Analysis of velocity distributions in projectile fragmentation reactions of $^{18}$O ions on $^9$Be and $^{181}$Ta targets at 35 $A$ MeV

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Abstract. Up to date analysis of velocity and isotope distributions of light fragments obtained in the projectile fragmentation reactions of $^{18}$O at 35 $A$ MeV on $^9$Be and $^{181}$Ta targets measured at COMBAS fragment separator at the U400 M Research Facility in JINR are presented. The results of velocity spectra analytical parameterization and isotopic ratios are compared with the ones obtained in the experiments presented in the literature. The discussion of the different mechanisms involved in these types of the reactions is given.

1. Introduction

Heavy ions fragmentation reactions at Fermi energies (about 40 $A$ MeV) are a powerful tool for obtaining new isotopes far from the stability line which can be used to produce secondary beams and also for radio therapy. For these studies it is necessary to make correct predictions of the cross-sections of secondary fragments produced in these type of reactions and their energies (or velocities). To make such predictions one has to understand the mechanism of these reactions. There are successful empirical methods [1, 2], but a more microscopic models would be desirable. To develop such models the better understanding of the fragmentation process at Fermi energies is necessary. Velocity distributions give valuable information on contributions of different modes in the nuclear reactions. In this report we present the parameterization of experimental data obtained in the collision of $^{18}$O ions with the $^9$Be and $^{181}$Ta targets at energy 35 $A$ MeV [3]. Velocity distributions are parameterized following the scheme proposed in papers [4, 5]. In contrast with the results from these two papers we see an additional peak at lower energies. We assume this difference can be explained by the fact that the beam energy in experiment [3] is lower than those of [4, 5].

The experimental results in this report were obtained at magnetic separator COMBAS at FLNR JINR. The details of the experiment and the setup are presented in [3, 6].

2. Momentum distributions

The velocity distributions of the projectile-like fragments produced in the reactions of fragmentation give more information about the reaction mechanism than the isotope distributions. Studying them one can learn about different modes involved in the process. Looking at the figure 1a-c one can see that the reactions of fragmentations at energies close to the Fermi energy show an unexpected feature, namely, the peaks of velocity distributions of the projectile-like fragments $v$ are very close to the beam velocity $v_0$ ($v/v_0\approx 1$) as should be expected at relativistic energies. Another
remarkable feature of the velocity distributions is their similarity in the reactions: on heavy $^{181}$Ta and light $^9$Be targets. The right slopes of these distributions can be described by Gaussians with a width $\sigma_R$ compatible with the Goldhaber model [1], while the left slopes of these distributions have a long shoulder as shown in figure 1d.

Figure 1. Forward-angle velocity distributions (relative yields) of isotopes $^{16}$O (a), $^{14}$N(b) and $^{12}$C(c) produced in $^{18}$O(35 AmMeV)$+^9$Be (open circles) / $^{181}$Ta (solid lines) reactions [3] as a function of relative velocity $v/v_0$. In panel (d) the details of the velocity parameterization are shown.

In papers [4, 5] it was suggested that the shape of the velocity distributions of fragments close to the projectile could be described as

$$\frac{d\sigma}{dp} = \begin{cases} s \cdot \exp\left[-\frac{(p - p_0)^2}{2\sigma^2_L}\right] & (p \leq p_0) \\ s \cdot \exp\left[-\frac{(p - p_0)^2}{2\sigma^2_R}\right] & (p > p_0) \end{cases} \tag{1}$$

Where $p$ is the momentum of the fragment, $p_0$ – projectile momentum, $s$ and $p_0$ are the height and the position of the maximum of momentum distribution, $\sigma_L$ and $\sigma_R$ are the widths of left and right slopes.

The experiments presented in [4, 5] were performed at higher energies (57 and 140 $A$ MeV) than the data presented in [3]. The experimental data from [3] show an additional peak to the left of the beam velocity. In this report we made an attempt to parameterize the velocity distributions for the reactions $O+Be / Ta$ at 35 $A$ MeV. We modified the formula 1 and used the following expression:

$$\frac{d\sigma}{dp} = \begin{cases} s \cdot \exp\left[-\frac{(p - p_0)^2}{2\sigma^2_L}\right] + s_1 \cdot \exp\left[-\frac{(p - p_1)^2}{2\sigma^2_{L1}}\right] & (p \leq p_0) \\ s \cdot \exp\left[-\frac{(p - p_0)^2}{2\sigma^2_R}\right] & (p > p_0) \end{cases} \tag{2}$$

Here $s_1$, $p_1$, $\sigma_{L1}$ have the same meaning as in formula 1, but for the left hand side peak (see fig. 1d).
Figure 2. Velocities at peaks in the units of beam velocity for isotopes from B to O produced in the reactions $^{18}\text{O}+^9\text{Be}$ (a) / $^{181}\text{Ta}$ (b). Solid symbols - the main peak, open symbols - left-hand side peak. The solid curves are the predictions of the transport model calculations [7], the dashed ones are the predictions of the Borrel’s formula [8].

In Figure 2 the positions of the fragments relative velocities maxima for the main (solid symbols) and for the left-hand side (open symbols) peaks are shown in comparison with the transport model (Dubna modification of BNV codes developed in LNS-INFN, Catania, Italy) calculations for excited (hot) fragments [7] and also for the estimation according to Borrel’s formula [8]. The velocities at maximum agree well with those obtained in [4, 5]. One can see that both calculations predict the process to be much more dissipative. One has to investigate these data more thoroughly but it is highly possible that the left-hand side peak displays the dissipative mode of the reaction.

Figure 3. The widths of asymmetric Gaussians describing the main peak of momentum distributions for isotopes from B to O for the reactions $^{18}\text{O}+^9\text{Be}$ (a, b) and $^8\text{O}+^{181}\text{Ta}$ (c, d). The lines show the predictions of Goldhaber model.
The widths of the Gaussians $\sigma_L$ and $\sigma_R$ (see formula 2) which fit the experimental velocity distributions are shown in fig 3. The right slope widths $\sigma_R$ (fig.3 a, c) show the dependence on mass number of fragments similar to the one predicted by Goldhaber statistical model [1]

$$\sigma^2 = \sigma_0^2 \frac{A_F(A_p - A_F)}{A_p - 1}, \quad \sigma_0 \approx 90 \text{ MeV} / c$$  \hspace{1cm} (3)

where $A_F$ is the mass number of the fragment and $A_p$ is the mass number of the projectile and $\sigma_0$ is normalization constant, but with the smaller value of $\sigma_0$ ($\sigma_0 = 58 \text{ MeV} / c$ in our case instead of $90 \text{ MeV} / c$ in [1]). In paper [4] the $\sigma_0$ estimation value is in the range $[85.4, 92.7] \text{ MeV} / c$, in [5] it is higher than $106 \text{ MeV} / c$. As was mentioned above, the energy of the collisions in [4, 5] are higher than in [3]. In accordance with the results of [4, 5] left-slope widths $\sigma_L$ (fig.3 b, d) are larger than the right-hand side ones.

3. Conclusions

The parameterization of velocity distributions obtained in the projectile fragmentation reactions of $^{18}$O beam on $^9$Be and $^{181}$Ta targets at 35 $A$ MeV beam energy with a modified asymmetric Gaussian expression was completed. The results show that the mechanism of these types of reactions is complicated; the data indicate competition between direct and dissipative components. The direct component is prevailing forming the larger part of the cross-section of the reaction. The direct component follows the Goldhaber predictions. However the normalization parameter is smaller than that predicted by Goldhaber for the collisions at larger energies. The nature of the left-hand side peak and its connection with dissipative mode of the reaction has to be investigated in more detail. It is shown that transport model calculations can be used for describing dissipative component of fragmentation reactions.

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