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Elastic scattering studies of ^{16}C at 50 MeV/A on proton and deuteron targets with the CHIMERA multidetector at INFN-LNS

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Abstract. At the Laboratori Nazionali del Sud (LNS) in Catania (Italy), light radioactive ion beams have been produced through the In Flight Fragmentation method, using ^{18}O and ^{13}C at 55 MeV/A as primary beams impinging on a ^{9}Be production target. Elastic scattering angular distributions of ^{16}C+p and ^{16}C+d at 50 MeV/A, ^{10}Be+p at 56 MeV/A and ^{13}B+d at 52 MeV/A systems were measured by using the CHIMERA (Charge Heavy Ion Mass and Energy Resolving Array) multidetector and kinematical coincidence technique. The experimental data are fitted by using the optical model.

1. Introduction

Progress in nuclear science is often driven by new accelerator and other advanced facilities, which allow probing more and more deeply into the structure of the nucleus, or even to discover new states of nuclear matter. Most of the elements in the cosmos are formed in stellar environments via reactions that involve many rare isotopes, which are short-lived nuclei (called exotic nuclei) very far from the line of stability. The properties of most of these isotopes are unknown and they can be studied thanks to new facilities in the world and to the theoretical model calculations. In

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this scenario, nowadays different facilities are running to produce exotic beams and new projects and techniques are going to reach new exotic beams with high energy and intensity.

At LNS, exotic beams have been produced for many years at low and intermediate energies using Isotope Separation On Line (ISOL) [1] and In Flight Fragmentation (IFF) [2, 3] methods. In this paper, we discuss the study of direct reactions, using the CHIMERA multidetector [4, 5, 6] and beams produced by the IFF technique. Two experiments, with ^{18}O and ^{13}C primary beams at 55 MeV/A impinging on a ^{9}Be production target, have produced light Radioactive Ion Beams (RIBs) with enough rate (10^3 - 10^4 p/s) to study direct reactions on proton and deuteron targets.

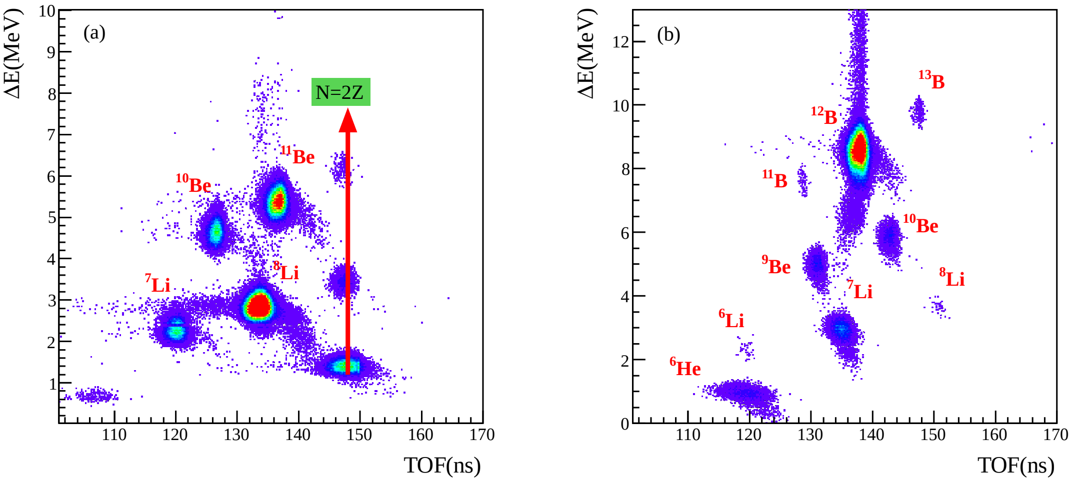

Figure 1. ΔE measured by the DSSSD against TOF between the silicon detector and the MCP. ^{13}C primary beam at 55 MeV/A impinging on a ^{9}Be (1500 μm) production target. The magnetic fields in the FRS are optimized to transport: (a) ^{11}Be isotope; (b) ^{12}B isotope.

CHIMERA is a 4π multidetector made of 1192 telescopes, it has been built at LNS to study heavy-ion collisions in the intermediate energy range (20-200 MeV/A)[5]. The set up experiment has required some upgrading in order to use radioactive beams produced by IFF technique. A tagging system, consisting of a Double Side Silicon Detector (DSSSD) and a MicroChannel Plate (MCP), has been installed on the CHIMERA multidetector [7, 8]. Energy loss (ΔE) in the DSSSD and Time of Flight (TOF) measurements between the two detectors give the isotopic identification of the incoming beams. The elastic scattering angular distributions of ^{16}C+p, ^{16}C+d, ^{10}Be+p and ^{13}B+d systems were measured. Taking into account that CHIMERA is a 4π multidetector, measurements of events in coincidence between telescopes coupled kinematically have been performed. The results are very encouraging for future studies of transfer reactions and/or other direct reactions.

2. Production of neutron rich nuclei

In flight production of Radioactive Ion Beams (RIBs) at LNS was achieved by projectile fragmentation on light targets at incident energies in the interval from 40 to 62 MeV/A [3]. In the production of RIBs by the IFF method, the key role is played by the Fragment Recoil Separator (FRS), a magnetic filter which selects, according to their magnetic rigidity, the fragments produced in the reaction. At LNS, the standard extraction line of the accelerator was employed as a FRS, since it was already built as an achromatic fragment separator [2, 3].

During 2009-2011 different experiments and upgrading of the beam line were performed to study the opportunities offered by such beams using the CHIMERA 4π multidetector [9, 10]. Event by event isotopic identification of the incoming beams was obtained by a tagging system implemented on CHIMERA. This tagging system consists of a MicroChannel Plate (MCP) and a 16x16 strip Double Side Silicon Strip Detector (DSSSD) [7, 8]. The MCP gives the start time reference and the DSSSD gives the stop time reference and measures the position and the energy loss of the impinging beams. Time of Flight (TOF) and energies loss (ΔE) measurements allow selection of the incoming beam reaction channel.

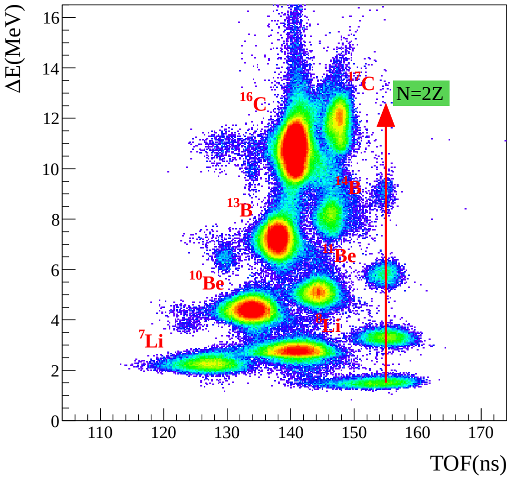

Figure 2. ΔE - TOF scatter plot. ^{18}O primary beam at 55 MeV/A impinging on a ^{9}Be (1500 μm) production target.

Primary beams of ^{13}C and ^{18}O at 55 MeV/A delivered by the Superconductive Cyclotron produced secondary beams around the ^{11}Be region which were transported to the CHIMERA. By using two different set ups of the FRS, the ^{13}C primary beam at 55 MeV/A impinging on a ^{9}Be target produces mainly ^{11}Be and ^{12}B beams which are quite pure and intense (10 kHz and 160 Khz respectively). The corresponding scatter plots are reported in Figure 1. An ^{18}O primary beam impinging on the same production target can also produce also ^{11}Be with less intensity (3 kHz), but more heavy neutron rich beams like ^{16}C and ^{13}B (8 and 4.5 kHz respectively) (see Figure 2).

3. Elastic scattering data

The main purpose of the experiments performed was to measure the intensity of beams at the scattering chamber and study the capabilities of CHIMERA by using kinematical coincidence and IFF beams. Considering that the CHIMERA multidetector covers 94% of the total solid angle, the kinematical coincidence technique reveals all of its power. The study of events in coincidence between two telescopes is based on the comparison with the kinematics expected for the direct reaction involved (elastic or inelastic scattering, transfer reaction, etc.). The energy spectra are cleaned of background and the reaction mechanisms involved are uniquely identified. In this case, the effective polar and solid angle of the measured cross section is not the opening of the detector but the result of the matching between the kinematic rules and the detector.

Initially the method was tested with a ^{7}Li beam at 52 MeV on a proton target, obtaining an energy resolution better that 400 keV [11]. Using the IFF beam, some problems arise because the directions of the incoming beams do not correspond to the symmetry axis of the detector array geometry. The lack of a beam tracking has revealed some difficulty in the beam line reconstruction. Analyzing events detected in the forward part of the CHIMERA array and

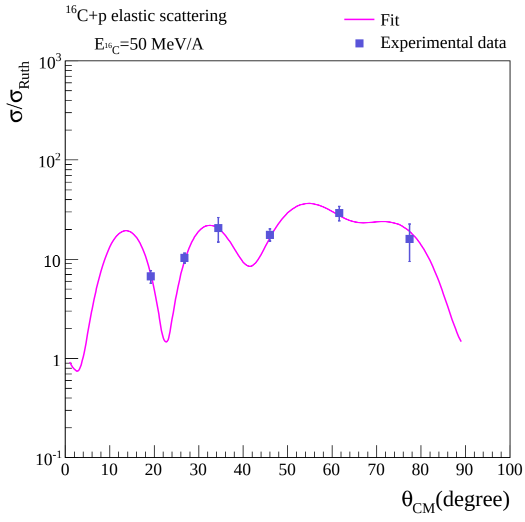

Figure 3. ^{16}C+p at 50 MeV/A elastic scattering angular distribution.

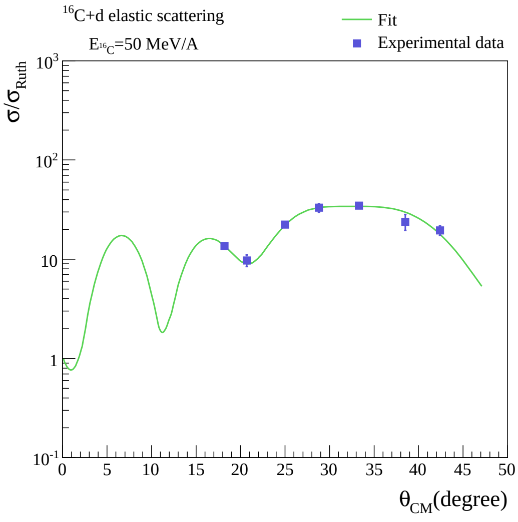

Figure 4. ^{16}C+d at 50 MeV/A elastic scattering angular distribution.

punching through the DSSSD has allowed some reasonable assumptions to be applied to the data reduction. Next improvements with a position sensitive MCP, positioned in front of the target, together with a DSSSD will permit accurate beam path reconstruction.

Selecting the initial reaction channel and measuring the number of incoming particles in kinematical coincidence, the elastic scattering angular distributions were obtained for the following systems: ^{16}C+p and ^{16}C+d at 50 MeV/A, ^{10}Be+p at 56 MeV/A and ^{13}B+d at 52 MeV/A. Errors in the cross sections are given by the Poisson statistic. The few data points are due to the lack of statistics.

Table 1. WS optical potentials obtained from the fit of the experimental data.

Reaction channel	V(MeV)	R_0	a	W(MeV)	R_{0i}	a_i	R_{C0}	chi^2/point
^{16}C+p	270	1.20	0.85	45.9	1.20	1.20	1.26	0.20
^{16}C+d	246	1.17	0.90	28.6	1.20	1.70	1.26	0.40
^{13}B+d	219	0.82	0.75	23.5	1.10	0.99	1.25	0.05
^{10}Be+p	278	0.57	0.31	16.8	0.90	0.40	1.25	4.50

The experimental data are fitted using optical model with calculations performed by the PTOLEMY code [12]. A Woods-Saxon (WS) form of the real and imaginary potential was used. To avoid a fit with too many free parameters, that can produce ¨unphysical¨ results, initially the radius and diffuseness (real and imaginary parts) were fixed and the potential depths were set as ¨free¨ fit parameters. The initial values to the fit were taken from similar system in [13, 14].

The potential parameters are shown in Table 1 and the corresponding cross section angular distribution with respect to the Rutherford cross section, in the centre of mass frame, are shown in Figures 3 - 6. As expected, due to the short range of the nuclear force, the Coulomb force is sizeable only for scattering at very small angles. At increasing angles the nuclear force becomes predominant leading at high values of the cross section relative to the Rutherford values [15].

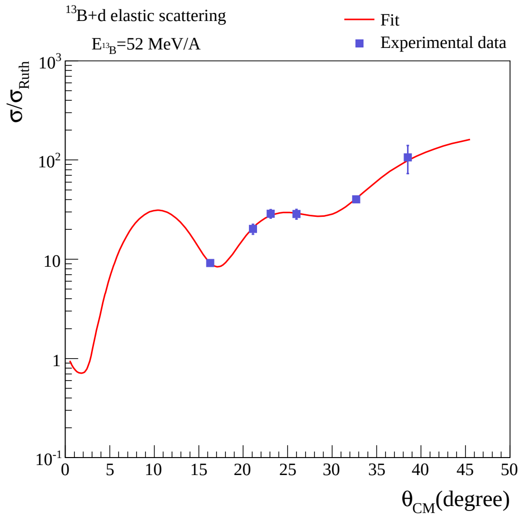

Figure 5. ^{13}B+d at 52 MeV/A elastic scattering angular distribution.

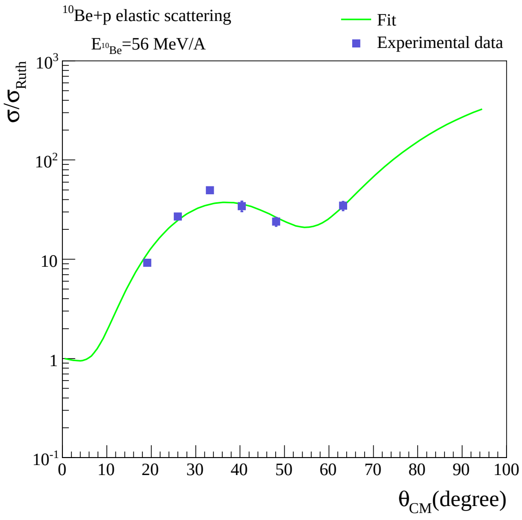

Figure 6. ^{10}Be+p at 56 MeV/A elastic scattering angular distribution.

4. Conclusion

The present paper reports the first results concerning the production of radioactive beams and the investigation of their properties with the CHIMERA multidetector, exploring the capabilities of this array to perform kinematical coincidences. Two experiments, with ^{18}O and ^{13}C primary beams at 55 MeV/A impinging on a ^{9}Be production target, were made to produce light RIBs with a high enough rate (10^3- 10^4 p/s) to study elastic scattering of ^{16}C+p and ^{16}C+d at 50 MeV/A, ^{10}Be+p at 56 MeV/A and ^{13}B+d at 52 MeV/A.

The fit to the data of the reactions ^{16}C+p and ^{16}C+d, leads to ¨anomalous¨ diffuseness of the imaginary potential. These results could confirm the anomalous structure of the ^{16}C. Presently, its structure is not well understood, even if ^{16}C can also be treated as a core+n+n three-body system, it is not a Borromean system because the subsystems n-^{14}C is bound. However, the paring effect of the two neutrons added to ^{14}C seems to play an important role [16, 17, 18, 19]. On the other hand, lifetime measurements for the first-excited state in ^{16}C [17] and transfer reaction d(^{15}C,^{16}C)p requires no exotic interpretation [16].

An interpretation of the ¨anomalous¨ diffuseness can be suggested by Ref. [20]. If the absorption of the elastic scattering ^{16}C+p is dominated by breakup of the n-^{15}C, and ^{16}C+d by deuteron breakup, the theoretical values of the diffuseness are 1.10 and 1.53 fm respectively. This explains the high values of diffussness of the two reactions with ^{16}C beam especially with deuteron target.

New larger quadrupoles and sextupoles already mounted have increased the beam intensity by a factor 10. Further analysis is going on new higher statistics experimental data with better determination of the beam direction than these test experiments. We will be able to investigate accurately ^{16}C structure with elastic scattering reaction as well as transfer, break up and other direct reactions.

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