

# ANALYSIS OF VELOCITY AND ISOTOPE DISTRIBUTIONS IN PROJECTILE FRAGMENTATION REACTIONS OF $^{18}\text{O}$ AT 35 MEV/NUCLEON ON $^9\text{Be}$ AND $^{181}\text{Ta}$ TARGETS

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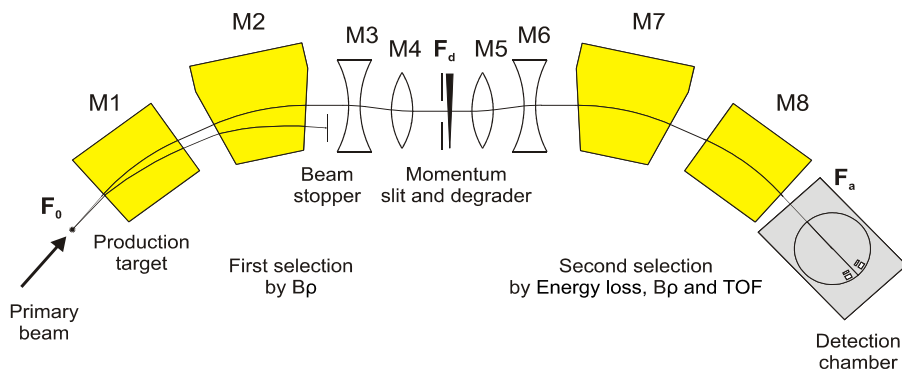
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# Abstract

Up to date analysis of velocity and isotope distributions of light fragments obtained in the projectile fragmentation reactions of  $^{18}\text{O}$  at 35 MeV/nucleon on  $^9\text{Be}$  and  $^{181}\text{Ta}$  targets measured at COMBAS fragment separator at the U400M Research Facility in JINR [1] 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 [2,3]. The discussion of the different mechanisms involved in these types of the reactions is given.

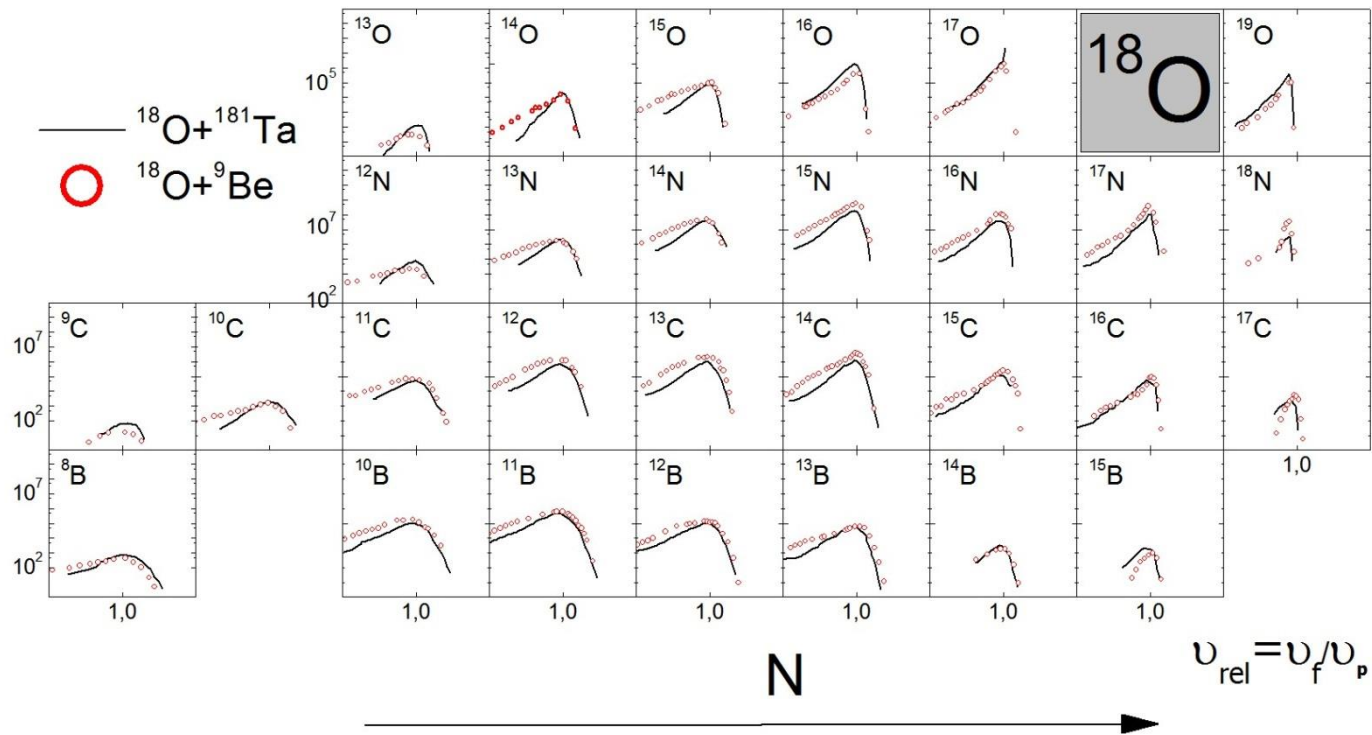
# The experimental details

- 14-mg/cm<sup>2</sup> <sup>9</sup>Be and <sup>181</sup>Ta target foil was irradiated with a 35A-MeV <sup>18</sup>O beam of (electric) intensity up to 2 μA from the U-400M cyclotron installed at the Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research (JINR, Dubna). The target was placed at the entrance focus of the COMBAS separator (Fig. 1). The diameter of the beam spot on the target did not exceed 3 mm. Nuclear products emitted at forward angles within a COMBAS solid angle (6.4 msr) were separated from the intense beam of bombarding particles by magnetic rigidity and identified by the mass number A and atomic number Z with a (ΔE, E) telescope placed at the exit achromatic focus of the COMBAS separator. The yields of isotopes were measured by scanning the range of magnetic rigidities covering the velocity distributions of the 2 ≤ Z ≤ 11 light element isotopes studied here. The products were detected in the achromatic focus F<sub>a</sub> by a telescope consisting of silicon detectors—ΔE1(0.38 mm, 60 × 60 mm<sup>2</sup>), ΔE2 (3.5 mm, Ø60 mm), and E (7.5 mm, Ø60 mm)—and were identified by the nuclear charge and by the mass number by combining two methods: magnetic rigidity and (ΔE, E):
- $E = (B\rho)^2 \times Z^2/A$ , (1)
- $\Delta E \approx A \times Z^2/E$ . (2)
- Here, A, Z, and E are, respectively, the mass number, the atomic number, and the energy of the detected product. The yields of all of the isotopes are presented in relative units after the normalization of the recorded isotopic events to the monitor detector counting.

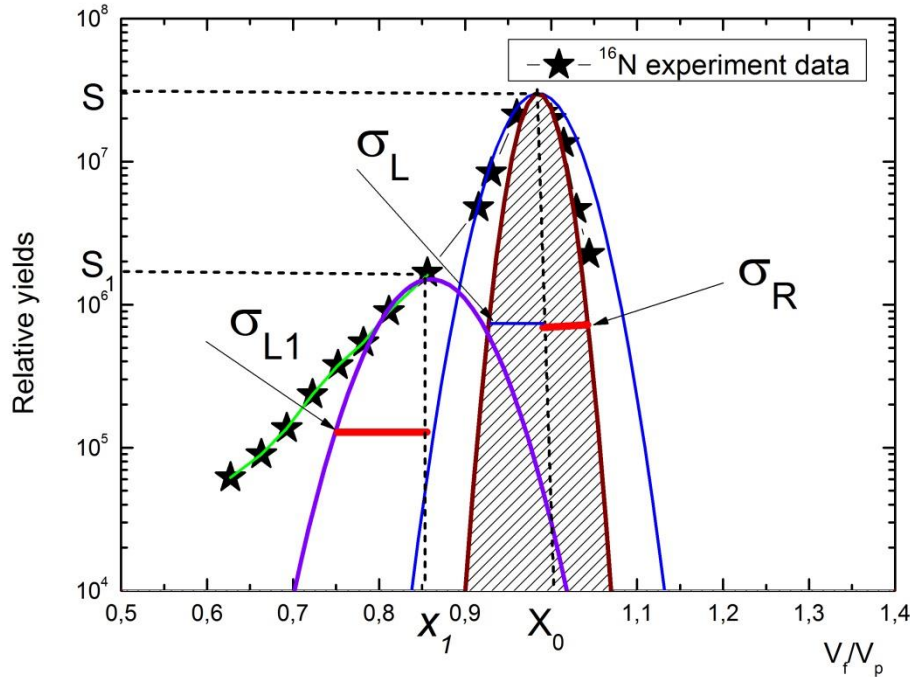


**Fig.1.** Magneto-optical scheme of the separator COMBAS **Fig.2.** View of the separator COMBAS in the experimental hall of the cyclotron U-400M (beam direction from the left to the right)

**Fig.3. Forward-angle inclusive velocity distributions (relative yields) of isotopes produced in (red)  $^{18}\text{O}(35\text{Mev/nucleon})+^9\text{Be}$  reactions and (black)  $^{18}\text{O}(35\text{Mev/nucleon})+^{181}\text{Ta}$  reactions [1].**



# Momentum distributions



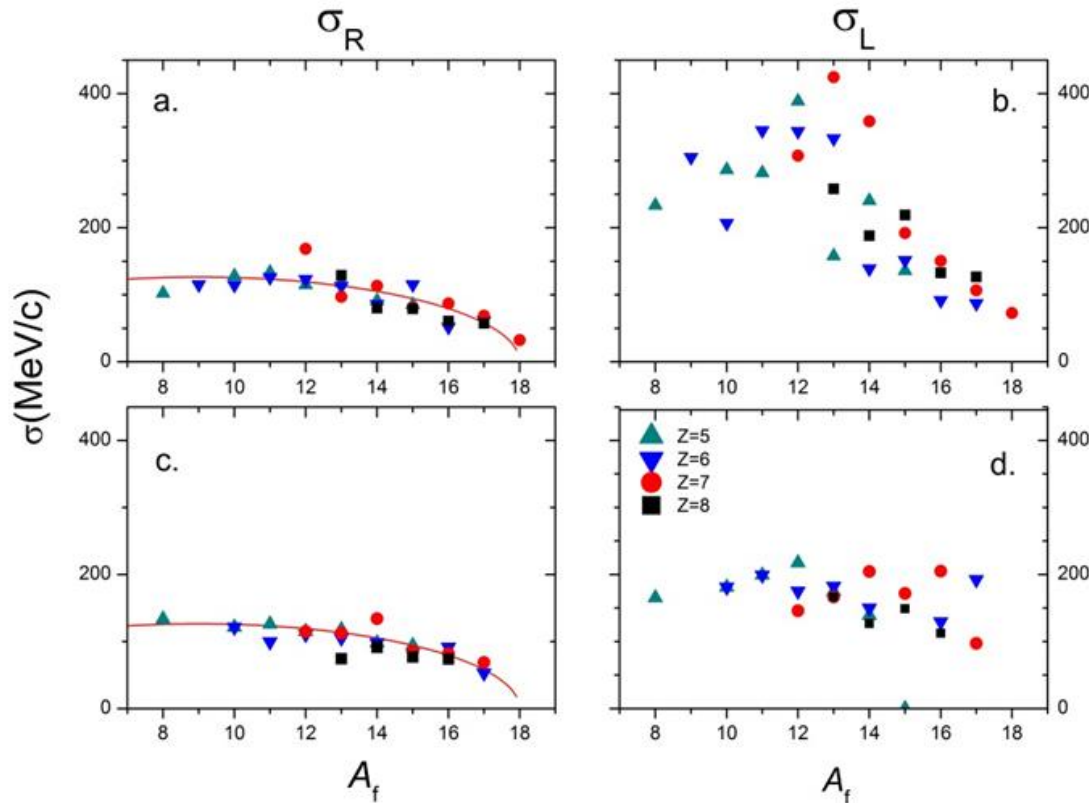
**Fig.4** . Velocity distributions for  $^{16}\text{N}$  (scattered stars) produced in fragmentation of  $^{18}\text{O}$  primary beam on Be target. The brown curve is a Gaussian fit to the right side of the velocity distribution. The left side solid curves Blue and Violet represent a sum of two Gaussians and to show the asymmetry of the experimental distributions.

The reactions of fragmentations at energies close to Fermi energy are the powerful tool in producing new isotopes. This can be helpful in producing radioactive ion-beams to study the laws of physics and also in medicine and technic. These reactions show an unexpected feature: the peak of velocity distributions for projectile-like fragments are very close to the velocity of the beam as should be expected at relativistic energies. Their right slopes can be described by a Gaussian with a width compatible with Goldhaber model [G], while the left slope has a long shoulder. In papers [2,3] the shape of velocity distributions of fragments close to the projectile are described as

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

The experiments presented in [2,3] were performed at somewhat higher energies (57 and 140 A MeV). Our data shows an additional peak at the left of the maximum of the velocity distribution. Here we present the parameterization of the velocity distribution for the reactions O+Be/Ta at 35 A MeV. Where  $S_0, X_0, \sigma_l$  and  $\sigma_r$  are the height, the position, the width of the left and right slopes,  $S_1, X_1, \sigma_{l,1}$  the same for the left peak (see Fig.4)

$$\frac{d\sigma}{dp} = \begin{cases} s \cdot \exp[-(p - p_0)^2/2\sigma_L^2] + s_1 \cdot \exp[-(p - p_1)^2/2\sigma_{L1}^2] & (p \leq p_0) \\ s \cdot \exp[-(p - p_0)^2/2\sigma_R^2] & (p > p_0) \end{cases}$$



The widths of asymmetric Gaussians describing the main peak of velocity distributions for isotope from B to O for the reactions  $^{18}\text{O}+^9\text{B}$  (panels a, b) and  $^8\text{O}+^{181}\text{Ta}$  (c, d) The lines show the predictions of Goldhaber model with the parameter 58 MeV/c.

The momentum distributions of projectile-like fragments provide valuable information about the reaction mechanism. To study this, only the isotopes with fully measured momentum distributions have been used in the analysis.

In the nuclear fragmentation process at low energies, the velocity of the fragment is smaller than that of the projectile, for part of the projectile kinetic energy has been converted into excitation energy of the fragment. This energy loss is called "momentum peak shift," it follows the solid curves in fig the predictions of the Borrel model, which suggests that the momentum peak shift can be simply explained by the amount of binding energy (8 MeV/nucleon in average) of the removed nucleons will be subtracted from the kinetic energy of the remaining part of the projectile (solid brown line in Fig.5). As we can see the velocity distributions in the case of fragmentation reactions at Fermi energy has maximum close to the beam energy that means that the more mechanisms are involved.

We also compare the experimental data [1] with the transport calculations [5]. In fig.5 the results for the positions of velocity distribution maxima are shown for hot (excited) fragments. One can see that they would predict the process to be much more dissipative.

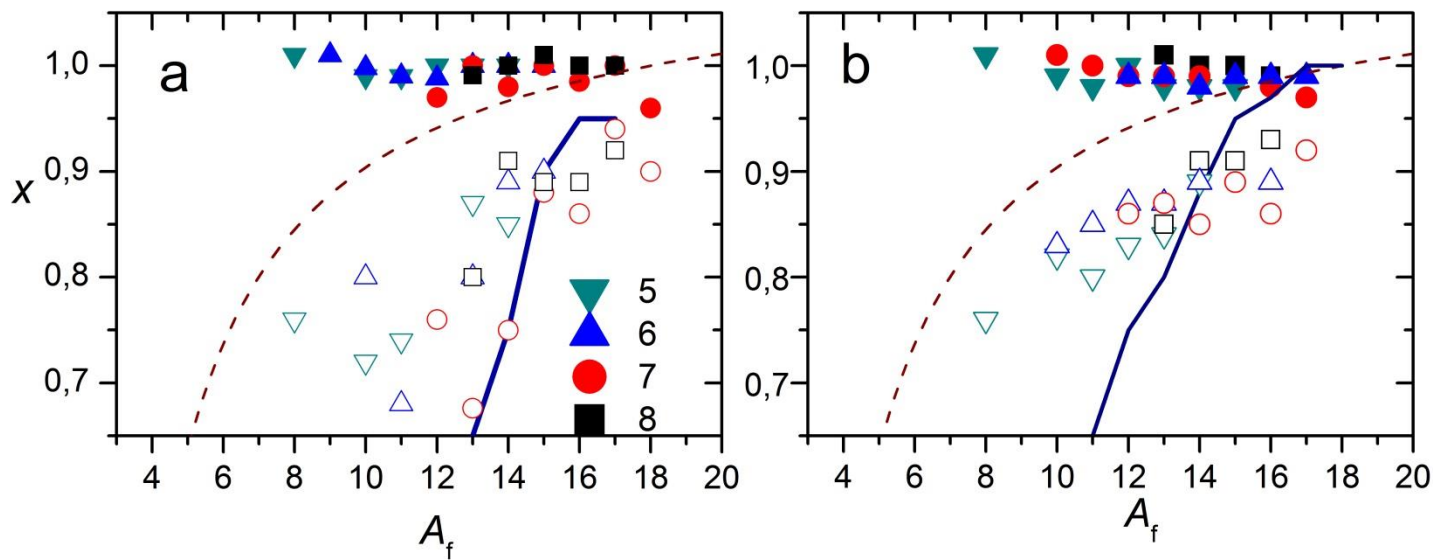
The results for the width of gaussian distributions are shown in figs 6 and 7. The right slope widths show dependence on mass number of fragments similar to the one predicted by Goldhaber for the reactions at relativistic energies[6] but with the smaller normalization constant ( $s = 58 \text{ MeV}/c$  instead of  $90 \text{ MeV}/c$ ).

In accordance with the results of [2,3] left-slope widths are higher than the right-hand side ones.

In fig. 8 the heights of main gaussians and the left hand-side gaussians are shown. The nature of the left-hand side peak should be investigated more thoroughly. We hope it could cast the light on competition between direct in dissipative processes in these type of reactions.

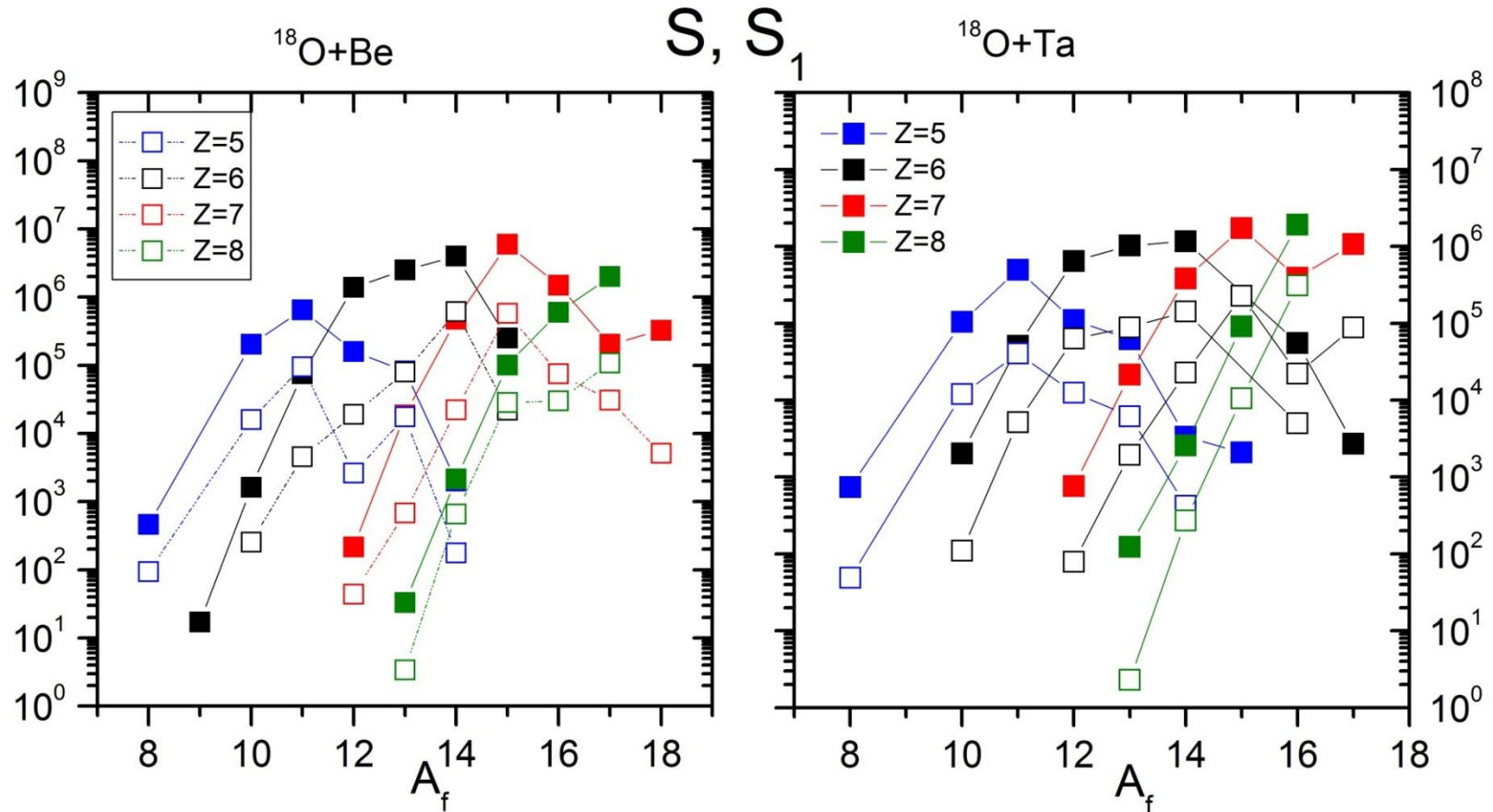


**Fig 5.** Velocities at peaks in the units of beam velocity for isotopes from B to O produced in the reactions  $^{18}\text{O}+^9\text{Be}$  (a)/ $^{181}\text{Ta}$  (b). Solid symbols-the main peak, open symbols left-hand side peak. The solid curve is the prediction of transport model calculations [6], the dashed one- of Borrel formula[7].





The heights of relative yields dependences  $S$  and  $S_1$  (see fig.4) for the reactions  $^{18}\text{O}$  at 35 MeV/nucleon on the  $^9\text{Be}$  and  $^{181}\text{Ta}$  targets.



# Conclusions

- 1. The parameterization of velocity distributions obtained in the projectile fragmentation reactions of  $^{18}\text{O}$  beam on  $^9\text{Be}$  and  $^{181}\text{Ta}$  targets at 35 A MeV beam energy with a modified asymmetric Gaussian expression was completed.
- 2. The results show that the mechanism of these types of reactions is complicated; the data show competition between direct and dissipative components. The direct component is prevailing forming the larger part of the cross-section of the reaction.
- 3. The direct component follows the Goldhaber predictions, however the normalization parameter is smaller than that predicted by Goldhaber for the collisions at larger energies.
- 4. The nature of the left-hand side peak and its connection with dissipative mode of the reaction has to be investigated in more details.
- 5. Transport model calculations are a tool to describe dissipative component of fragmentation reactions.