Physics Letters B 299 (1993) 11–15
North-Holland

PHYSICS LETTERS B

^{16}O breakup on Al, Ni and Au targets at 94 MeV/nucleon ☆

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Received 8 June 1992; revised manuscript received 10 November 1992

The He–He–He–He disassembly channel of the ^{16}O on ^{27}Al, ^{58}Ni and ^{197}Au targets has been studied at 94 MeV/nucleon. Charged particles have been detected by a multielement array of plastic scintillators covering the zenithal angular domain between 3° and 30° and the total azimuthal one. Standard relativistic kinematics has been used to reconstruct the excitation energy of the primary projectile-like nucleus. Mean values of the excitation energy are found independent of the target mass. The comparison with data taken at lower bombarding energies is compatible with a saturation of the mean excitation energy.

One important open question regarding the study of the nucleus–nucleus collisions at intermediate energies concerns the space–time evolution of the reaction [1–4]. This subject has been explored in the last few years through the analysis of single-particle observables (such as energy spectra [3] and angular distributions [3,4]) and of particle–particle angular correlations at small [1,2] and large [3,4] relative momenta. Many efforts have also been made [5–7] to characterize the event shape in momentum space by a global variable approach based on the geometrical properties of the kinetic flow tensor [6,7]. More recently some experiments have been performed to study the breakup of symmetric projectiles like ^{16}O [5,8–12] and ^{28}Si [12,13] at bombarding energies between 30 and 70 MeV/nucleon. At lower energy [5] the experimental results are well reproduced by a dynamical model based on a sequential binary fission emission [7]. The mean excitation energy of the primary projectile-like nucleus (PLN) extracted from the data is about 30 MeV [11]. With the increase of the bombarding energy the value of this quantity slowly increases from 30 to about 50 MeV while most of the available energy is taken by the target-like nucleus [11] in agreement with suggestions made in ref. [13]. Authors of ref. [11] claim for a possible existence of a plateau for E^*_{PLN} which is reached above 3–4 MeV/nucleon independently of the particular decay channel.

In this letter we report on an experiment in which the He–He–He–He breakup of the ^{16}O projectile has been observed in reactions induced on different targets at 94 MeV/nucleon. The beam was pulsed with a repetition rate of 13.5 MHz. The FWHM of the beam pulse was 1 ns. The thickness of the used targets was 6.76 mg/cm^2 for ^{27}Al, 8.9 mg/cm^2 for ^{58}Ni, and 19.3 mg/cm^2 for ^{197}Au. Light charged particles ($1 \leqslant Z \leqslant 8$) have been detected by a large area multidetector [14], consisting of an array of 96 plastic scintillators, 2 mm thick, arranged in seven concentric rings located at the zenithal angles 4°, 6°, 8.5°, 12°, 16.5°, 21.5° and 27°. It covers the whole azimuthal dynamics with a total solid angle of 0.85 sr. The distance from the target was 210 cm. The particles have been identified by means of a standard ΔE-TOF technique but a very clean separation of the different charges was obtained only for particles crossing the scintillators, while those stopped in the detectors could not be easily identified [15]. Only charge identified particles have been taken into account. A

☆ Experiment performed at GANIL, Caen, France.

velocity threshold of about 5 cm/ns has been imposed due to the thickness of the detectors.

Typical velocity spectra of He ions detected with the ^{197}Au target are shown in fig. 1 for those events containing only four $Z=2$ particles. The phenomenology of this kind of reactions between heavy ions at intermediate energies generally shows the fragmentation of projectile and the formation of a participant zone [4]. So, two components are visible in the velocity spectra. The first one is centered close to the projectile velocity and essentially appears at forward angles. The second one is centered around half of the beam velocity and is attributed to a more relaxed source [4]. The latter is present at all angles and becomes the main contribution when the zenithal angle is increased beyond 20°. This seems quite reasonable if one considers that grazing angles for the reactions induced by the ^{16}O at 94 MeV/nucleon on ^{27}Al, ^{58}Ni and ^{197}Au are 0.7°, 1.4° and 3° respectively. Some particles from target-like fragments could also be present in the spectra of fig. 1 but the relatively low excitation energy of these fragments [16,17] coupled with the experimental high value of the velocity threshold strongly reduces such a contribution.

In the present paper we have restricted the analysis to the events with only four particles with $Z=2$, all detected in the angular range between 3° and 16.5° with a velocity greater than 8 cm/ns. These severe conditions reasonably select those events resulting from the breakup of the primary projectile-like nucleus. In what follows we shall assume that the recorded events correspond predominantly to the four alpha-particle channel [5]. By means of standard relativistic kinematics [18], we have reconstructed the velocity of the center of mass of these fragments. The distribution of this quantity for each of the three targets is given in fig. 2. These PLN velocities are strongly peaked very close to the beam velocity and, moreover, no evidence of a dependence on the target mass is observed.

The excitation energy of the primary projectile-like nucleus can be calculated [10] as the sum over the relative kinetic energies K_{He} of all fragments detected in an event in the rest frame of the PLN, shifted by the Q-value of the He–He–He–He breakup channel:

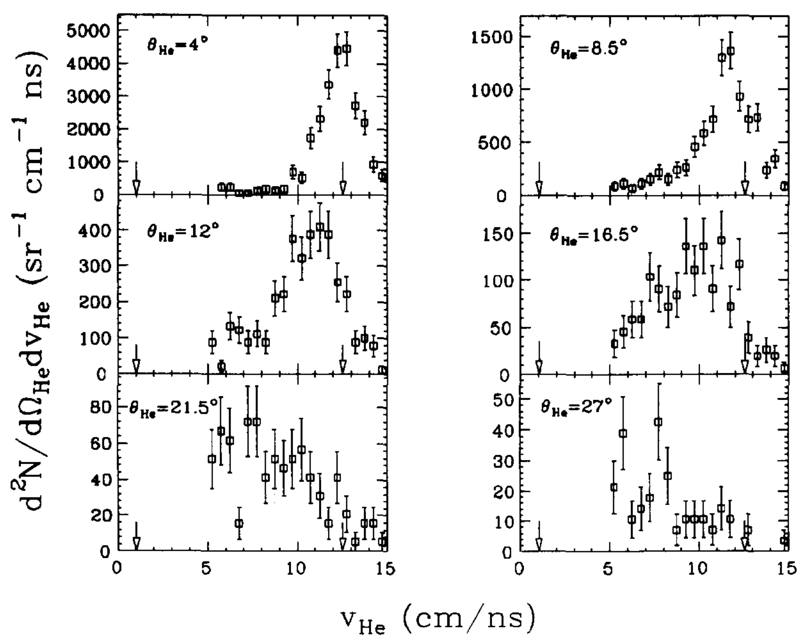

Fig. 1. Velocity distributions of the He ions detected in the ^{16}O+^{197}Au reaction at 94 MeV/nucleon. Only those events containing four $Z=2$ particles are taken into account for these spectra. In each plot right and left arrows indicate the projectile velocity and the compound nucleus velocity respectively.

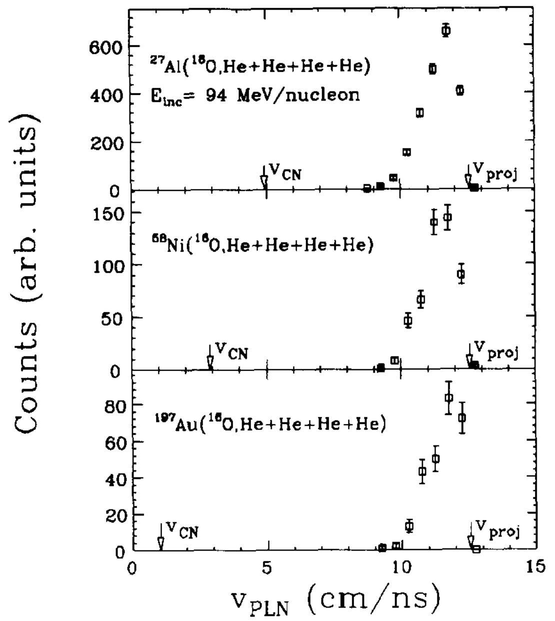

Fig. 2. Velocity distributions of the four He ions center of mass for the ^{27}Al, ^{58}Ni and ^{197}Au targets. In each histrogram the arrows indicate the projectile velocity (v_{proj}) and the compound nucleus velocity (v_{CN}).

$$E^*_{PLN} = \sum_{\nu=1}^{4} K_{He_\nu} + Q_{^{16}O \to 4He} . \quad (1)$$

Fig. 3 shows the PLN excitation energy distribution for the Au target compared to those obtained for the same target at lower bombarding energies. The data have been normalized so that each spectrum has the same total number of counts. Table 1 shows mean values of the extracted PLN excitation energies E^*_{PLN} and the values of the slope p of the excitation energy spectra as a function of the target mass and bombarding energy. The errors are the statistical ones. The same value is found for the three targets indicating that the breakup process, for the observed channel, has to be related mainly to the internal structure of the projectile. E^*_{PLN} values show a slight increase with the incident energy going from 30 MeV at 32.5 MeV/nucleon [11] to 53 MeV at 70 MeV/nucleon [11]. Our mean value of 54 ± 2 MeV at 94 MeV/nucleon is similar to that observed at 70 MeV/nucleon revealing some saturation of the excitation energy which can be stored in such a projectile. This value has been obtained imposing the above mentioned

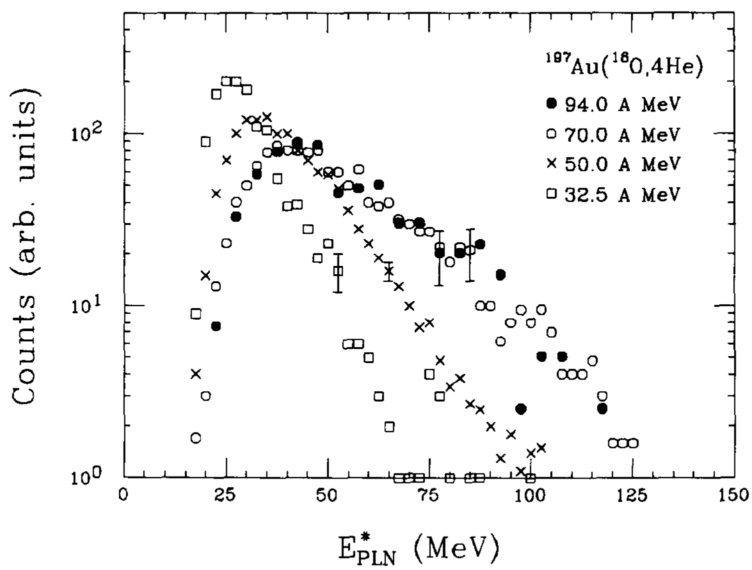

Fig. 3. Experimental excitation energy distributions of the primary projectile-like nuclues for the breakup process $^{16}O \to He+He+He+He$ in the reaction $^{16}O + ^{197}Au$ at different bombarding energies. The data have been normalized so that each spectrum has the same total number of counts.

Table 1
Mean values of the projectile-like nucleus excitation energy E^*_{PLN} (in MeV) as a function of the target mass and bombarding energy per nucleon. The data at 32.5, 50 and 70 MeV/nucleon comes from ref. [11]. The errors are the statistical ones.

Target	E_{beam} (MeV)	E^*_{PLN} (MeV)	p (MeV)	p_{corr} (MeV)
^{197}Au	32.5 *A*	30	8.0	10.9
^{197}Au	50.0 *A*	40	12.0	17.3
^{197}Au	70.0 *A*	53	18.0	22.7
^{197}Au	94.0 *A*	54±2	21.0±4.0	22.0±2.0
^{58}Ni	94.0 *A*	54±1	21.0±4.0	
^{27}Al	94.0 *A*	54±1	19.0±2.0	

conditions on the detection angle ($\theta \leqslant 16.5°$) and particle velocity ($v > 8$ cm/ns). Slightly varying these conditions we find a value of 53±2 MeV, taking into account all particles with $\theta \leqslant 12.5°$ and $v > 7$ cm/ns, and a value of 58±2 MeV, taking into account all particles with $\theta \leqslant 16.5°$ and $v > 7$ cm/ns, which are still compatible with the value extracted at 70 MeV/nucleon. The extreme value of 58±2 MeV found with the low velocity threshold is probably too high due to the fact that too many He ions from the more relaxed source [4] are included in the analysis. A Monte Carlo simulation of the breakup process via a binary sequential decay has been performed taking into account the experimental angular distribution of the primary fragment, its velocity distribution and the complete geometry of the experimental setup in order to evaluate the detection efficiency as a function of the PLN excitation energy. The efficiency correction, calculated only for the Au target, does not affect the mean value of E^*_{PLN} but only the excitation energy distribution's slope in agreement with the results of ref. [11] obtained with a very similar multidetector. The corrected value p_{corr} of the slope of the excitation energy distribution is also shown in table 1 and confirms the trend of the experimental data with the bombarding energy. The observed saturation value of about 3 MeV/nucleon is in agreement with the suggestions made for this [11] and other interacting systems [12,13]. Attempts to increase the available energy by raising the beam energy will probably result in more excitation energy in the target and/or in the primer of different disassembly channels not observed in our experiment. Thus, one goal in the understanding of the breakup mechanism is to determine whether the splitting of the highly excited projectile takes place instantaneously or following a sequence of binary, fission-like steps.

The experimental data have been submitted to an event-by-event analysis performed in order to extract the average values of the sphericity S and coplanarity C from which the mechanism of the PLN disassembly can be investigated [5–7]. Average values $\langle S \rangle$, $\langle C \rangle$, for the Au target at 94 MeV/nucleon are reported in table 2 and compared with those extracted at 32.5 MeV/nucleon [5]. The lower values at 32.5 MeV/nucleon have been taken in ref. [5] as an indication of a sequential decay process. The higher values of $\langle S \rangle$ and $\langle C \rangle$ found at 94 MeV/nucleon could be also attributed to a more prompt decay process such as multifragmentation. However, we are aware our analysis of data in terms of coplanarity and sphericity is relative to events with only four particles and this low multiplicity can introduce larger fluctuations in the coplanarity and sphericity mean values [19].

The velocity distribution of the alpha particles could be also affected by the long-range Coulomb field of the target. In refs. [20,21] it was shown how one can exploit this feature to learn about the time-scale of the break-up process. The method consists in the characterization of the distortions of the velocity tensor [21] – where the summation must be extended over all detected alpha particles – by means of the total coplanarity C_T. The reaction plane is not identified in our experiment and, consequently, the velocity tensor has the beam direction as a symmetry axis. Under these particular circumstances the coplanarity of the total distribution can also be written in term of the variances of the velocity in the beam direction, $\sigma_\parallel$, and in a transverse direction, $\sigma_\perp$, as follows:

Table 2
Mean values of the sphericity and coplanarity extracted by the ^{197}Au (^{16}O, He+He+He+He) events detected at 32.5 and 94 MeV/nucleon. The data at 32.5 MeV/nucleon comes from ref. [5]. The errors are the statistical ones.

E_{inc} (MeV/nucleon)	Sphericity	Coplanarity
32.5	0.191±0.004	0.101±0.002
94.0	0.378±0.011	0.160±0.006

$$C_T = \frac{\sqrt{3}}{4} \frac{1 - 2(\sigma_\parallel/\sigma_\perp)^2}{1 + (\sigma_\parallel/\sigma_\perp)^2} \,. \quad (2)$$

We have constructed a series of velocity distribution as a function of the lifetime τ and, for each of them, we have derived the corresponding value of C_T. All the points of the simulation fall in the shaded area of fig. 4. In contrast to refs. [20,21] we have here a region in the (C_T, τ) plane and not a line because a range of impact parameters has been included. The dashed lines in the figure represent the value of C_T, extracted from the experiment. The results of this analysis are thus consistent with a lifetime for the disassembly process in the order of $\tau = 40$–80 fm/c.

In conclusion the He–He–He–He breakup channel has been observed in reactions induced by a ^{16}O beam at 94 MeV/nucleon on targets spanning the whole mass range of stable nuclei. An event by event analysis has allowed to extract the mean values of the projectile-like nucleus excitation energy. This quantity has been found independent of the target mass. The comparison of these mean values with those extracted at lower bombarding energy for the same He–He–He–He channel indicates a saturation of the mean energy transferred to the projectile in the collision. Characteristic decay times in the order of a few tens of fm/c are inferred from the data.

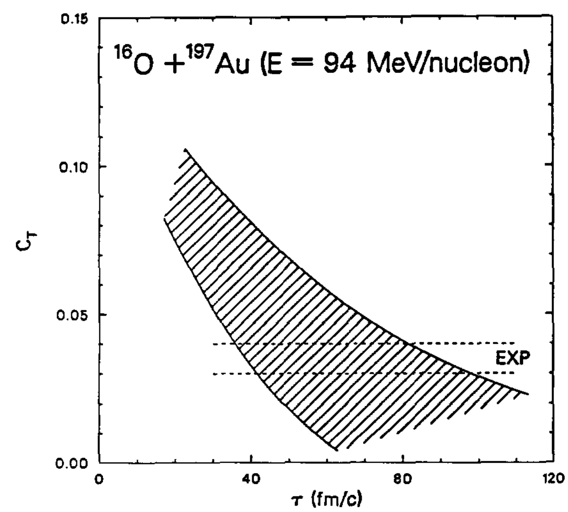

Fig. 4. Total coplanarity C_T versus lifetime τ for the projectile breakup $^{16}O \to He + He + He + He$ in the reaction $^{16}O + ^{197}Au$ at 94 MeV/nucleon. The shaded area corresponds to the simulated events, while the dashed lines mark the experimentally extracted value.

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