. For example, the channel B+He+H contains the isotopic contributions of ^{12}B+^{3}He+p, ^{11}B+^{4}He+p and ^{10}B+^{4}He+d, and is plotted at the most positive of the three Q-values, viz., -23.1 MeV. The detection of ^{8}Be poses an additional complication in that there is a 60% probability that a ^{8}Be(g.s.) nucleus will result in the detection of two ^{4}He nuclei in the same detector element. These events (see Fig. 2) are identified as Z=4 and are summed with ^{7,9}Be. Therefore, all combinations involving two He nuclei and a single Be nucleus (such as He+He+He+He, He+He+Be, and Be+Be) are summed and plotted versus the most positive Q-value. These data points are indicated by an arrow in Fig. 6. The channels and their Q-values for each of the three beams are given in table in the figure.

The yields of the different channels are seen to correlate, to within factors of about 2, with the exponential of the Q-value for yields varying in intensity over a range of 3 to 4 orders of magnitude. (The yields do not seem to correlate strongly with particle multiplicity, except in so far as channels with more particles tend to have more negative Q-values.) Thus, the yields can be used to determine an approximate slope parameter, T, which has values of 6.2, 5.0, and 6.0 MeV ($\pm$0.3) for ^{16}O, ^{14}N, and ^{12}C, respectively. This approximate exponential relationship is the justification for plotting the yield of a given channel versus the most positive Q-value.

3.2 Relative kinetic energies and excitation spectra

The knowledge of the positions and energies of each of the detected particles in a given event enables the calculation of the center-of-mass velocity of the primary nucleus and the individual and total relative kinetic energies of the fragments in this coordinate system. In this calculation, the mass of the detected element is taken as that of the most abundant isotope (except for protons and deuterons, which are identified). The exact position of a particle recorded in a particular detector was chosen at random over the face of the detector. Fig. 7 shows some of these relative kinetic energy spectra. The excitation spectrum of the primary fragment is then constructed by summing the relative kinetic energy spectra for the individual channels, each off-set by an appropriate Q-value. In this case, a correction is
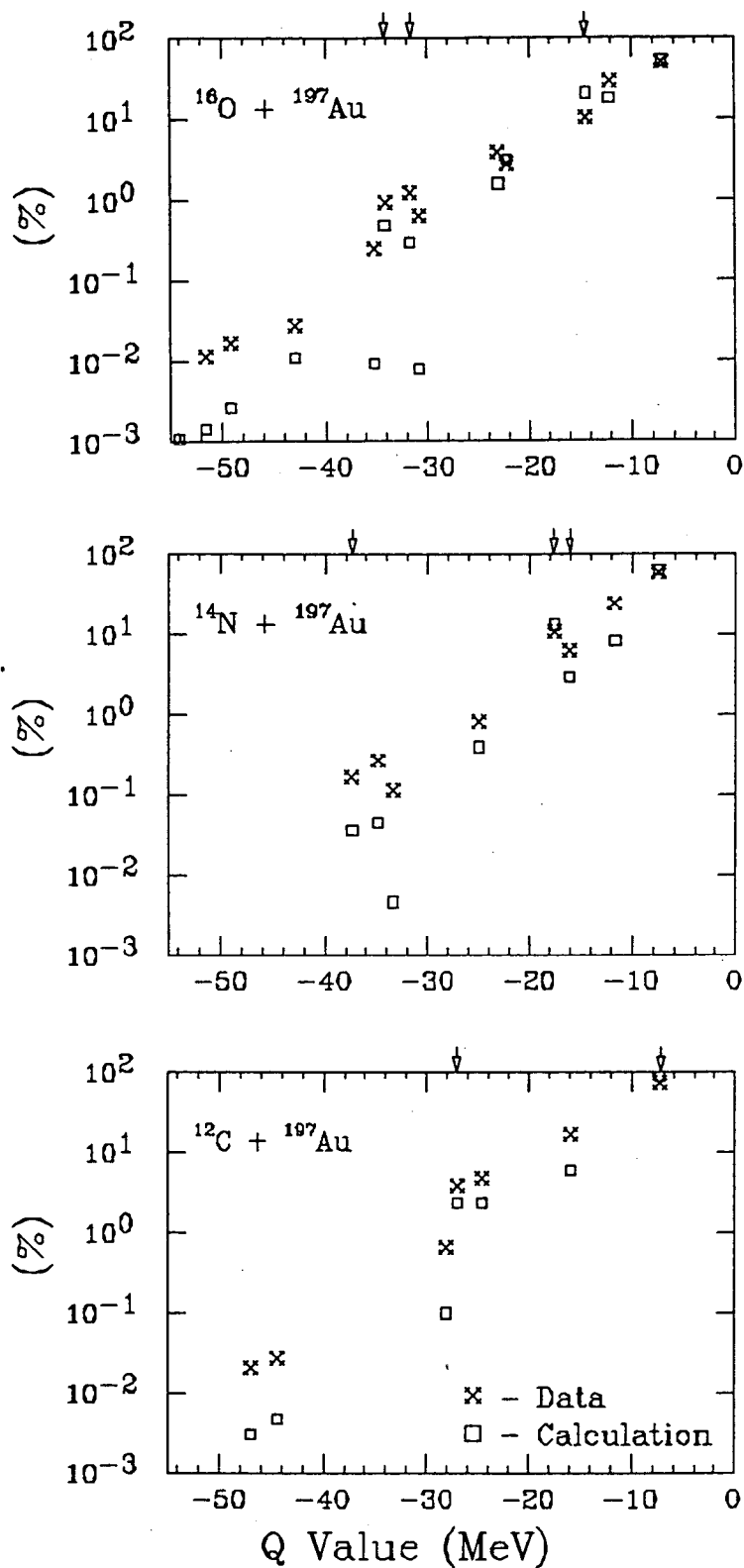
Fig. 6　The yields of the different channels, expressed as a percentage of the total, and plotted versus the most positive Q-value of all isotopic combinations consistent with the elements making up that channel. The channels containing a combination of two alpha particles or a Be nucleus have been summed and are indicated by an arrow. No correction has been made for the efficiency of the array. The predictions of the statistical decay code are shown.

made for the different isotopic composition of a given channel. This is done by estimating the yields of the individual isotopic combinations using the above slope parameter and a weighting $\approx \exp(Q/T)$. The relative number of events are then off-set by the more negative Q-value associated with that isotopic combination. Fig. 8 shows the primary excitation spectra that result from this procedure. They represent the excitation of a primary fragment having an atomic number equal to that of the beam, but of undetermined atomic mass. Note that the spectra in Fig. 8 also have an approximately exponential shape. These spectra are characterized by typically larger slope parameters than either the channel yields or the relative kinetic energy spectra, having values of about 10.5, 9, and 10.5 MeV at an excitation of 50 MeV for ^{16}O, ^{14}N, and ^{12}C. In each case there is a dip in the spectrum at 20, 22, and 25 MeV, respectively. In the case of ^{16}O, this dip is related to the missing channel $^{15}O+n$.

4. STATISTICAL DECAY

A standard interpretation of projectile breakup consists of factoring the reaction into two stages - first, a fast excitation process, and second, the decay. The decay may be slow and involve a series of sequential, binary decays. Or the decay may be prompt, implying that the dissociation into three or more fragments occurs more or less simultaneously. A complete theory of projectile breakup predicts both the first and the second stage of the reaction: an example is the abrasion-ablation model (Hufner, 1975). It is possible, however, to analyze only the second stage of the reaction if one takes as given the primary excitation spectrum determined by experiment. With this spectrum as input, we have calculated the yields of the different channels in two slightly different ways, each way employing a series of binary splits. The first method uses the Monte Carlo code LILITA (Gomez del Campo, 1979). The advantage of this code is that it has been developed and tested in the light mass region, includes angular momentum, and is particularly accurate in the later stages of decay where the region of discrete states becomes important. Finally, since it calculates the energies and angles of the fragments in the laboratory system, we will be able to use it to estimate the efficiency of the array for different channels.

The second way is to calculate the average probability of each energetically allowed binary split according to the density of states at the saddle point, and to use an average relative kinetic energy of twice the temperature. This calculation is similar to one described by Auger, et al., (1987) with the exception that it uses ground state masses throughout and neglects rotational energy. An added feature of the present code, called BRANDEX, is that, in any binary split, each of the two fragments may undergo further decay (Knop, 1988).

Fig. 7 Relative kinetic energy spectra for selected channels of the $^{16}O + ^{197}Au$ Reaction.

Fig. 8 The spectrum of excitation energy in the primary fragment, made up by adding the relative kinetic energy spectra of the different channels, off-set by the appropriate Q-value.
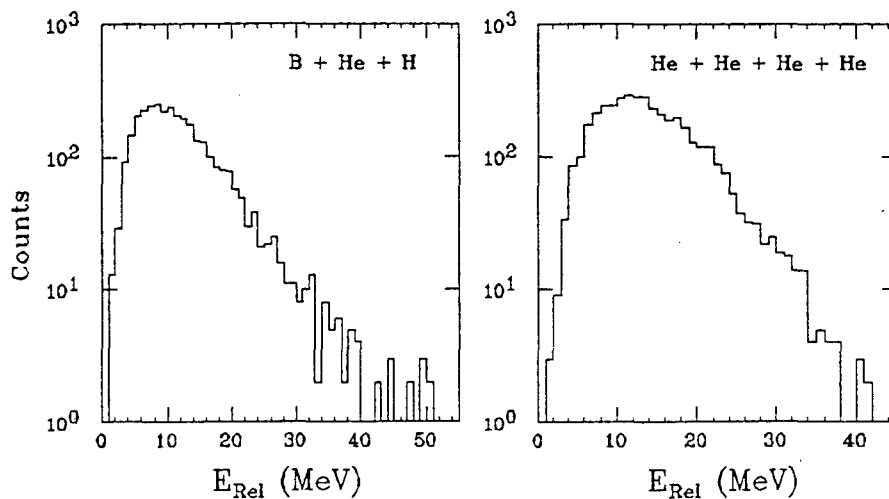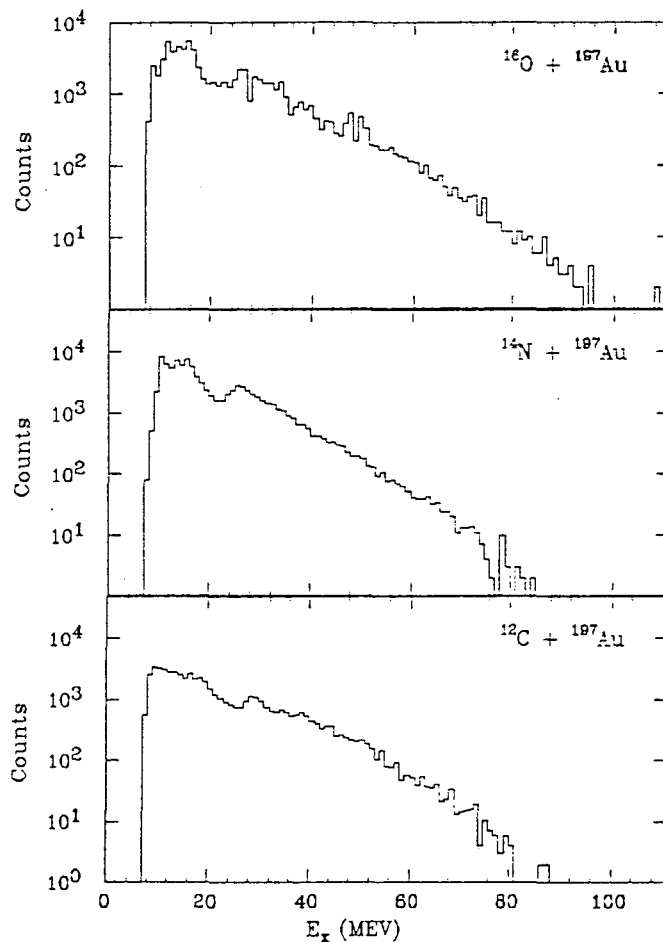
The results of this calculation are shown in Fig. 6 (black square). In each case the input was the corresponding primary excitation spectrum shown in Fig. 8. For the output, the individual isotopic channels with the same combination of atomic numbers were summed to correspond to the experimental channels. The calculation compares favorably with experiment for Q-values extending to about -30 MeV. The magnitudes of yields at more negative Q-values are poorly reproduced, with the calculation being low by factors of three to ten. However, the trend of the results in this region is reproduced.


5. PICKUP REACTIONS

One of the interesting recent results to come out of the two-particle coincidence measurements is that nucleon or cluster pickup occurs with substantial intensity even at intermediate energies (Rae, 1984; Siwek-Wilczynska, 1987; Gazes, 1988). Since the pickup of a nucleon by the projectile implies that this nucleon is carried along with the projectile for at least some time, the signature of charge pickup is that the sum of the charges of the projectile-like fragments exceeds that of the projectile. Thus, for a nitrogen beam, those events for which the sum of the charges is 8 comprise the reactions in which a proton (or deuteron) was captured by the projectile. We have observed the pickup of both hydrogen and helium. In the following, we give an example for hydrogen pickup.

The relative intensities of a selected set of decay channels for $\Sigma z=7$ and $\Sigma z=8$, populated by the nitrogen beam on a carbon target, are shown in Fig. 9. Note the close correlation of channels that *differ* by the addition of an extra unit of charge. It appears to us that this correlation arises from the pickup of a proton to form an excited ^{15}O nucleus, which then decays by the emission of a proton (the most energetically favored decay channel) to leave an excited ^{14}N that undergoes further decay. Thus, the relative probability for dissociation by inelastic scattering and by the pickup of a proton is the ratio of the sum of the counts in curves (a) and (b) in Fig. 9. An overall estimate of the relative strengths of inelastic scattering and single charge pickup is obtained by simply comparing (for the nitrogen beam) the ratio of total charge 8 to total charge 7. This ratio is approximately 0.03, 0.14, and 0.13 for a nitrogen beam and targets of ^{197}Au, ^{12}C, and ^{9}Be, respectively. In determining these ratios, we required that each event had to have at least 80% of the beam energy. This "cut" on the data helps eliminate non-peripheral reactions on the lighter targets.
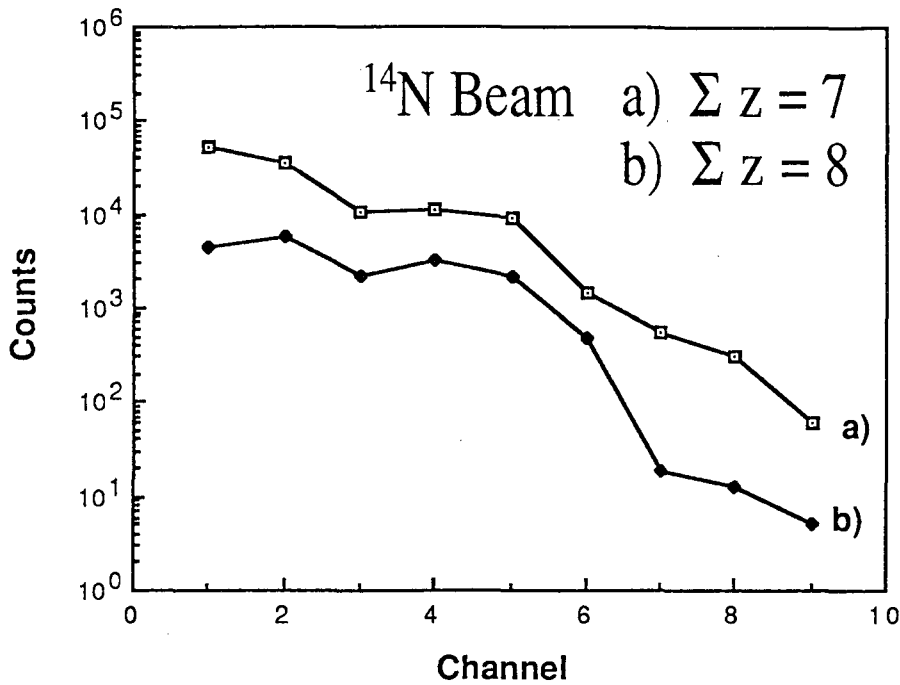
#	a	b
1	C·H	C·H·H
2	B·He	B·He·H
3	Li·He·He	Li·He·He·H
4	Be·He·H	Be·He·H·H
5	He·He·He·H	He·He·He·H·H
6	Be·Li	Be·Li·H
7	B·H·H	B·H·H·H
8	Li·He·H·H	Li·He·H·H·H
9	Li·Li·H	Li·Li·H·H

Fig. 9 Comparison of the relative intensities for (a) inelastic scattering and (b) the pickup of one H from a C target. The channels are listed in the adjacent table.
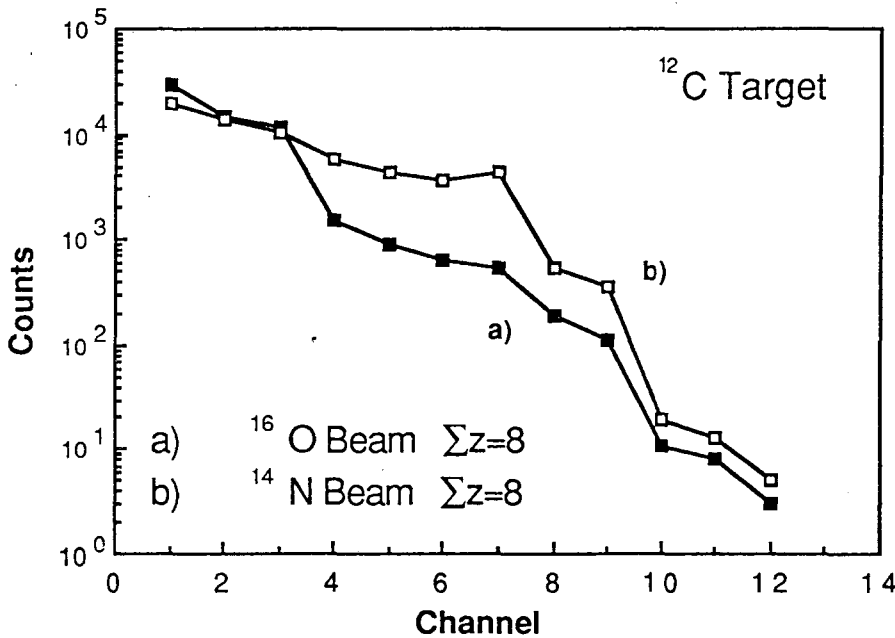
#	Channel
1	C·He
2	Be·He·He
3	N·H
4	B·He·H
5	C·H·H
6	Li·He·He·H
7	Be·He·H·H
8	B·Li
9	Li·Li·He
10	B·H·H·H
11	Li·He·H·H·H
12	Li·Li·H·H

Fig. 10 Decay channels populated (a) by ^{16}O, and (b) by ^{14}N with $\Sigma z=8$. The channels are the same for (a) and (b) and are given in the adjacent table.

It is also of interest to compare the relative intensities of the *same* decay channels populated by a) the ^{16}O beam and $\Sigma z=8$ and b) a ^{14}N beam with $\Sigma z=8$, as in Fig. 10. The shapes of these curves, arbitrarily normalized, show interesting similarities and a striking difference. Note that channels 1 and 2, and channels 8-12 have a similar shape in both curves. These are channels that one would expect to be populated through the decay of ^{16}O, and much less probably through the decay of ^{15}O (which would rather emit a proton in the first step). This suggests that these channels for curve (b) are produced when the ^{14}N projectile picks up a deuteron to form an excited ^{16}O. The discontinuity in the shapes of curves (a) and (b) occurring from channel 3 to 4 can be explained by the presence of the two different sources of oxygen (^{15}O and ^{16}O) of comparable intensity in the case of pickup by the ^{14}N beam and only one main source of oxygen in the case of the ^{16}O beam. We have not attributed the third channel (N+H) to one or the other source because it can be populated in two ways: it is the second most populous decay channel for ^{16}O and should be the strongest for ^{15}O. Experiments with an ^{15}N beam are planned to study the pickup reactions further and to check the interpretation suggested here.

6. DISCUSSION

A main result of the present experiments is the determination of the relative cross section for producing the primary fragment as a function of excitation energy. These results should prove particularly useful for comparison with theory because they do not depend on the observation of a particular exit channel. Since most all of the possible exit channels have been detected and summed, the determination of the primary excitation spectrum is largely independent of the subsequent decay mechanism. It is clear that this cross section decreases exponentially with increasing excitation energy (although when the data are corrected for efficiency, the slope will be less steep.) Yet, we see that there is still an observable probability for depositing energies up to 5 MeV/nucleon in ^{16}O. In the following we place these excitation energies in context:

A number of the models for energy deposition in nuclear collisions incorporate nucleon exchange and nucleon-nucleon scattering as the means of generating excitation energy. In this context, the excitation energy of the projectile can be quite high; it extends up to about three times the relative kinetic energy of a target nucleon at the point of contact. (It will also be of interest to examine the primary excitation spectra for the pickup reactions.) If the excitation energy of the projectile is converted to temperature, as is appropriate when making an equilibrium model for the subsequent decay, we have an ensemble of excited nuclei varying in temperature from about 2 MeV to 6.5 MeV (for a=A/8.5). The latter is a

rather high temperature. To place the upper excitation energy of 5 MeV/nucleon in yet another context, the value of 3 MeV/nucleon has been suggested as a threshold above which multifragmentation should occur (Campi, 1984).

A consequence of the exponential decrease of the primary cross section with excitation energy is that a breakup channel requiring a significant conversion of excitation energy into the masses of its fragments will have, in general, a correspondingly smaller cross section. This result depends only on conservation of energy and not on the mechanism for decay. In particular, it does not depend on exit channel multiplicity. Thus, the strongest channel, in all three cases studied here, is the channel with the most positive Q-value, whether or not it corresponds to the emission of a proton or an alpha particle (or three alpha particles). To show that multiplicity *per se* is not a factor, consider ^{16}O, in which case the exit channels involving four alpha particles are more intense than the particular two-body channel, B+Li.

A comment on "temperature": Often when there is a spectrum in which the yield of some quantity varies exponentially with energy, be that kinetic energy, or Q-value, or excitation energy, there has been an attempt to identify the slope of that spectrum with the temperature of some appropriately defined system, or sub-system, in equilibrium. In the case of the Q-value dependence of projectile breakup, this was done some time ago by Lukyanov and Titov (1975). More recently, the slopes of light particle spectra, and relative yields for different excited states have been interpreted in this way. It is clear that the "temperatures" that could be deduced from the slopes found in the different parts of the present analysis (e.g., from Q-value dependence, and dependence on E_{rel} and E_x) would vary considerably. This does not seem to us to be the appropriate way to interpret the meaning of these slopes. Within the context of interpreting the data in a two step mechanism -- a fast excitation followed by equilibration before decay -- it appears to us that the appropriate temperature is the one which is defined by, and varies with, the excitation energy of the primary projectile as given by the sum of the separation energy and relative kinetic energy (Fig. 8). For a nucleus having the level density of a Fermi gas, that temperature is given approximately by $T= (E_x/a)^{1/2}$.

The persistent (and most difficult) question in the study of projectile (or target) breakup concerns the time scale of the decay process - prompt or sequential? Precise two-body coincidence experiments performed at bombarding energies up to typically 15 MeV per nucleon have shown that the two-body (+target) channels proceed through excitation of discrete (though unbound) states in the projectile that have lifetimes long compared to the reaction time (Rae, 1981 and 1984; Bhowmik, 1982; Homeyer, 1982; Siwek-Wilczynska, 1987). Sequential decay is thus known to be important in certain cases,

including a case involving neutron pickup by the projectile, and subsequent decay of it into three particles (Gazes, 1988; Chavez, 1988).

The present experiment covers a wide variety of channels, extending up to multiplicity 5. How will one determine whether those decays are prompt or sequential? One way, of course, is to calculate the branching ratios for decay based on the phase space of sequential binary splits. Two such calculations have been done and yield similar results. The results of one of these calculations are shown in Fig. 6. The underprediction of the yields of the very negative Q-value channels is interesting, but it would be premature at this point to claim this as evidence for non-sequential decay. Further work on these calculations is in progress. It is interesting to note that Harvey, et al., (1988) have made a statistical analysis, also similar in nature to that of Auger (1987), for coincidence experiments on the breakup of 12C+12C at 2.1 GeV/nucleon. They concluded that statistical decay of primary excited fragments is very probably responsible for the production of the bound nuclei observed in that experiment.

It will also be important to make a comparison with the results of branching ratio calculations based on a prompt decay. Examples of this type of calculation are given by Gradsztajn, et al. (1965) and by Gokmen, et al., (1984) and use the phase space for prompt decay derived by Fermi (1950). Of course, it will be of interest to compare with current theories of multifragmentation provided that appropriate calculations can by made for the light systems under consideration here (Boal and Glosli, 1988).

The directional correlations of the particles can shed light on the time dependence of the decay. First, these correlations can be used to determine the probability that two alpha particles came from the decay of a ^{8}Be(g.s.) nucleus. This reflects on the sequential nature of the decay. Second, the velocity distributions of the particles (in an appropriate rest frame) can indicate whether there is a Coulomb repulsion correlation characteristic of sequential decay or of a prompt "explosion". Analysis of the data along these lines is in progress (Lopez, 1988).

Finally, we note that the experimental data presented here have certain limitations, even though they represent a significant step beyond our previous measurements. The most obvious limitation is that of mass resolution for the heavier ions. Another limitation is the insensitivity to neutrons. (These limitations, however, are not easily remedied without giving up some desirable feature of the present detector system, such as close packing, or the ability to stop high energy protons.) Some of these difficulties can be ameliorated in the analysis. For example, we are able to calculate the effects of neutron pickup and the

subsequent decay of $^{17}O^*$ on the distribution of fragments we observe for an ^{16}O projectile. The limitation imposed by the size and granularity of the array can be estimated and corrected for by the use of Monte Carlo calculations, and this work is in progress. Of course, the size of the array can be expanded.

7. SUMMARY

An array of 34 fast/slow plastic scintillators has been used to identify fragments from the breakup of ^{16}O, ^{14}N, and ^{12}C projectiles at 32.5 MeV/nucleon, scattered by a Au target. The dissociation of ^{16}O into as many as five charged particles has been observed. The yields of the different channels correlate approximately with the threshold energy for separation of the projectile into the observed fragments. The excitation spectrum of the primary projectile fragment was deduced from the measured positions and kinetic energies of the individual fragments. These spectra show that, although most of the decomposition proceeds through excitation energies within ~20 MeV of the lower particle-decay thresholds, excitation energies extending up to ~ 80 MeV can be produced in the primary stage of the reaction. This represents a significant acquisition of energy by the projectile. Calculations of the yields based on a sequence of binary decays have been presented. Reactions in which one or two units of charge are acquired by the projectile were also observed.

FOOTNOTES

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