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SEMICLASSICAL ANALYSIS OF FRAGMENTATION OF ^{18}O-NUCLEUS ON THE ^{181}Ta AND ^{9}Be TARGETS AT 35 MeV/u

V. P. Aleshin [1], A. G. Artukh[2], B. Erdemchimeg[2,3], G. Kaminski[2,4], S. A. Klygin[2], Yu. M. Sereda[1,2], Yu. G. Teterev[2], A. N. Vorontsov[1,2]

[1] *Institute for Nuclear Research, National Academy of Sciences of Ukraine, Kyiv*
[2] *Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, Dubna, Russia*
[3] *Nuclear Research Centre of Mongolian National University, Ulanbator, Mongolia*
[4] *The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland*

In the framework of the classical-trajectory method, we analyse zero-angle yields and velocity distributions for the products of fragmentation of ^{18}O-nucleus with $Z > 2$ on the ^{181}Ta and ^{9}Be targets at the energy 35 MeV/u. The analysis is based on the hypothesis of a two-step mechanism of which the first step is stripping of few nucleons from the projectile during its motion through the target and the second step is fragmentation of the projectile residue when it already left the target. The stripping probability of a nucleon is related with the imaginary part of the nucleon-target optical potential, while fragmentation is described within the Fermi statistical breakup model. The calculations reproduce the general trends of 0^0 yields of $^{13-17}$O, $^{12-17}$N, $^{9-16}$C, $^{8,10-15}$B, $^{7,9-12,14}$Be, and $^{6-9,11}$Li nuclei, which implies that the two-step mechanism of fragmentation prevails. However, the inability of our calculations to reproduce the complex shape of the velocity spectra indicates that also the prompt disintegration of projectile within the target nucleus contributes to 0° yields.

1. Introduction

In order to clarify the mechanisms of nuclear reactions in the Fermi-energy domain, zero-angle velocity distributions for nuclei with $2 < Z < 11$ produced in the collisions of a 35 MeV/u ^{18}O beam with ^{181}Ta and ^{8}Be targets were measured in Refs. [1, 2]. The experiment was conducted at the Flerov Laboratory of Nuclear Reactions cyclotron U400M by utilising for the detection of zero-angle products an in-flight separator COMBAS [3]. The zero-angle velocity distributions of projectile-like products of stripping reactions in both systems are found to have a maximum at the beam velocity $V = V_{\rm beam}$ which broadens with the increasing number of nucleons removed from the projectile but does not change its position even for the products with $A < 10$.

This pattern suggests the idea that these reactions proceed as two-step process (see Fig. 1). First, the projectile during its motion through the target looses a certain number of nucleons, which we denote by ΔA_0. As a result one gets a primary product with the vacancies on *s*, *p*, *d* levels which moves at a velocity close to the beam velocity, if, as we suppose, ΔA_0 is much smaller than the projectile mass number $A_{\rm beam}$. Then this primary product decays in-flight primarily by neutron and proton emission that changes little its mean velocity but certainly increases the velocity dispersion.

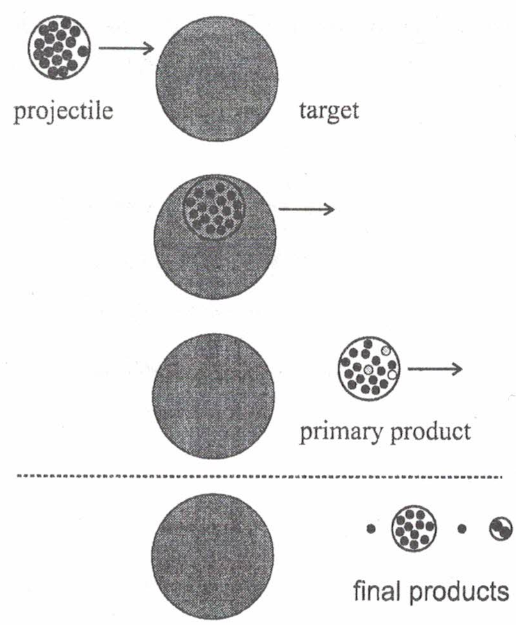

Fig. 1. Illustration of the two step process of nuclear fragmentation above the Fermi energy. Note that the Pauli's principle does not forbid the densities of two nuclei to overlap.

In this paper we develop a model, which realises this two-step mechanism and employ it to analyze the ^{18}O + ^{181}Ta and ^{18}O + ^{8}Be reactions at the beam energy of 35 MeV/u [1, 2]. In the model, the projectile constituent nucleons are treated as classical particles whose trajectories are compatible with the intrinsic wave function of the projectile, while the target nucleus is treated as an absorptive medium. This approach was suggested in [4, 5] for analysis of low-energy reactions of loosely-bound projectiles with heavy targets.

Unlike [4, 5], where the projectile wave function was that of a K-harmonic method, in this work we apply to projectiles the shell model description. The corresponding nucleonic trajectories are constructed in Sec. 2. In Sec. 3 we define the nucleon stripping rate in terms of the imaginary part of the appropriate nucleon-nucleus optical potential and construct the production cross sections of primary products. A simple description of direct population of particle-bound states in many-nucleon stripping processes is given in Sec.4. In Sec.5 we present the Fermi breakup statistical model. In Sec. 6 we apply our formalism to analyse the data. The implications of this analysis are discussed in the summary section.

2. Nucleonic trajectories

In this section we construct classical trajectories for nucleons which constitute the projectile nucleus. For simplicity we assume that the corresponding mean-field potential $U(r)$ is not depending on the spin and isospin of the nucleon and take it in the form of the harmonic oscillator potential

$$U(r) = \frac{1}{2} m\omega^2 r^2 ,$$

where m is the nucleon mass and ω is the frequency parameter.

In the following the nucleon energy is denoted as ε, the length of its angular momentum as l and the corresponding z-component as l_z. The unit orts $\{\mathbf{e}_x, \mathbf{e}_y, \mathbf{e}_z\}$ of the laboratory frame are defined so that $\mathbf{e}_y$ is directed along the beam velocity V_{beam}, while $\mathbf{e}_x$ and $\mathbf{e}_z$ are lying in a plane perpendicular to the beam. We find the values of ε, l, l_z for all nucleons of the beam nucleus from their shell-model quantum numbers, whose classical analogues are known as the action variables. In order to prescribe the classical trajectory to nucleon ε, l, l_z we then specify its angle variables φ_1, φ_2, φ_3, each of which changes between 0 and 2π. This is done using the formula $\varphi_i = 2\pi\xi_i$, i=1,2,3, where ξ_1, ξ_2, ξ_3, are the random numbers uniformly distributed between 0 and 1. Given ε, l, l_z, ξ_1, ξ_2, ξ_3, we generate the trajectory of the particle using the following procedure, illustrated in Fig. 2.

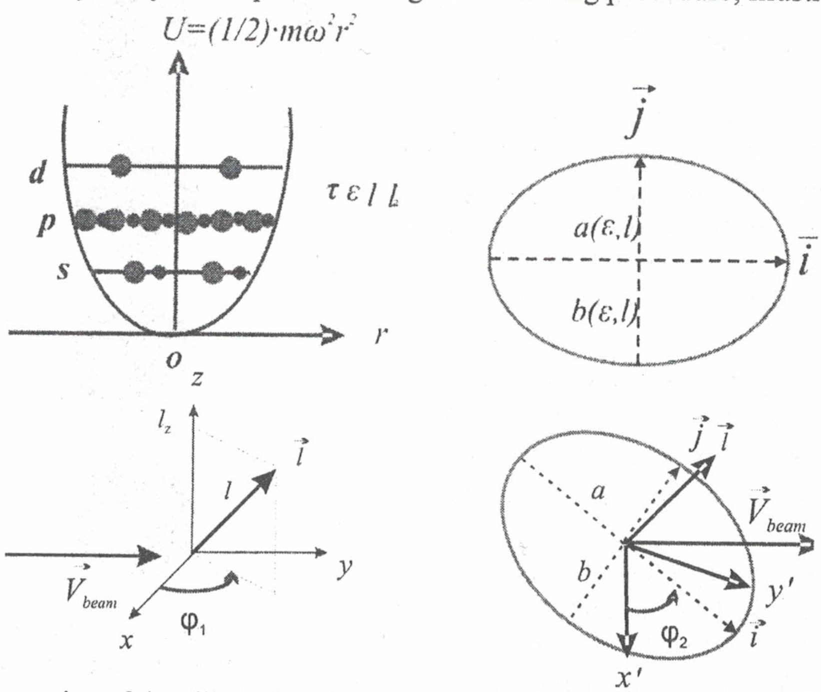

Fig. 2. Reconstruction of the elliptical orbit for given ε, l, l_z with the aid of φ_1 and φ_2. The axis x' is perpendicular to $\boldsymbol{l}$ and the beam directions; the axis y' is perpendicular to $\boldsymbol{l}$ and to the x'-axis.

The orbit of the particle, bound in the harmonic oscillator potential is an ellipse. Given ε and l the semi axes of this ellipse are given as

$$a = c\sqrt{1+d}\,, \quad b = c\sqrt{1-d}\,,$$

$$c = \frac{1}{\omega}\sqrt{\frac{\varepsilon}{m}}\,, \quad d = \sqrt{1-\left(\frac{l\omega}{\varepsilon}\right)^2}\,.$$

Given l and l_z, we use angle $\varphi_1 = 2\pi\xi_1$ to fix the two remaining projections l_x and l_y of the angular momentum vector $\boldsymbol{l}$ in the laboratory frame defined above:

$$l_x = \sqrt{l^2 - l_z^2}\cos\varphi_1\,, \qquad l_y = \sqrt{l^2 - l_z^2}\sin\varphi_1\,.$$

Once $\boldsymbol{l}$ is known we introduce the 2-dimensional Cartesian coordinate system in the plane of the particle orbit with the orts

$$\boldsymbol{e}_{x'} = \frac{\boldsymbol{V}_{\text{beam}} \times \boldsymbol{l}}{|\boldsymbol{V}_{\text{beam}} \times \boldsymbol{l}|}\,, \qquad \boldsymbol{e}_{y'} = \frac{[\boldsymbol{V}_{\text{beam}} \times \boldsymbol{l}] \times \boldsymbol{l}}{|[\boldsymbol{V}_{\text{beam}} \times \boldsymbol{l}] \times \boldsymbol{l}|}\,,$$

where $|\boldsymbol{a}|$ denotes the modulus of $\boldsymbol{a}$. The unit vectors $\boldsymbol{i}$ and $\boldsymbol{j}$ pointing along the main axes of the ellipse are then defined as

$$\boldsymbol{i} = \boldsymbol{e}_{x'}\cos\varphi_2 + \boldsymbol{e}_{y'}\sin\varphi_2\,, \quad \boldsymbol{j} = \boldsymbol{e}_{x'}\sin\varphi_2 - \boldsymbol{e}_{y'}\cos\varphi_2\,,$$

where $\varphi_2 = 2\pi\xi_2$. Finally, the nucleonic trajectory in the projectile-fixed frame is given by

$$\boldsymbol{r}(t;\vec{\xi}) = \boldsymbol{i}\cdot a\cos(\omega t + \varphi_3) + \boldsymbol{j}\cdot b\sin(\omega t + \varphi_3)\,,$$

where $\varphi_3 = 2\pi\xi_3$ fixes the position of the particle at $t = 0$.

3. Stripping stage

Let j = 1,2,…, J, where $J = A_{\text{beam}}$, count the single-particle quantum states in the projectile. Given 3 random numbers $\vec{\xi}_j = (\xi_1, \xi_2, \xi_3)_j$ uniformly distributed in (0,1) for a nucleon number j (that is the nucleon in the state j) we use the procedure of previous section to find its trajectory $\boldsymbol{r}(t;\vec{\xi}_j)$ in the body fixed frame and eventually its trajectory $\boldsymbol{r}(t;\vec{\xi}_j;\boldsymbol{b})$ in the laboratory frame:

$$\boldsymbol{r}(t;\vec{\xi}_j;\boldsymbol{b}) = \boldsymbol{r}(t;\vec{\xi}_j) + \boldsymbol{V}_{\text{beam}}t + \boldsymbol{b}\,,$$

where $\boldsymbol{b}$ is the impact-parameter vector. This expression is used not only in the approach stage of the reaction, but also when the projectile moves through the target. The Pauli blocking does not forbid doing this if the beam velocity exceeds the Fermi velocity as is assumed in this paper.

During traversal of the target by the projectile the nucleon j can be either absorbed in the target or it can survive the absorption. In the latter case its orbit is distorted, but we shall assume that it is possible to disregard the distortion effects. This assumption is known as the frozen internal-motion approximation. According to [6], in the d- and ^{6,7}Li-induced reactions treated as three-body problem, which can be solved exactly, this approximation becomes reasonable for incident energies exceeding 30 MeV/u. In [7 - 9] the frozen internal-motion approximation was used in the studies of 2-neutron stripping within the four-body approach.

It is convenient to denote the stripping probability and the survival probability for nucleon j as $T(0;\vec{\xi}_j;\boldsymbol{b})$ and $T(1;\vec{\xi}_j;\boldsymbol{b})$, respectively. Given $\boldsymbol{r}(t;\vec{\xi}_j;\boldsymbol{b})$, we find them from the formulas

$$T(1;\vec{\xi}_j;\boldsymbol{b}) = \exp\left(-2\int_{-\infty}^{\infty} dt\,|W(\boldsymbol{r}(t;\vec{\xi}_j;\boldsymbol{b}))|/\hbar\right),$$

$$T(0;\vec{\xi}_j;\boldsymbol{b}) = 1 - T(1;\vec{\xi}_j;\boldsymbol{b}),$$

where $W(\boldsymbol{r})$ is the imaginary part of the optical potential describing interactions of nucleons with the target nucleus. In the following we treat $\boldsymbol{b}$ as a random vector, given by

$$\boldsymbol{b}(\eta,\zeta) = R_{\text{int}}\eta\cdot(\boldsymbol{e}_x\sin 2\pi\zeta + \boldsymbol{e}_z\cos 2\pi\zeta),$$

where η, ζ are the random numbers uniformly distributed between 0 and 1 and R_{int} is the nucleus-nucleus interaction radius.

Let $\{n_1, n_2, ..., n_J\}$ be the set of occupation numbers, characterizing some primary product with $n_j = 0$ (1) if the state j is empty (occupied). Then neutron number N_0, proton number Z_0, excitation energy E_x, and velocity V_0 of this product are calculated as

$$N_0 = \sum_j (\frac{1}{2} + \tau_j) n_j, \qquad Z_0 = \sum_j (\frac{1}{2} - \tau_j) n_j,$$

$$E_x = \sum_j \varepsilon_j n_j - \sum_j \varepsilon_j n_j^{g.s.}, \qquad V_0 = (N_0 + Z_0)^{-1} \sum_j n_j \boldsymbol{v}_j,$$

while the probability for this product to emerge is the following

$$P(n_1 n_2 ... n_J; \vec{\xi}_1 \vec{\xi}_2 ... \vec{\xi}_J; \eta, \zeta) = \prod_{j=1}^{J} T(n_j; \vec{\xi}_j; \boldsymbol{b}(\eta,\zeta)).$$

Here, τ_j is the isospin of the state j (τ = 1/2 for neutron and -1/2 for proton), $n_j^{g.s.}$ is the value of n_j in the lowest shell-model configuration of a nucleus with $Z = Z_0$ and $N = N_0$ and $\boldsymbol{v}_j$ is the velocity of the jth nucleon at $t = 0$.

The differential cross section for the production of a nucleus with Z_0 protons, N_0 neutrons and excitation energy E_x is given by

$$\frac{d^3\sigma^c}{d^3V_0} = 10\times\frac{2\pi R_{\text{int}}^2}{\Delta V^3}\frac{1}{\mathcal{N}}\sum_{\{n_1 n_2 ... n_J; \vec{\xi}_1\vec{\xi}_2...\vec{\xi}_J;\, \eta,\zeta\}\to(c,V_0)} \eta P(n_1 n_2 ... n_J; \vec{\xi}_1 \vec{\xi}_2 ... \vec{\xi}_J;\, \eta,\zeta), \qquad (1)$$

with $\mathcal{N}$ being the total number of nucleus-nucleus collisions sampled by the Monte Carlo method. The sum is running over those sets $\{n_1, n_2, ..., n_J; \vec{\xi}_1, \vec{\xi}_2, ..., \vec{\xi}_J;\, \eta, \zeta\}$, which lead to the primary quasi-projectile $c = \{N_0, Z_0, E_x\}$, having the velocity within a cube centred at V_0 with the side length ΔV. The interaction radius has the form $R_{\text{int}} = r_{0i}(A_{\text{beam}}^{1/3} + A_{\text{target}}^{1/3})$ fm. The factor 10 in Eq. (1) is inserted to transform the units of fm^2 to millibarns.

It is evident that the account for interactions between projectile and target nucleons by means of the frozen internal motion approximation overestimates the cross sections for the primary products with large $\Delta A_0 \equiv A_{\text{beam}} - (Z_0 + N_0)$. Indeed, contrary to this approximation, after stripping of big number of nucleons the projectile residue becomes in fact a cloud of alpha particles and nucleons not driven any longer by common mean-field potential, which implies a strong declining in the yields of primary products for big ΔA_0. In the following we calculate $d^3\sigma^c / d^3V_0$ according to (1) at $\Delta A_0 = 1 \div \Delta A_c$ and put it equal 0 for $\Delta A_0 > \Delta A_c$, where ΔA_c is fitting parameter.

4. Stripping to particle-bound states

In order to find the cross sections for many-nucleon stripping to quasi-projectile states with too little excitation energy to permit further particle-emission de-excitation it is necessary to know the wave functions of those states, which requires accounting for residual interactions and the difference in the mean field potentials of projectile and quasi-projectile. Incorporation of such structure calculations [10] into many-nucleon stripping reactions is a difficult problem, whose solution is still limited to stripping of no more than 2 nucleons [9]. Therefore in the present work we account for the effects of residual interactions and *Z*, *N*-variation of the mean field with the aid of an approximate procedure, extending somewhat the model of Ref. [11].

Qualitatively, owing to the above effects, cross section $\sigma_{Z_0,N_0}^{E_x=0}$ to populate $E_x = 0$ shell-model configurations of (Z_0, N_0)-nucleus will spread over both particle- bound and unbound states of this nucleus. To account for the spreading to unbound states we multiply $\sigma_{Z_0,N_0}^{E_x=0}$ with the ablation factor F_{Z_0,N_0} and add $(1 - F_{Z_0,N_0})\sigma_{Z_0,N_0}^{E_x=0}$ to the cross section $\sigma_{Z_0,N_0}^{E_x=\hbar\omega}$ to populate its shell model configurations with $E_x = \hbar\omega$. Following [11], F_{Z_0,N_0} will be defined as

$$F_{Z_0,N_0} = \int_0^{S_{Z_0,N_0}} dE_x \left[\int_0^\infty de_1 f(e_1) \int_0^\infty de_2 f(e_2) ... \int_0^\infty de_z f(e_z) \delta(e_1 + e_2 + ... + e_z - E_x) \right], \tag{2}$$

where S_{Z_0,N_0} is the particle emission threshold for the nucleus (Z_0, N_0), $z = \Delta A_0$ is the number of stripped nucleons and *f*(*e*) is the distribution function over the excitation energy *e* of a nucleus emerging in a one-nucleon stripping process. For simplicity, we take *f*(*e*) in the exponential form $f(e) = \langle e \rangle^{-1} \exp(-e / \langle e \rangle)$, where $\langle e \rangle$ is a fitting parameter, one and the same for all Z_0, N_0.

Inserting in (2) the standard presentation $\delta(e) = (2\pi)^{-1} \int_{-\infty}^{\infty} dt \exp(iet)$ for the δ-function, we may perform the integrals over e_1 e_2, ..., e_z explicitly to obtain

$$F_{Z_0,N_0} = \frac{1}{(-i)^{z-1}} \int_0^q dp \frac{1}{2\pi i} \int_{\infty}^{-\infty} d\tau \frac{\exp(-ip\tau)}{(\tau - (-i))^z},$$

where $q = S_{Z_0,N_0} / \langle e \rangle$. By closing the contour of integration over τ with the semicircle of infinite radius in the lower half plane of complex τ, we find

$$F_{Z_0,N_0} = \frac{1}{(-i)^{z-1}} \int_0^q dp \frac{1}{(z-1)!} \left[\frac{d^{z-1}}{d\tau^{z-1}} \exp(-ip\tau) \right]_{\tau=-i} = \frac{1}{(z-1)!} \int_0^q dp p^{z-1} \exp(-p). \tag{3}$$

Upon expansion of the exponent into the Taylor series and integration over *p* we obtain for F_{Z_0,N_0} an infinite series, identical to equations (5), (6) of Ref. [11]. A finite series expression for it results on using the tabulated formula

$$\int dp p^n \exp(-p) = -n! \exp(-p) \sum_{s=0}^{n} \frac{p^s}{s!}.$$

The expression reads

$$F_{Z_0,N_0} = 1-\exp(-q)\sum_{s=0}^{z-1}\frac{q^s}{s!}, \qquad q = S_{Z_0,N_0}/\langle e\rangle . \tag{4}$$

5. Fragmentation of primary quasi-projectiles

For treating the particle-emission decay of primary quasi-projectiles, which emerge in the first step of the two-stage process, we use the Fermi breakup statistical model in which an excited nucleus decays at once into several fragments. This model was initially designed [12] and developed formally [13] in order to describe the multiplicity of mesons produced in p-p and π-p collisions. Detailed description of the model formalism in both relativistic and non relativistic cases within the context of multi-meson production may be found in Ref. [14].

The idea of using the general concept of the Fermi breakup model to simulate the explosive-like disintegration of light nuclei was proposed by Zdanov and Fedotov [15]. Gradsztain *et al.* [16] realized this suggestion to treat de-excitation of remnants of intra-nuclear cascade in the p + ^{12}C reaction at 156 MeV. Quite satisfactory agreement for the yields of ^{6}He, $^{6\text{-}9}$Li, ^{9,10}Be, ^{10,11}B, and ^{10,11}C nuclides was obtained. The detailed account of the present status of the Fermi breakup model of nuclear fragmentation may be found in Ref. [17].

According to the Fermi breakup model, the rate at which a nucleus with the mass M_0 and excitation energy E_x decays into a channel containing k "particles" with masses M_i and spins s_i ($i =$ = 1,..., k) is given by

$$\Delta\Gamma \sim \frac{S}{G} V_f^{\,k-1} M_0^{-3/2}\left(\prod_{i=1}^{k} M_i\right)^{3/2} \frac{(2\pi)^{(3/2)(1-k)}}{\Gamma(\frac{3}{2}(k-1))}\left(E_{kin}-U_f^C\right)^{(3/2)k-5/2}, \tag{5}$$

where $S=\prod_{i=1}^{k}(2s_i+1)$ is the spin-degeneracy factor, $G = p_1!\,p_2!...$ is the particle identity factor (p_b denotes the number of particles of sort b), V_f is the frieze-out volume of the decaying system,

$$E_{\rm kin} = E_{\rm x} + M_0c^2 - \sum_{i=1}^{k} M_i c^2$$

is the total kinetic energy of all outgoing particles, U_f^C plays the role that the Coulomb barrier plays in the case of the two-particle decay.

As, for the moment, we have no simple picture leading to Eq. (5), the quantities V_f and U_f^C therein are defined heuristically. In this paper $\Delta\Gamma$ are calculated with the aid of the code RAZVAL, designed by Botvina as subroutine of the code for the statistical multifragmentation model [18]. It should be noted that excited nuclei are also treated in RAZVAL as particles if their excitation energy is lower than the particle emission threshold. In addition, for few unstable nuclei, the most long living resonance is treated as particle and its sequential decay is followed.

RAZVAL is a Monte Carlo code. Given Z_0, N_0, E_x , and V_0 of the decaying nucleus as input, it returns, for one call, the total number of emitted particles k and the charge number Z_i, mass M_i and velocity V_i for each product of the decay i = 1, 2,…, k. The set k, Z_i, M_i is generated using $\Delta\Gamma$, while V_i are generated on the basis of the velocity distribution

$$\delta\left(M_0V_0 - \sum_{i=1}^{k} M_i V_i\right) d^3V_1 d^3V_2 ... d^3V_k .$$

6. Analysis of experimental data

Now we apply the above formalism to analyse fragmentation of ^{18}O-nucleus on the ^{181}Ta and ^{9}Be targets at the beam energy of 35 MeV/u. In calculations described below, the energies of s,

p, d levels in ^{18}O were taken equal to 3/2, 5/2 and 7/2$\hbar\omega$, respectively, with $\hbar\omega = 40A_{beam}^{-1/3}$ [19]. The angular momentum for s, p, d orbits was taken 1/2, 3/2, and 5/2 $\hbar$, respectively. The proton-^{181}Ta and proton-^{9}Be absorptive potentials were taken from [20] and [21], respectively. Absorptive potentials for neutrons were taken the same as for protons. Parameter r_{0i} of the nucleus-nucleus interaction radius was 1,4 fm. The list of "particles" in RAZVAL was extended to include the spectroscopic characteristics of ^{17}O, ^{17}N [22] and their excited states [23].

Evaluating the 0th, 1st and 2nd moments of $d^3\sigma^c / d^3V_0$ as a function of V_0 with the aid of Eq. (1) we can find the total cross section σ^c, mean values $U_{\parallel}^c$, $U_{\perp}^c$ and dispersions $\Delta_{\parallel}^c$, $\Delta_{\perp}^c$ of the parallel and perpendicular to the beam components of V_0. With these parameters we can construct the Gaussian approximation for $d^3\sigma^c / d^3V_0$ and compare it with $d^3\sigma^c / d^3V_0$ itself. Such comparison is made in Fig. 3 for few representative cases. We see that Gaussian approximations to $d^3\sigma^c / d^3V_0$ reproduce them in a sufficiently large neighbourhood of the maximum. This enabled us to generate V_0, to be supplied as input to RAZVAL, with the aid of normally distributed random numbers [24] and parameters σ^c, $U_{\parallel}^c$, $U_{\perp}^c$, $\Delta_{\parallel}^c$, $\Delta_{\perp}^c$. The calculations show that $U_{\parallel}^c$ are very close to V_{beam} for small ΔA_0 and slightly grow, when ΔA_0 increases. Therefore we put $U_{\parallel}^c = V_{beam}$ for all c.

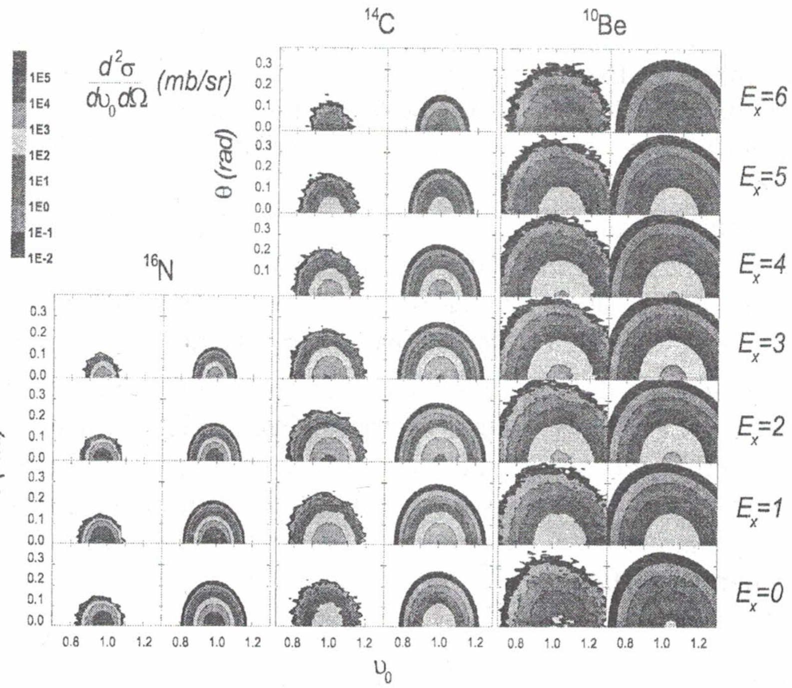

Fig. 3. Comparison of $d^2\sigma^c / d\upsilon_0 d\Omega \equiv V_0^2 V_{beam} d^3\sigma^c / d^3V_0$ (left columns) with the Gaussian distributions (right columns) in the ^{18}O(35 MeV/u) + ^{181}Ta collisions. The excitation energy E_x of primary quasi-projectiles ^{16}N, ^{14}C and ^{10}Be is in units of $\hbar\omega \approx 15$ MeV.

In Fig. 4, we show the measured and calculated zero-angle velocity distributions for $^{13\text{-}17}O$, $^{12\text{-}17}N$, $^{9\text{-}16}C$, $^{8,10\text{-}15}B$, $^{7,9\text{-}12,14}Be$, and $^{6\text{-}9,11}Li$ nuclei from the ^{18}O(35 MeV/u) + ^{181}Ta reaction. In these calculations we account for break up of primary excited products with Z_0 = 3÷8 and N_0= 3÷10. Ablation factor F_{Z_0,N_0} was found from Eq. (5) with $\langle e \rangle$= 5 MeV for A_0= Z_0+N_0 = 14÷17 and it was taken zero for A_0 < 14. The number of samples was 1,5 · 10^4 in the stripping stage and about 5 · 10^4 for each c = {N_0, Z_0, E_x} in the breakup stage. Since experimental cross sections are given in [1, 2] up to an unknown universal factor, we normalised them by the requirement for the maximum of the velocity spectrum for ^{16}O to coincide with the model prediction.

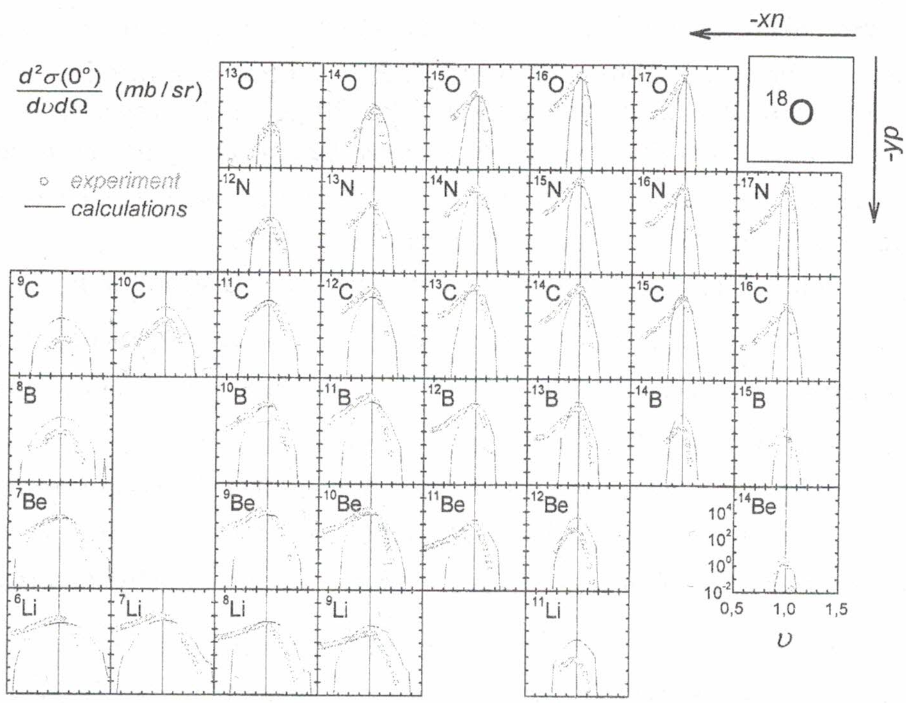

Fig. 4. Zero-angle velocity distributions for $^{13\text{-}17}$O, $^{12\text{-}17}$N, $^{9\text{-}16}$C, $^{8,10\text{-}15}$B, $^{7,9\text{-}12,14}$Be, and $^{6\text{-}9,11}$Li nuclei from the ^{18}O(35 MeV/u) + ^{181}Ta collisions. Experimental data are shown as circles, the calculations as solid lines. The vertical lines indicate the position of the beam velocity. The quantity $\upsilon = V_i/V_{beam}$ is the nucleus velocity in units of the beam velocity. The Friedman-Tsang procedure is applied. No cutting of hot sources.

Zero-angle yields $d\sigma(0°)/d\Omega$ of $^{13\text{-}17}$O, $^{12\text{-}17}$N, $^{9\text{-}16}$C, $^{8,10\text{-}15}$B, $^{7,9\text{-}12,14}$Be, and $^{6\text{-}9,11}$Li nuclei obtained by summation of the velocity spectra from Fig. 4 are plotted in Fig. 5, *a*. One can see that the yields of products with $A \geq 14$ are reasonably reproduced by calculations, whereas those for $A < 14$ are strongly over predicted. The calculations of $d\sigma(0°)/d\Omega$ shown in Fig. 5, *b* were performed by putting $\sigma^c = 0$ for $A_0 < 14$. One observes noticeable improvement of the description of the yields of products with $A < 14$. The same cut-off was applied in Fig. 6, where we compare the calculated and measured zero-angle yields of the same nuclei produced in the reaction ^{18}O(35 MeV/u) + ^{9}Be. From Fig. 5, *b* and 6 we see that (*Z*, *A*) distributions for fragmentation products of ^{18}O on very light target (^{9}Be) are similar to those on very heavy one (^{181}Ta). This similarity is reproduced by our calculations.

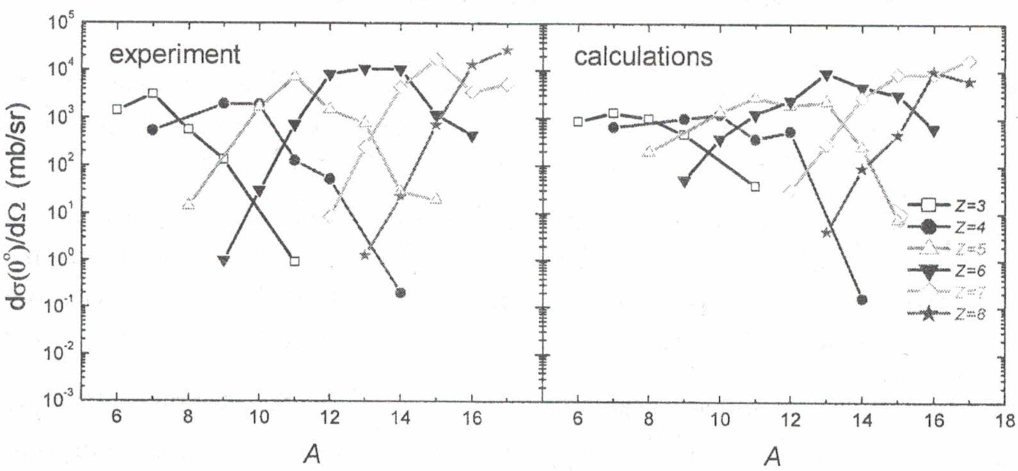

Fig. 5, *a*. Isotopic distributions in the reaction ^{18}O(35 MeV/u) + ^{181}Ta.
Left box: experiment. Right box: theory.

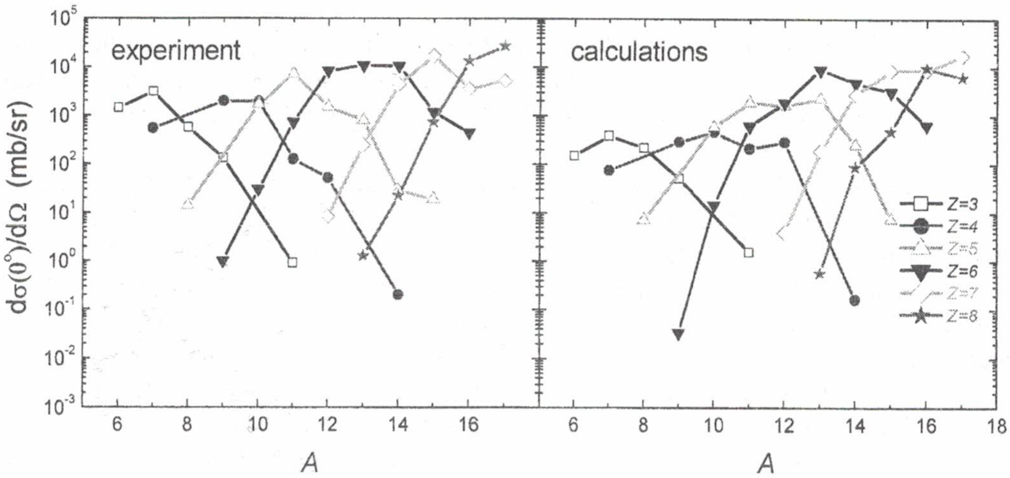

Fig. 5, *b*. Isotopic distributions in the reaction ^{18}O(35 MeV/u) + ^{181}Ta. Left box: experiment. Right box: calculations in which the cross sections for the formation of primary products with A_0 <14 were put 0.

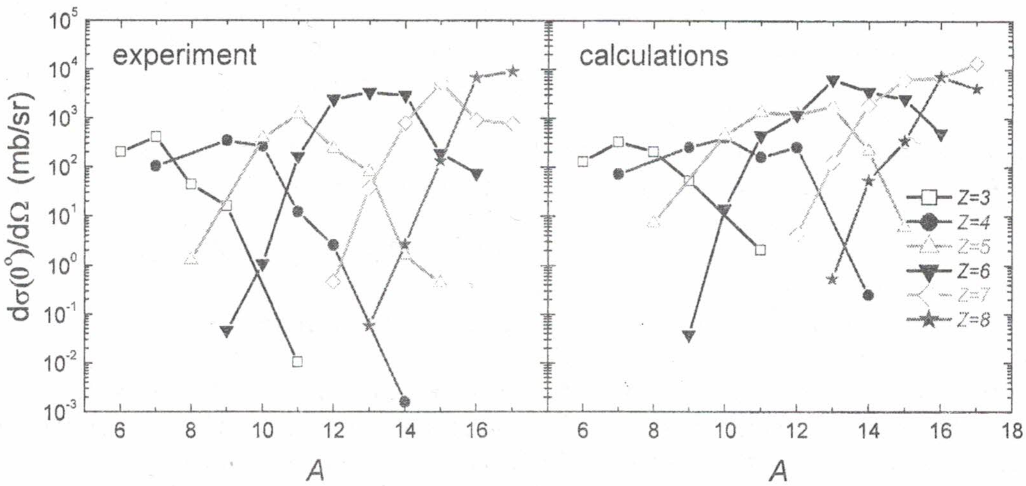

Fig. 6. The same as in Fig. 5, *b* but for the ^{18}O(35 MeV/u) + ^{9}Be reaction.

7. Concluding remarks and outlook

According to Fig. 5, *a*, 5, *b* and 6 the yields $d\sigma(0°)/d\Omega$ are reasonably reproduced by the model, if we take for two our fitting parameters the values $\langle e \rangle$=5 MeV and $\Delta A_c = 4$. From Fig. 4 one can see that calculations are not capable to reproduce the shape of measured velocity spectra. The calculated spectra may be fitted by one Gaussian, whereas the measured ones look as a sum of two Gaussians, one around $V_1 \approx V_{beam}$ and another, with much smaller magnitude, at the velocity V_2 somewhat lower than V_{beam}. It is tempting to attribute this smaller component of velocity spectra to direct disintegration of projectile within the target nucleus.

For further testing of the classical trajectory approach to fragmentation and exploring the interplay between the two-step mechanism of fragmentation and the direct disintegration inside the target it is desirable to apply this approach to fragmentation of ^{18}O-nucleus at somewhat higher energies. From this viewpoint of considerable interest are the data on products of fragmentation of ^{18}O(80 MeV/u-nucleus on ^{27}Al and ^{181}Ta targets from 0° measurements reported in [25, 26].

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НАПІВКЛАСИЧНИЙ АНАЛІЗ ФРАГМЕНТАЦІЇ ЯДРА ^{18}O НА МІШЕНЯХ ^{181}Ta ТА ^{9}Be ПРИ ЕНЕГІЇ 35 МеВ/нуклон

В. П. Альошин, А. Г. Артюх, Б. Ердемчимег, Г. Камінскі, С. О. Клигін, Ю. М. Середа, Ю. Г. Тетерев, А. М. Воронцов

У рамках методу класичних траєкторій аналізуються швидкісні розподіли та виходи продуктів фрагментації ядра ^{18}O на мішенях ^{181}Ta та ^{9}Be при енергії 35 МеВ/нуклон. Аналіз спирається на гіпотезу про двоступеневий механізм фрагментації: спочатку від ядра-снаряда, що рухається крізь мішень, зривається декілька нуклонів, а далі його залишок, залишивши мішень, розвалюється на уламки. Імовірність зриву нуклона пов'язуємо з уявною частиною оптичного потенціалу "нуклон - мішень", а фрагментацію описуємо за допомогою фермієвської моделі розвалу. Розрахунки передають загальний характер виходів ядер $^{13-17}$O, $^{12-17}$N, $^{9-16}$C, $^{8,10-15}$B, $^{7,9-12,14}$Be та $^{6-9,11}$Li під 0°, що підтверджує гіпотезу про домінуючу роль двохступінчатого механізму фрагментації. Але той факт, що розрахунки не спроможні відтворити складну форму швидкісних спектрів, вказує на те, що й раптова дезінтеграція налітаючого ядра всередині ядра мішені дає свій внесок у виходи під 0°.

ПОЛУКЛАССИЧЕСКИЙ АНАЛИЗ ФРАГМЕНТАЦИИ ЯДРА ^{18}O НА МИШЕНЯХ ^{181}Ta И ^{9}Be ПРИ ЭНЕРГИИ 35 МэВ/нуклон

В. П. Алешин, А. Г. Артюх, Б. Эрдэмчимэг, Г. Камински, С. А. Клыгин, Ю. М. Середа, Ю. Г. Тетерев, А. Н. Воронцов

В рамках метода классических траекторий анализируются выходы и скоростные распределения продуктов фрагментации ядра ^{18}O с Z >2 на мишенях ^{181}Ta и ^{9}Be при энергии 35 МэВ/нуклон. Анализ основан на гипотезе о двухступенчатом механизме: сначала от ядра-снаряда, движущегося сквозь мишень, отрывается несколько нуклонов, а потом его остаток, покинув мишень, разваливается на куски. Вероятность срыва нуклона выражаем через мнимую часть оптического потенциала "нуклон - мишень", а фрагментацию описываем с помощью фермиевской модели развала. Расчеты воспроизводят общее поведение выходов ядер $^{13-17}$O, $^{12-17}$N, $^{9-16}$C, $^{8,10-15}$B, $^{7,9-12,14}$Be и $^{6-9,11}$Li под 0°, что подтверждает гипотезу о доминирующей роли двухступенчатого механизма фрагментации. Однако тот факт, что расчеты не в состоянии передать сложную форму скоростных спектров, указывает на то, что и мгновенная дезинтеграция налетающего ядра внутри ядра мишени вносит вклад в выходы под 0°.

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