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Carbon Fragmentation Cross Sections for Hadrontherapy and Space Radiation Protection

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Fragmentation reactions represent a serious complication in hadrontherapy and space radiation protection. In order to predict their effects, both reliable Monte Carlo codes and experimental data are needed. The shortage of precise measurements, especially of double differential cross sections, has triggered many dedicated experiments at relativistic energies. Aiming to explore the Fermi energy regime, as well, where different reaction mechanisms are involved, we measured the ^{12}C fragmentation at 62 AMeV on a ^{12}C and a ^{197}Au target. A high granularity Si-CsI hodoscope allowed to identify the charge and the mass of detected fragments and measure their energy and emission angle. In this work we report the double differential cross sections for the production of different fragments as a function of the emission angle. Experimental results are compared with the GEANT-4 Monte Carlo predictions performed using two reaction models, the Quantum Molecular Dynamic and the Binary Light Ion Cascade.

I. INTRODUCTION

Nowadays there is a growing interest in nuclear fragmentation measurements for hadrontherapy, the new frontier for cancer therapy and space radiation protection. Treating tumors with carbon ions gives many physical and biological advantages, such as a high dose conformation and an enhanced biological effectiveness [1]. However, the fragmentation of the therapeutical beam within the patient body represents a serious collateral problem. The production of fragments affects the delivered dose inside and outside the tumor region, as well as the biological effectiveness, and hence needs to be taken into account when planning a tumor treatment. For similar reasons, nuclear fragmentation is a relevant complication also for space exploration. To calculate the radiobiological risk for the astronauts, originating from the space radiation exposure, the radiation field properties must be known. Thus the Galactic Cosmic Rays fragmentation in the space-vehicle materials and in the astronaut's body needs to be carefully estimated [2]. Monte Carlo simulations could allow to overcome the shortcomings of analytical calculations and provide realistic predictions even if they are presently not enough accurate for the mentioned purposes [3]. Experimental fragmentation cross sections are the key ingredient to better tune and validate the simulation codes but most of the existing data are limited to fragment production yields or total charge-changing cross-sections, whereas angular and energy distributions of the produced isotopes (i.e. the double-differential cross-sections) are scarce [4]. Dedicated experiments have been recently performed at energies above the Fermi regime [5]. In order to explore, as well, the Fermi energy domain we measured a large set of ^{12}C fragmentation cross sections at 62 AMeV. Carbon ions are used in most of the clinical experiences with heavy ions and they are a significant component of cosmic rays, too. Moreover, this energy region is of particular interest since different reaction mechanisms are in competition and, to our knowledge, no double differential cross sections are present in the literature. In this paper we report the double differential cross sections measured for the ^{12}C + ^{197}Au reaction, compared with those measured for the ^{12}C + ^{12}C reaction at the same incident energy [6]. The experimental data are also compared with the Quantum Molecular Dynamic (QMD) [7] and the Binary Light Ion Cascade (BIC) [8] predictions obtained using the GEANT-4 Monte Carlo code [9].

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II. THE EXPERIMENT

The beam was accelerated by the Superconducting Cyclotron of the INFN-LNS laboratory in Catania and was focused onto a 147 μg/cm^2 thick ^{197}Au target. The produced fragments were detected by an array of 88 Si-CsI telescopes, placed 60 cm downstream the target and covering the angular region between $7.6° \leq \theta_{lab} \leq 21.8°$ [10], being θ_{lab} the scattering angle in the laboratory reference frame. Each telescope has an active area of 3x3 cm^2 and consists of two Si detectors, 50 μm and 300 μm thick, followed by a 6 cm long CsI(Tl). The detected fragments were identified in charge and mass using the ΔE-E$_{res}$ technique, being ΔE and E$_{res}$ the energy loss and the residual energy measured in the Si and CsI detectors, respectively. The absolute cross sections were extracted from the measured counting rate, normalized for the acquisition system dead-time, the target thickness, the solid angle covered by each telescope and the integrated beam charge measured by a Faraday cup. The associated uncertainties were estimated from the statistical errors in the measured fragment yields and the uncertainties on the target thickness, the number of incident ions and the measured dead-time.

III. DOUBLE DIFFERENTIAL CROSS SECTIONS

The double differential cross sections of the fragment production provide valuable informations about the reaction mechanisms involved. For projectile-like fragments produced at energies larger than 200 AMeV, the momentum distribution has a Gaussian shape [11] centered around the projectile velocity [12]. It's width is well understood within the Goldhaber model [13]. On the other hand, the intermediate-energy region is a transition regime where the mean-field description of the collision begins to give way to the nucleonic degree of freedom. As a result of the transient nature of this energy region, different reaction mechanisms contribute to the angular and energy distributions of the produced fragments.

A typical example of double differential cross sections for the production of ^{6}Li, ^{7}Li, ^{7}Be and ^{9}Be fragments in the ^{12}C + ^{197}Au reaction at $\theta_{lab} = 8.6°$ are shown in Fig. 1 and are listed in Table I. It is evident that the cross section is dominated by a Gaussian-like peak that, in contrast to what observed at relativistic energies, has an asymmetric shape and a low-energy tail. Such asymmetry was interpreted in Refs. [14–16] as a signature of the presence of dumped fragmentation processes, together with the direct projectile fragmentation, due to frictional forces and nucleon flows between projectile and target during the collision time.

In the same figure, we also show the cross sections previously measured at the same incident energy using a carbon target [6]. Their values are listed in Table I.

The similar shape of the cross sections for the two targets indicates that the direct and dumped projectile fragmentation is the dominant reaction mechanism at this angle.

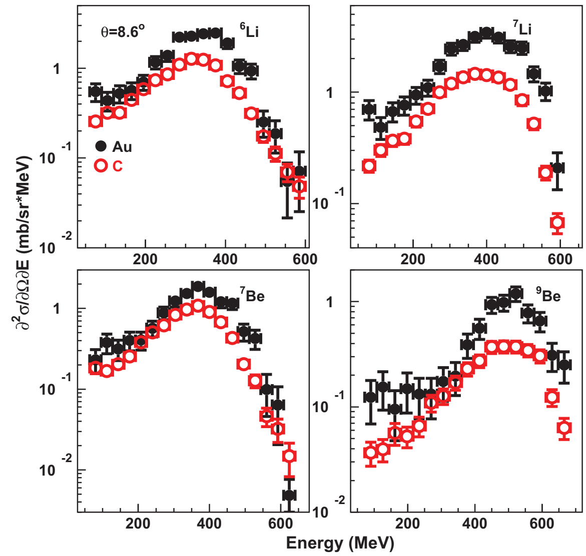

FIG. 1. Double differential cross sections measured at $\theta_{lab} = 8.6°$ for the production of ^{6}Li, ^{7}Li, ^{7}Be and ^{9}Be in the ^{12}C + ^{197}Au (•) and ^{12}C + ^{12}C [6] (◦) reactions at 62 AMeV.

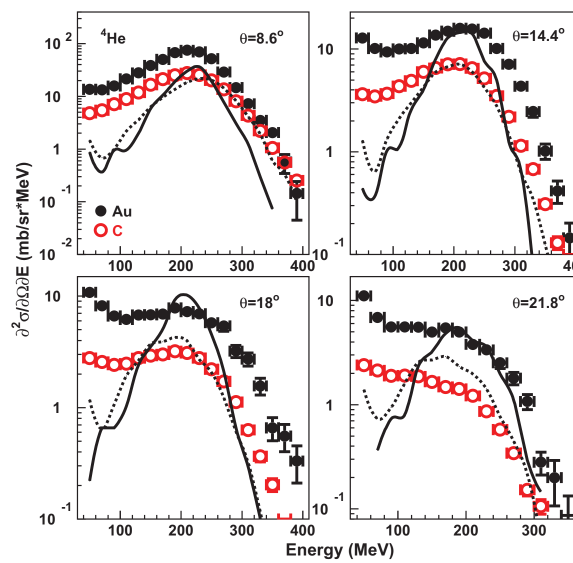

FIG. 2. Double differential cross sections measured at $\theta_{lab} = 8.6°$, 14.4°, 18° and 21.8° for the ^{4}He production in the ^{12}C + ^{197}Au (•) and ^{12}C + ^{12}C [6] (◦) reactions at 62 AMeV. Quantum Molecular Dynamics (solid lines) and Binary Light Ions Cascade (dashed lines) predictions for the ^{12}C + ^{197}Au reaction are also shown.

The behavior significantly changes at larger angles. Fig. 2 shows the double differential cross sections for the ^{4}He produced with the ^{197}Au target at four different angles. The cross section values are listed in Table II. As the emission angle increases, the main Gaussian-like bump is less and less pronounced until the low energy