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Splitting of fragmentation peaks of light ions in ^{56}Fe + ^{9}Be collisions at 0.23 GeV/nucleon

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Abstract. The FRAGM experiment at the ITEP-TWA heavy ion facility has a unique opportunity of measuring the momentum distributions of nuclear fragments. We present the results of ^{56}Fe fragmentation into light ions on ^{9}Be target at 0.23 GeV/nucleon. The momentum spectra of projectile like fragments were measured with a high resolution beam line spectrometer. In contrast to the carbon fragmentation, where the momentum spectra have Gaussian-like shapes, in the emission of the light fragments the shapes have a double-humped structure. This splitting is most pronounced in proton spectra. The possibility of describing this effect by asymmetric fission and multifragmentation is discussed. A comparison is made with the results of the FRS measurements at GSI. The obtained experimental data are in a reasonable agreement with the predictions of several transport codes such as BC, INCL and LAQGSM.

1 Introduction

During a long-term study of ion-ion interactions, a considerable progress has been made in understanding the physics associated with these interactions; a large amount of experimental data has been accumulated in a wide energy range from the Coulomb barrier to several TeV per nucleon. Nevertheless, previous and new unsolved problems of the dynamics of these interactions still appear. Some of them are proposed to be studied in this paper. In the FRS-GSI experiment [1], new interesting effects were detected, which contradict to the current picture of heavy ions fragmentation. Following this point of view, the momentum spectra of fragments have a well known form close to a Gaussian. In statistical models the parameters of this form are related to the Fermi-motion of nucleons in the incident nucleus. Moreover, these parameters defined in the projectile rest frame are in good agreement with the hypothesis of limiting fragmentation, and they depend neither on the type of the target nucleus nor on the energy of the incident nucleus. However, in the mentioned work at GSI in the process of iron fragmentation at the energy of 1 GeV/nucleon, it has been found, that momentum spectra of the light ions, such as lithium and beryllium, have a splitting structure in the peak maximum. For boron and carbon isotopes, the shapes of these spectra were of the almost expected statistical shape. This phenomenon is observed on the hydrogen target and is absent on the titanium one. The obtained results have been confirmed in the fragmentation of ^{128}Xe [2, 3] for ^{11}B and ^{20}F ions, but the effect of the peak splitting has been seen less clearly.

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Several hypotheses were suggested describing this effect such as Coulomb effects, asymmetric fission and so on. The dominant role of strongly asymmetric fission was supported by the FRS-GSI group. At the same time, our scientific group has collected a unique data set based on fragmentation of iron with the experimental setup, which could detect light ions in a wide energy range. The hodoscope system of the beam line spectrometers could improve the measured momentum up to 0.2%. This allowed us to perform a study of the iron fragmentation products in the region inaccessible for FRS-GSI from protons to lithium isotopes and in the area overlapping with it to carbon isotopes. Besides, it can significantly expands the range of possible manifestations of this effect and will provide additional information for theoretical analysis, which, hopefully, will provide an opportunity to explain this effect.

2 Experimental setup

The experiment FRAGM was performed at the Institute for Theoretical and Experimental Physics (ITEP) at multipurpose accelerator complex ITEP-TWAC, which provided proton and ion beams for different research and application fields [4]. FRAGM was optimized to register nuclear fragments produced on the beryllium target 50 μm thick. The experimental setup represents a double-stage beam line spectrometer located at an angle of 3.5^0 with respect to the internal ion beam. Each stage consisted of a doublet of quadrupole lenses and bending magnet. Two foci of the beam line spectrometer were at a distance of 26 and 42 m from the target. Scintillation detectors to measure the ionization losses and time of flight were positioned at other focus. The coincidence of signals from two counters at different foci served as a trigger for the readout of amplitude and time information. A scintillation counter hodoscope consisting of 20×8 elements was used to control the beam size and improve the momentum resolution at the first focus. As a monitor, it was used a telescope of three scintillation counters oriented directly to the target. The beam line spectrometer efficiency to detect specific fragment was obtained by GEANT4 simulation tool. This code takes into account ionization losses, multiple scattering, and inelastic interactions in the detector material. A more detailed description of the setup is given in [5].

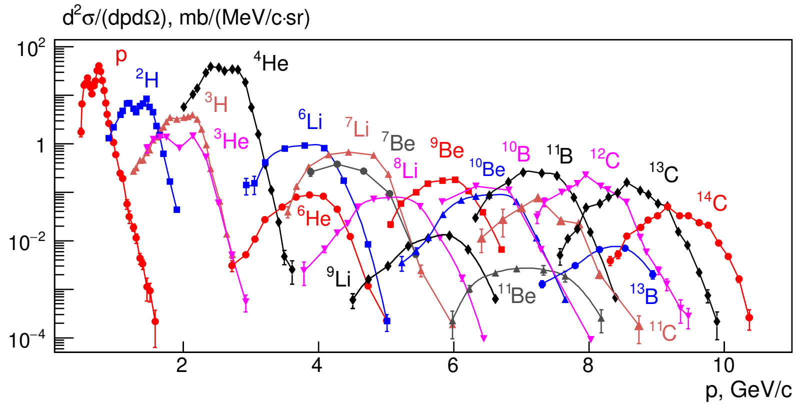

Figure 1. Differential cross sections for the yield of fragments as a function of the laboratory momentum

3 Measurements of the light fragments

The yields of different fragments were measured by rigidity scanning of the beam line spectrometer with a step of 50 to 200 MeV/c. A large set of fragments was identified on the basis of two-dimensional correlation plots by a TOF signal from a time-to-digital converter (function of the fragment mass number) versus the amplitude of a scintillation-counter pulse from a charge-to-digital converter (function of fragment charge). This analysis allowed us to clearly define the certain fragment. The relative yields of fragments were calculated via normalizing the number of detected fragments to monitor readings with allowance for their detection efficiency. To obtain absolute values of the differential cross sections $d^2\sigma/dpd\Omega$, it was used the total cross section for the interaction of iron ions with the beryllium target at the energy of 230 MeV per nucleon equal to 1579 mb. In view of the absence of experimental data on inelastic cross sections for this interaction, this value was extracted from the LAQGSM/MCNP6 [6]. Fig. 1 shows the differential cross section for measured fragments from protons to isotopes of carbon as a function of the laboratory momentum. These cross sections extend over five orders of magnitude. For each fragment, the momentum distributions have a Gaussian shape with a maximum at a momentum per nucleon close to the iron-projectile momentum per nucleon. For light fragments with the momentum significantly higher, the exponential decrease of the cross section is clearly seen. This behavior, which is especially pronounced for protons, is typical for cumulative fragments. The momentum spectra of (^{3}H, ^{3}He), (^{7}Li, ^{7}Be), (^{10}Be, ^{10}B), (^{11}B, ^{11}C) fragment pairs are nearly coincident as a result of the fragmentation of nucleus close in composition to the isotopic symmetry. The systematic uncertainty in the differential cross sections determined primarily by the stability of the monitor can be estimated at the level of 15%.

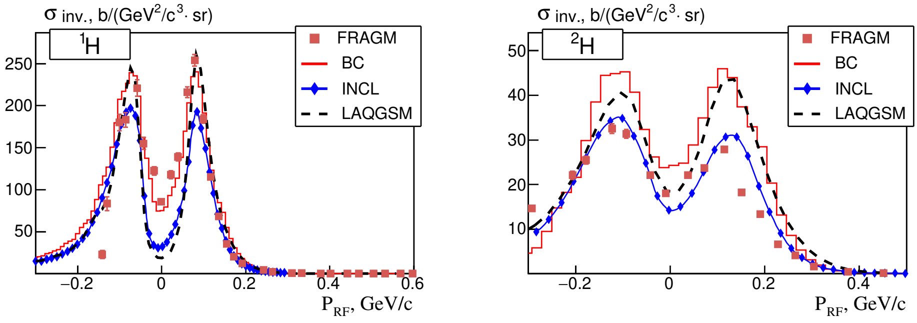

Figure 2. Invariant cross sections of the fragment momentum in the rest frame of iron projectile nucleus in comparison with different models of ion-ion interactions

4 Estimation of the excitation energy

Fig. 2 shows invariant cross sections $\sigma_{inv} = Ed^2\sigma/p^2dpd\Omega$ of the fragment momentum in the rest frame of iron projectile nucleus for protons and deuterons. The plots demonstrate both: our experimental data and predictions of the different models such as BC [7], INCL [8] and LAQGSM(MCNP6) [9]. It should be emphasized, that these cross sections of the light fragments were measured for the first time. LAQGSM and BC models have better agreement among themselves and also for the proton data. The BC model has a satisfactory description of the experimental results for both spectra. Besides, all the models reproduce a peak splitting effect as a result of the dominant influence of Coulomb forces.

For a more substantial investigation of ion-ion interaction mechanisms based on our experimental data, it would be interesting to investigate the dynamic fragmentation process. The collision of nuclei can occur in two stages. Initially, compression and heating of the system take place with subsequent expansion and cooling accompanied by the emission of non-equilibrium particles. In this stage, it is possible to establish thermodynamic equilibrium in the system as a form of the nuclear fireball. In the second stage, this nuclear fireball disintegrates into nucleons and fragments which fly away under the influence of Coulomb forces. The statistical multifragmentation model (SMM) [10] is designed to describe the second stage of ion-ion interactions. The basic idea of this model is to assign each final state a certain probability, depending only on the thermodynamic parameters of the system and the energies of these states. The statistical approach makes it possible to identify the main statistical features of nuclear multifragmentation using the example of the decay of an idealized excited nucleus, when it does not matter how this system was formed. The excitation energy of fireball and mass of the final state are free parameters for the SMM model. Fig. 3 (left) shows a way to define excitation energy of the fireball by comparison between our experimental data for protons with different predictions of the SMM model. It's seen, that a better agreement can be achieved for the excitation energy equal to 6 MeV per nucleon.

The experimental spectra of kinetic energy in the rest frame of the incident nucleus, shown in Fig. 3 (right), can be fitted by a sum of two exponents [11]. Each exponent has two slope parameters, T_S and T_C, which are usually referred to as temperatures. The first one can be taken into account as the temperature of the nuclear fireball. $T_S = 5.2 \pm 0.1$ MeV and this value is close to the excitation energy obtained from the SMM model. This parametrization differs from thermodynamic ideas of nuclear fragmentation, where there is only one temperature, and makes it possible to analyze deviations.

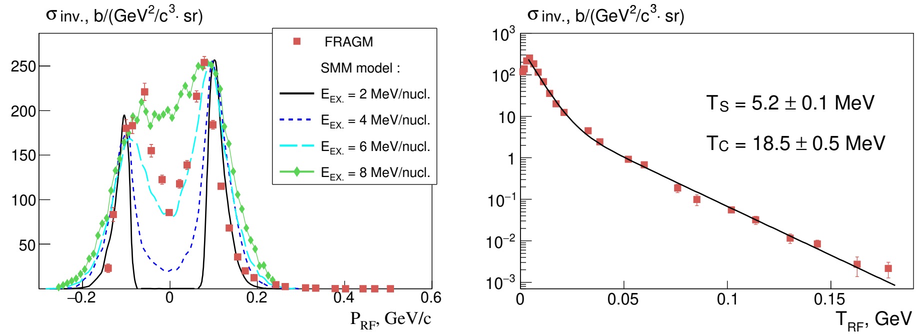

Figure 3. Two different methods to estimate the excitation energy on proton fragment spectra: the left plot shows the comparison between our experimental data and predictions of the SMM model, the right one demonstrates the invariant cross section fitted by a sum of two exponents

5 Conclusions

We have measured the differential cross sections for the yields of long-lived fragments at the angle of 3.5° in the fragmentation of ^{56}Fe on the beryllium target at the energy of 230 MeV per nucleon. Different fragments from protons to carbon isotopes have been clearly separated by the correlation measurements of time of flight versus ionization losses in scintillation detectors of the FRAGM experiment. Besides, the differential cross section of the light fragments with A < 6 were measured for the first time. For these fragments, the momentum spectra have a splitting structure in the peak maximum. Earlier this effect was measured in the iron fragmentation at the energy 1 GeV per nucleon in the GSI-FRS experiment but for lithium and heavier ions. Several models of ion-ion interactions, such as INCL, BC and LAQGSM, were tested to find a reason of the peak splitting. All models reproduce both the general shape and peak splitting of the momentum spectra in the rest frame of a projectile. It is obvious, that in these models the mechanism responsible for the peak division is associated with Coulomb repulsion. Also, we present two different ways to define the excitation energy of the nucleus fireball. The first method is based on the SMM model, where the excitation energy is a free parameter; in the second one the excitation energy is connected with the slope parameter of fragment kinetic energy spectra. The both methods have determined the value of excitation energy at the level of 5-6 MeV per nucleon, which is comparable to the nucleon binding energy in the nucleus. Similar measurements, performed at the GSI-FRS experiment for ions starting from lithium, have confirmed that splitting of fragmentation peak is a result of strongly asymmetrical fission.

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