Binary projectile fragmentation of ^{12}C at an incident energy of 33.3 MeV/nucleon

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Abstract
Direct binary projectile fragmentation is being investigated for the case where a 400 MeV ^{12}C projectile breaks up into an α particle and a ^{8}Be fragment in the interaction with a thin ^{93}Nb and ^{197}Au target. While the ^{8}Be fragments were measured at 9°, the correlated α particles were detected in an angular range between 16° and 30° on the opposite side of the beam. From the preliminary results presented here one may obtain information on the amount of quasi-elastic fragmentation (both fragments do not suffer any further interactions after they are produced). These experimental results indicate that the quasi-elastic break-up process is the dominant contribution to the measured correlation spectra. As was also observed in earlier work, the most forward quasi-elastically emitted α particles have energies exceeding the beam velocity.

1 Introduction

At energies of a few tens of MeV/nucleon, both experimental and theoretical efforts are still underway to fully understand the reaction mechanisms involving heavy ion interactions of light ion projectiles with both heavy and light target nuclei. Several experiments were performed by this collaboration during the past few years in which the energy spectra of projectile-like and intermediate mass fragments produced in the interaction of ^{12}C and ^{16}O at incident energies of 100 MeV to 400 MeV with different nuclei were measured. These target nuclei ranged from ^{12}C to ^{197}Au. All these spectra were characterized by two main features which could be reproduced successfully with theoretical calculations by applying the following two unrelated mechanisms: *projectile fragmentation* (which was evaluated within the local plane wave approximation [1]) and *nucleon coalescence*, a statistical process (which was described by means of a set of Boltzmann Master equations [2]) occurring during the *N-N* interaction cascade by means of which the nuclei, produced in the partial or complete fusion of the projectile and the target, reach a state of thermal equilibrium.

In contrast to *pure* break-up, first introduced by Serber [3] to describe the break-up of the deuteron, binary fragmentation of heavier nuclei lead to fragments with a slightly lower average energy as well as a broader energy distribution than predicted by the Serber formalism (see e.g. Ref. [4]). This implies either an *initial state* interaction between the projectile and the target and/or a *final state* interaction of the observed fragment with the residual nucleus. Based on the satisfactory description of the ^{8}Be spectra studied in the break-up of ^{12}C, it was concluded [5] that the initial state interaction plays an important role in reproducing the break-up contribution of these spectra. This interpretation was further supported in subsequent studies of intermediate mass fragments (IMF) produced in the interaction of ^{16}O with ^{59}Co, ^{93}Nb and ^{197}Au [6]. However, in all these experiments inclusive spectra were measured, i.e. essentially summing up the contributions of all processes in which the observed fragment is produced.

The motivation for this study, whereby a coincidence experiment is employed to measure the energies of the two fragments following projectile break-up, is twofold. Firstly, to test and further improve the theoretical framework in order to disentangle the direct binary fragmentation process from the competing sequential break-up mechanism as observed e.g. in similar studies [7,8]. Secondly, to ascertain the amount of *quasi-elastic* fragmentation (in which case both fragments do not suffer any further interactions after they are produced).

In this paper we present first experimental data of an experiment, carried out at iThemba LABS, South Africa, in which the correlation between α particles and ^{8}Be fragments were measured following the interaction of ^{12}C with ^{93}Nb and ^{197}Au targets at an incident energy of 400 MeV. The experimental set-up and technique is described in Section 2. As the data analysis is ongoing a selection of preliminary results of the experimental data, representing quasi-elastic break-up, is presented in Section 3. Hence only a qualitative discussion of these results is given in Section 4.

2 Experiment

The experiment made use of a 400 MeV ^{12}C beam supplied by the cyclotron facility of iThemba LABS, Somerset West, South Africa. The beam was focused on the target to a spot of less than 3 mm in diameter, mounted at the centre of a 1.5 m diameter scattering chamber. Beam intensities were kept at levels such that the electronic dead time never exceeded 2%. Targets of ^{12}C, ^{93}Nb and ^{197}Au with a thickness of 1.05 mg/cm^2, 1.05 mg/cm^2 and 0.9 mg/cm^2, respectively, were used. The self-supporting target foils were mounted on aluminium frames with 20 mm diameter apertures. The target frames were mounted onto an aluminium ladder, which fits into a target driving mechanism at the centre of the scattering chamber. The target thicknesses were confirmed to an accuracy of 5% by means of the energy loss of α-particles emitted from a ^{228}Th source.

Two detector telescopes, referred to as telescopes 1 and 2, respectively, were mounted inside the scattering chamber on rotatable arms on opposite sides of the beam direction in the same reaction plane. The α particles were measured with a standard ΔE-E detector telescope, labeled 1, which consisted of two silicon surface-barrier (ΔE) detectors of thickness 20 μm and 500 μm, respectively and a NaI (E) stopping detector. This detector configuration allowed for a low α-energy threshold of about 6 MeV. A 50 mm thick brass collimator equipped with a brass insert with an aperture of 14 mm in diameter defined the solid angle of 2.0 msr subtended by telescope 1. A resonant particle spectrometer, referred to as telescope 2, made up of a silicon strip detector (SSD), used as ΔE detector, in conjunction with a NaI (E) stopping detector was employed to detect and measure the energy spectra of the unbound ^{8}Be fragments in their ground state. Since the ^{8}Be nucleus consists of two correlated α particles, a 50 mm x 50 mm SSD with 16 strips was used to measure the two α particles in coincidence. The thickness of the SSD was 250 μm which resulted in a low energy threshold of about 50 MeV. By using a Monte Carlo simulation, the effective solid angle of telescope 2 was calculated varying between 1 msr and 4.2 msr in the energy range of the ^{8}Be fragments detected in their ground state. Further details on the application of the SSD can be found in [9]. The stopping E detectors each were a NaI(Tl) crystal of 3 inches in diameter and 5 inches in thickness. It has a HAVAR entrance window of 2.5 inches in diameter and 7 μm thickness.

Energy calibrations of the Si surface-barrier detectors were performed with characteristic α-particles emitted from a ^{228}Th source, while the calibration parameters of the NaI detector were taken from a previous experiment as described in Ref. [9]. Energy loss calculations of α particles traversing the SSD were used to calibrate the SSD by overlaying the calculated energies onto the experimental α-particle locus. The energy uncertainty in each detector telescope did not exceed 2 MeV.

Standard electronics were used to perform the particle identification, making use of the ΔE-E technique. ^{4}He events could be well separated from ^{3}He events while a technique described in [9] made it possible to distinguish between ^{8}Be events in the 0^{+} and 2^{+} states and to select the dominant ^{8}Be events in the 0+ ground state. Apart from recording data for ^{8}Be-alpha coincidence events, the electronics were also set up to process pre-scaled singles events in each of the two detector telescopes. The pre-scaling factor was chosen to accept 5% of all the events in each telescope. Energy spectra of pre-scaled singles events were extracted for both α particles and $^{8}Be_{gs}$ fragments. As a consistency check of the detector efficiencies, these spectra were compared to similar spectra measured in earlier studies. In Fig. 1 such a comparison is shown for the double differential cross sections of $^{8}Be_{gs}$ emitted at 9° in the interaction of 400 MeV ^{12}C with ^{197}Au.

Coincidence measurements were carried out with telescope 2 fixed at a laboratory angle of θ_{Be} = 9° while the angle of telescope 1 was positioned at an angle θ_α on the opposite side of the beam. A summary of the angle pairs at which the coincidence measurements were carried out, is provided in Table 1. The overall systematic uncertainty of the absolute cross sections is estimated to be less than 15%.

Table 1: Summary of angle pairs (θ_{Be} / θ_α) at which the coincidence measurements were carried out.

Target Nucleus	θ_{Be}	θ_α
^{93}Nb	+9°	-16°, -18°, -24°, -26°, -30°
^{197}Au	+9°	-16°, -18°, -20°, -24°, -26°

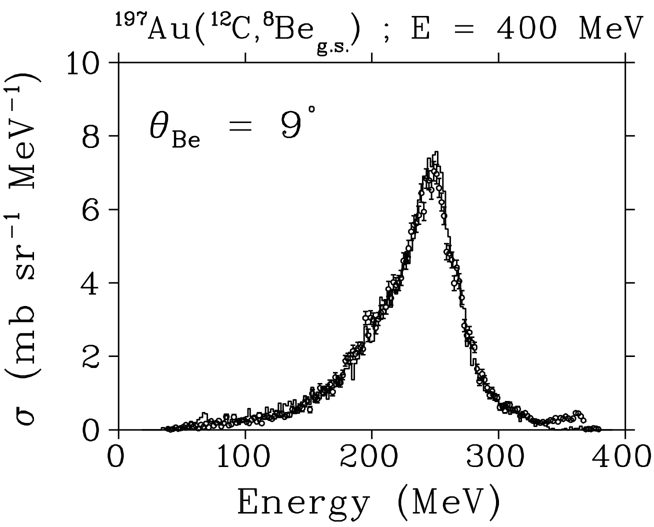

Fig.1: Double differential cross sections of $^{8}Be_{gs}$ emitted in the interaction of 400 MeV ^{12}C with ^{197}Au at a laboratory angle of 9°. The symbols are renormalized pre-scaled singles data obtained in the present experiment while the histogram represents data from Ref. [5].

3 Experimental Results

In this section, preliminary results are shown of the experimental data for the interaction of ^{12}C with ^{93}Nb and ^{197}Au, respectively, at an incident energy of 400 MeV. Since this experiment was specifically set up to investigate the binary breakup of ^{12}C into its constituent α particle and ^{8}Be partner, the first step of the data analysis was to obtain coincidence cross sections as a function of the sum of the kinetic energies of the α particles and $^{8}Be_{gs}$ fragments. A subset of these coincidence spectra are shown in Fig. 2 for the interaction of ^{12}C with ^{93}Nb and ^{197}Au, respectively, at 400 MeV incident energy. These spectra are characterized by a sharp peak at the energy corresponding to the beam velocity. This peak is referred to in the following discussion as the quasi-elastic break-up peak. Its yield decreases with increasing α particle emission angle. At about 20 MeV lower down in energy a second peak can be observed for α particle emission angles between 16° and 24°. The nature of this peak is most likely linked to the presence of hydrogen on the targets. Furthermore, the spectra reveal tails which extend from the quasi-elastic peak to lower energies and cover almost the entire energy range. It is assumed that these tails contain mainly events which originate from an inelastic break-up process whereby the α particle undergoes final state interactions with the target nucleus leaving the ^{8}Be partner intact in its ground state. In order to gauge the amount of hydrogen in the targets equivalent measurements were done with a $(CH_2)_n$ target. As part of the further analysis it is intended to complement these by measuring the elastic ^{1}H(p,p)^{1}H yields, using a proton beam together with the high resolving power of a magnetic spectrometer. With these additional data at our disposal will we be able to consistently correct the contribution due to scattering off hydrogen in the coincidence spectra. At this stage only very preliminary data are presented here and only the quasi-elastic break-up component of the coincidence spectra can be interpreted at this stage.

In order to extract information relating to the quasi-elastic break-up contribution to the coincidence spectra, two dimensional energy spectra were generated of which an example is shown in Fig. 3 for 400 MeV ^{12}C on ^{93}Nb at the emission angle pair of $\theta_{Be} / \theta_{\alpha}$ = 9° / -16°. Also shown in Fig. 3 is the gate defining the quasi-elastic break-up events. The event locus thought to be originating from the emission off hydrogen is also clearly visible in Fig. 3 at about 20 MeV below the quasi-elastic locus. Energy integrated cross sections were extracted for the binary quasi-elastic break-up of ^{12}C scattering off ^{93}Nb and ^{197}Au which are presented as function of the α particle emission angle in Fig. 4. These cross sections decrease with increasing angle and seem to be fairly similar in trend with respect to the target nucleus. The roles which both the α particles and the ^{8}Be fragments play in a quasi-elastic break-up process is closer examined by investigating the energy distributions of the α particles and the corresponding ^{8}Be fragments. These distributions are shown for the events defined by the gate in Fig. 3 and are presented as function of the respective energies and coincidence angle pairs as shown in Fig. 5. The arrows in Fig. 5 indicate the respective values of the beam velocity. While the energy distributions displayed at the larger α-particle angle of θ_{α} = -24° follow the expected trend, the result at the more forward emission angle of θ_{α} = -16° is surprising. The α-particle energy distribution is found to peak at an energy which exceeds the corresponding beam velocity by about 15%. Although this result is puzzling, it is consistent with earlier observations made for similar reactions of a binary break-up process whereby the α particle is emitted at a forward angle in coincidence with a heavier partner [7,10]. To our knowledge, no consistent explanation could thus far be given for this phenomenon and remains one of the unresolved issues in this field [10].

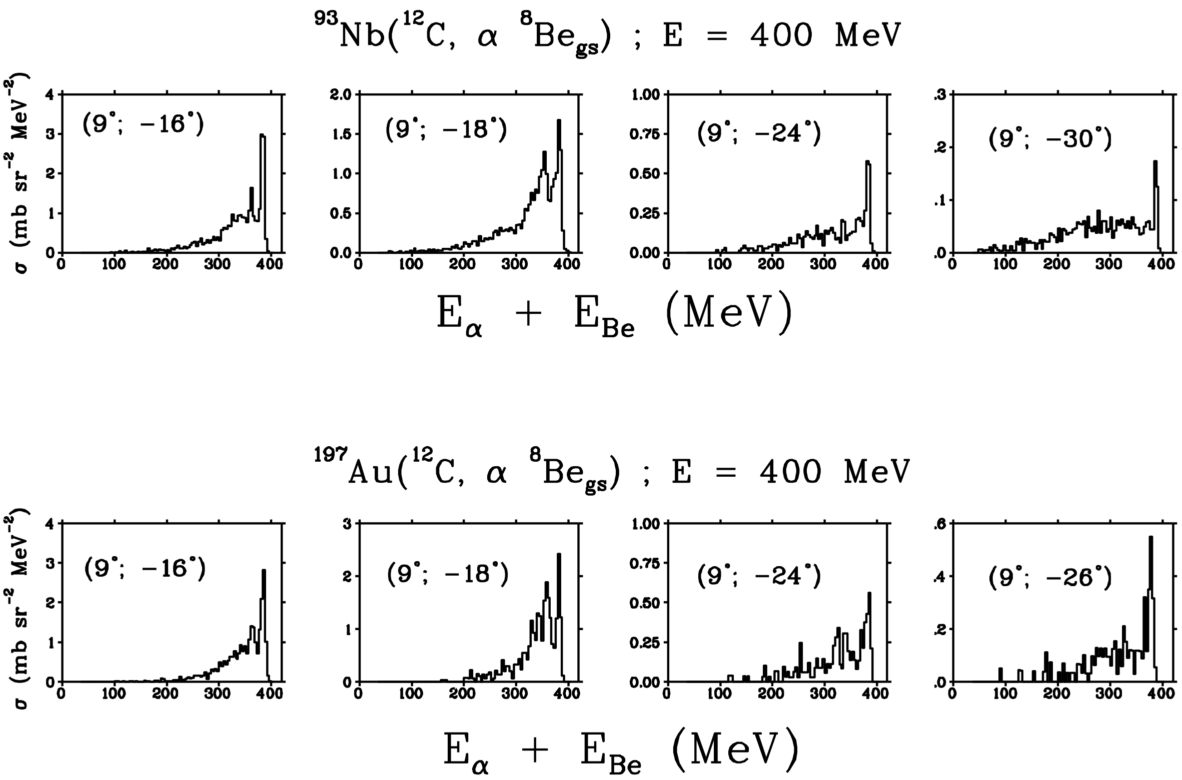

Fig. 2: Coincidence cross sections as a function of the sum of the kinetic energies of the ^{8}Be fragments detected in the ground state at 9° and the α particles detected at the angles as indicated.

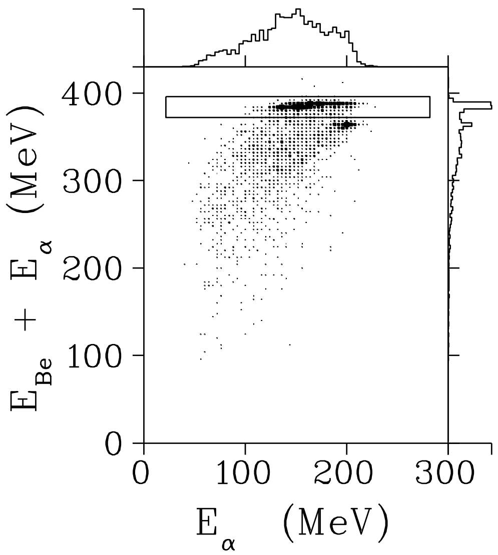

Fig. 3: An example of a two dimensional coincidence energy spectrum. Quasi-elastic events are selected by the gate. Also visible is the second locus most probably due to interaction with hydrogen on the target, as well as other events originating from inelastic break-up.

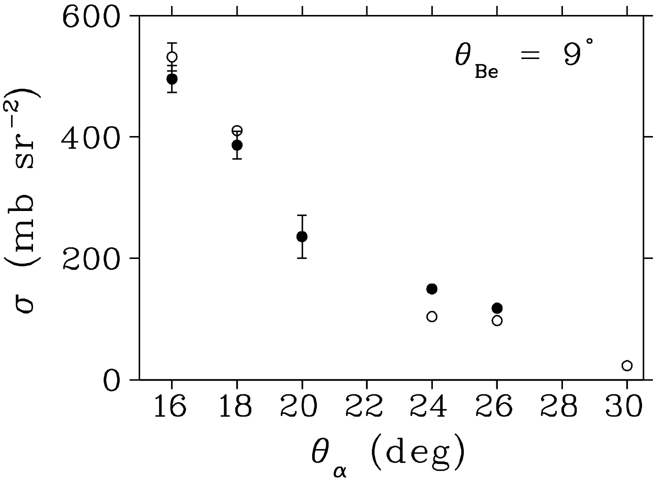

Fig. 4: Angular distributions of energy-integrated quasi-elastic coincidence cross sections. Open and solid symbols represent data from the ^{93}Nb and ^{197}Au target, respectively. Statistical errors are indicated by the bars.

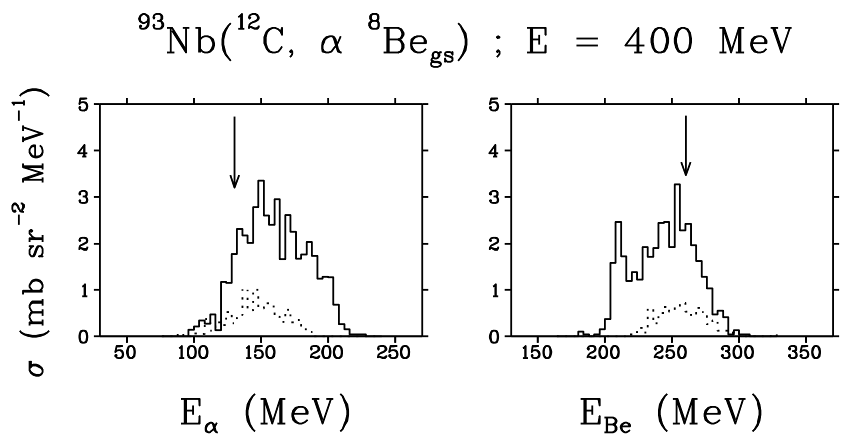

Fig. 5: Coincidence cross sections for quasi-elastic events as defined by the gate in Fig. 3 shown as function of the α-particle energy and ^{8}Be$_{gs}$ energy, respectively. The solid and dotted histograms represent data of the angle pairs ($\theta_{Be} / \theta_\alpha = 9° / -16°$) and ($\theta_{Be} / \theta_\alpha = 9° / -24°$), respectively. The arrows indicate the corresponding energies with respect to the beam velocity.

4 Summary and Outlook

A coincidence experiment was performed to measure the correlation of α particles and ^{8}Be fragments produced in the direct binary break-up of ^{12}C in the interaction with ^{93}Nb and ^{197}Au at an incident energy of 400 MeV. Coincidence energy spectra were obtained for a forward fixed ^{8}Be emission angle of +9° and α-particle angles ranging from -16° to -30°. The two detector telescopes employed in these measurements allowed for a clean particle separation between ^{3}He and ^{4}He events as well as to distinguish between the 0^+ ground state of interest and the first excited 2^+ state of ^{8}Be. The coincidence spectra as a function of the sum of the energies reveal two distinct regions, namely a quasi-elastic peak at around the beam energy and a tail consisting of inelastic break-up events. Since it is unlikely that the ^{8}Be fragments would survive any final state interaction with the residual target nucleus, such interactions are believed to be mainly inelastic processes between the α particle and the target nucleus. A second peak at about 20 MeV below the quasi-elastic peak which is observed for α particle angles between 16° and 22°, could originate from interactions between ^{12}C and hydrogen in the target. Analyses and measurements are underway to determine and correct for these contributions to the inelastic parts of the spectra. First and preliminary conclusions can therefore be drawn only from the quasi-elastic break-up of ^{12}C. Energy-integrated angular distributions would indicate that this break-up process seems to be dominant in the measured correlation spectra. The individual role of the α particles and ^{8}Be fragments in the binary quasi-elastic break-up process was investigated by extracting their respective energy distributions at the different α particle emission angles. As was previously found in similar studies, the α-particle distribution, at the most forward emission angle, is found to peak at an energy which is considerably higher than the corresponding beam velocity. Attempting to understand this phenomenon together with a consistent description of the inelastic break-up processes will be at the center of the further experimental and theoretical analyses of this work.

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