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Neutron pick-up reactions in ^{18}O (10 MeV/nucleon) + Ta

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The availability of new radioactive ion beams has broadened the study of nuclear reactions and nuclear structure. The main mechanism to produce the secondary beams is the fragmentation of the projectile. An alternative method for the production of the exotic nuclei is the multinucleon transfer. We measured production cross section for the B, C, N and O isotopes in the reaction ^{18}O + Ta and the beam energy at 10 MeV/nucleon. The cross-sections were obtained by integrating the momentum distributions of the isotopes. It was shown that in deep inelastic processes the production yields of different isotopes could be well described using statistical models and could also be explained by the Q_{gg}-systematic.

Keywords: neutron-rich nuclei, transfer reactions, heavy ions, multinucleon transfer.

Introduction

The utility of heavy-ion induced reactions is one of the most powerful experimental means to produce nuclei far from the valley of stability [1, 2]. One of the experiments carried out in Dubna using ^{22}Ne and ^{40}Ar beams of 7 MeV/nucleon resulted in the observation of about twenty exotic isotopes [2]. In these experiments, afterwards, a new heavy-ion-reaction mechanism was discovered which was called as deep inelastic transfer reactions or hot multinucleon transfer (MNT) reaction in which the transfer is mainly results of the friction mechanism accompanied by large kinematic energy dissipation and the angular distribution covers a wide range. The other important observation was that in deep inelastic processes the production cross section of isotopes was following by the values [2]. Nevertheless, the approach to the region of nuclear instability by using MNT reactions was limited by the low production cross sections and the wide angular distribution of the products.

Reactions with high-energy heavy ions on a thick target, later on, of which dominant mechanism is the fragmentation of the projectile, were used to produce many new neutron-rich light nuclei with relatively high production rates and the products were focused in forward angles. By taking advantage of the available radioactive ion beams, a tremendous success was proven to be the use of ^{48}Ca and ^{36}S beams in the fragmentation of which many new extremely neutron-rich nuclei lying close to the limit of nuclear stability were observed and investigated within the GANIL-Dubna Collaboration [3, 4]. So far, the major way to produce the secondary beams is the fragmentation of the projectile. However, the drawback of producing light exotic nuclei in fragmentation reactions depends mainly on the fact that in this situation one uses beams of relatively heavy nuclei, which are rather high-priced on condition that one desires to generate them with high intensity. Furthermore, the cross section for production of exotic nuclei in fragmentation processes declines dramatically when moving away from the stability line.

Alternative efficient method for the production of the exotic nuclei is the MNT reaction [5]. One of the crucial advents of the MNT process comparing with the fragmentation process is low excitation energy, introduced into reaction products. That could lead to higher survival probability in the case of the neutron-rich isotopes. In addition, MNT reactions occurring in low-energy collisions of heavy ions are currently considered to be the most promising method to produce unknown neutron-rich heavy nuclei and the trans-uranium nuclei, which could not be obtained by other reaction mechanisms. One the other hand, the low-energy MNT reactions may also do duty as a tool for the production and investigation of light exotic nuclei by using a neutron-rich light beam on a heavy target. Until now, this research still attracts the attention both for theoretical and experimental studies.

In MNT reaction, owing to hard-to-overcome difficulties in the beam separation at relatively low energy and to the broad transverse momentum distribution of products, only close to zero degrees, one of the measurements of production cross sections for O isotopes have been performed in Ref. [4] in the late 1990s. Recently, production cross sections and corresponding momentum distributions for the exotic nuclei obtained from a high intensity beam of ^{18}O at 8.5 MeV/nucleon impinging on a 1 mg$\cdot$cm^{-2} ^{238}U target have been measured at 0° for the first time [6] leading to the observation of exotic nuclei such as ^{15}B, ^{18,19}C, ^{20}N, ^{22}O, ^{24}F and ^{25}Ne. It was explored considerable cross sections for the production of exotic nuclei originating from the neutron transfer and proton removal from the projectile. As another conclusion, the differential reaction cross section for interested products, behaved as a function of the scattering angle, was reached its highest value at zero degree in the agreement between experimental results with calculations based on two different models of deep inelastic collision including the consideration of the particle evaporation process [5, 7]. This result is important in view of the new generation of zero degrees spectrometers under construction, such as the S3 separator at GANIL or MAVR at FLNR, for example.

Experiment

We were able to study MNT reaction induced by ^{18}O beam at 12° in laboratory system employing the availability of a magnetic spectrometer, which has the large acceptance and high efficiency, combining with high resolution detectors.

The experiment with ^{18}O beams at energy E = 10 MeV/nucleon was carried out at the U400 cyclotron of the Flerov Laboratory of Nuclear Reactions (JINR) using the high-resolution magnetic separator MSP-144 [8-10]. The target, Ta foil of 6 $mg \cdot cm^{-2}$ thick, was placed inside the scattering chamber. Identification of products was determined by measuring energy losses and residual energy by $dE - E_{\rm r}$ detectors, located in external focal plane of the MSP 144 spectrometer. A typical $dE - E_{\rm r}$ particle identification the double dimensional spectrum obtained in the telescope array is shown in Figure 1. It can be seen that an absolute separation of the He-O isotopes was achieved, allowing unambiguous identification of the reaction products.

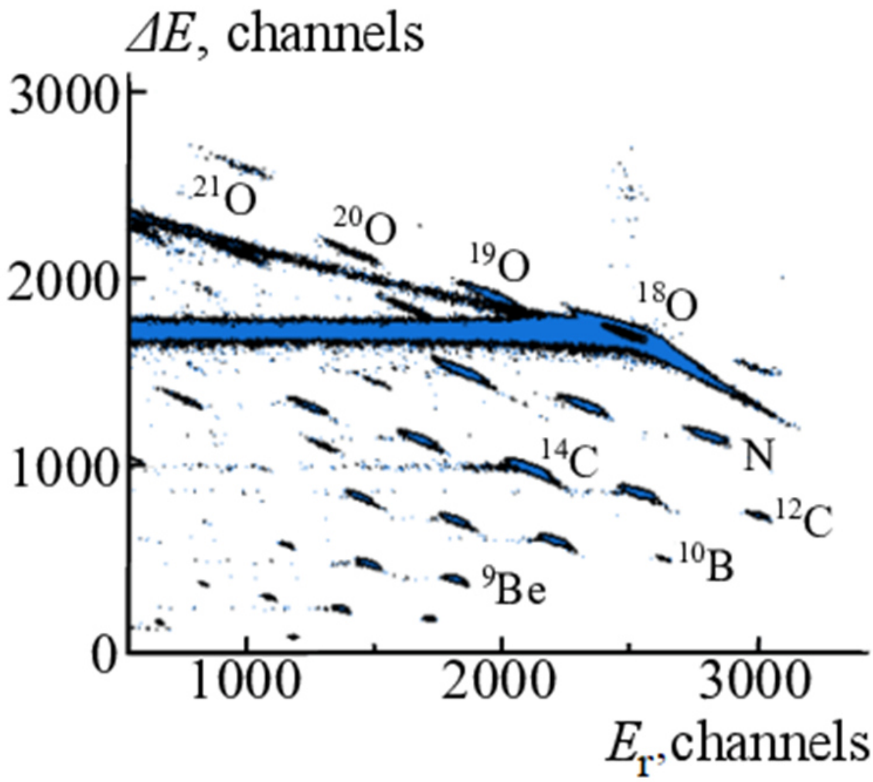

Figure 1. Identification matrix of the products of the ^{18}O (10 MeV/nucleon) + Ta reaction for energy 10 MeV/nucleon at 12° in laboratory system.

A few different magnetic settings were used to measure momentum distribution of the identified products such as C, N and O isotopes of which differential cross sections were determined by integrating the area of corresponding momentum distribution. Due to the near symmetrical shape, the momentum distributions were fitted with a Gaussian function. Figure 2 depicts the dependence of the measured differential cross section for various isotopes versus Q_{gg} value. The lines are plotted to guide to the eye. That is an evidence that the measured cross section follows to the Q_{gg}-systematics.

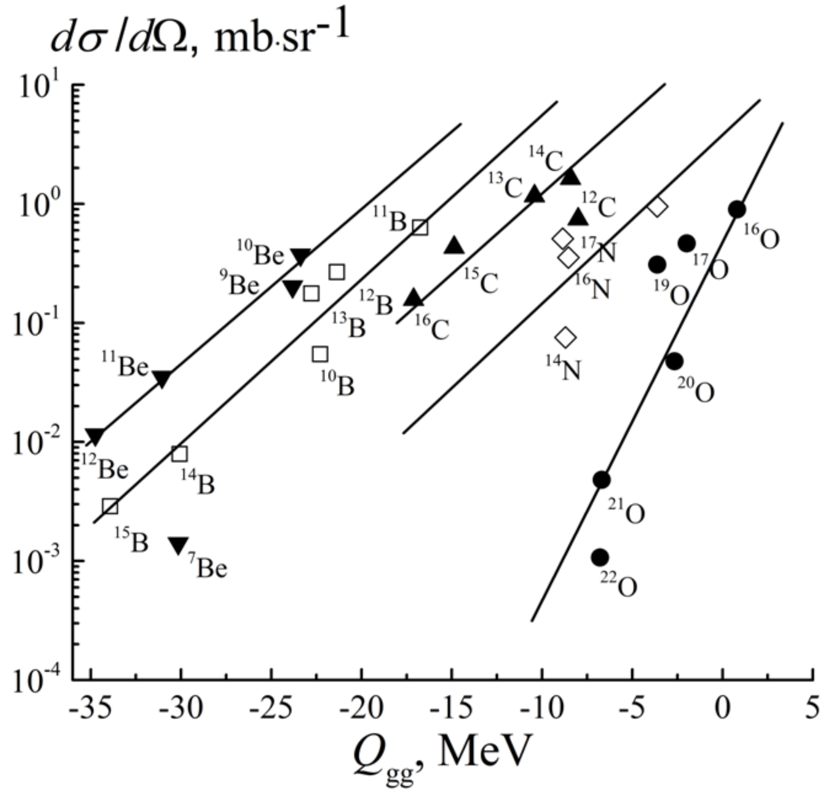

Figure 2. Experimental differential production cross sections of the ^{18}O (10 MeV/nucleon) + Ta reaction for energy 10 MeV/nucleon at 12° in laboratory system for beryllium (▼), boron (□), carbon (▲), nitrogen (◊) and oxygen (•) isotopes as a function of Q_{gg}. The lines are plotted to guide to the eye.

The transformation of the differential cross section into total cross sections was calculated by integrating over the angular distribution based on the method used in Ref. [4]. In the laboratory coordinate system, the angular distributions of products at intermediate energies can be described by the expression in following formula:

$$\frac{d^2\sigma}{d\Omega dE_A} \propto \sqrt{2AE_A}\exp\left[-\frac{A}{\sigma_p^2}\left(E_A - 2\cos\Theta\sqrt{E_A\bar{E}} + \bar{E}\right)\right] \quad (1)$$

where A and E_A are the mass number and the kinetic energy of the fragment, respectively, $\overline{E}$ is the most probable value of the energy and σ_p is the width of the fragment momentum distribution.

The yields of isotopes in deep inelastic processes are well described by the reaction energy Q_{gg} [2]. The cross sections are determined by the relation as given in Ref. [4]:

$$\sigma \sim \exp\{\left[Q_{gg} + \Delta E_C - \delta\right]/T\} \quad (2)$$

where Q_{gg} is the energy necessary for the rearrangement of the nuclei in the input channel into the nuclei in the exit channel, ΔE_C is the change in the Coulomb energy of the system due to the redistribution of protons between the nuclei and to the deformation of the system, δ is the nucleon pairing corrections, and T is the temperature of the dinuclear system.

Figure 3 illustrates the Q_{gg}-systematics for the production of oxygen isotopes obtained in various reactions, in which we compared the extracted cross-sections in the studied ^{18}O + Ta reaction to the predictions of the empirical parameterization of fragmentation cross-sections measured at various energies and different projectiles.

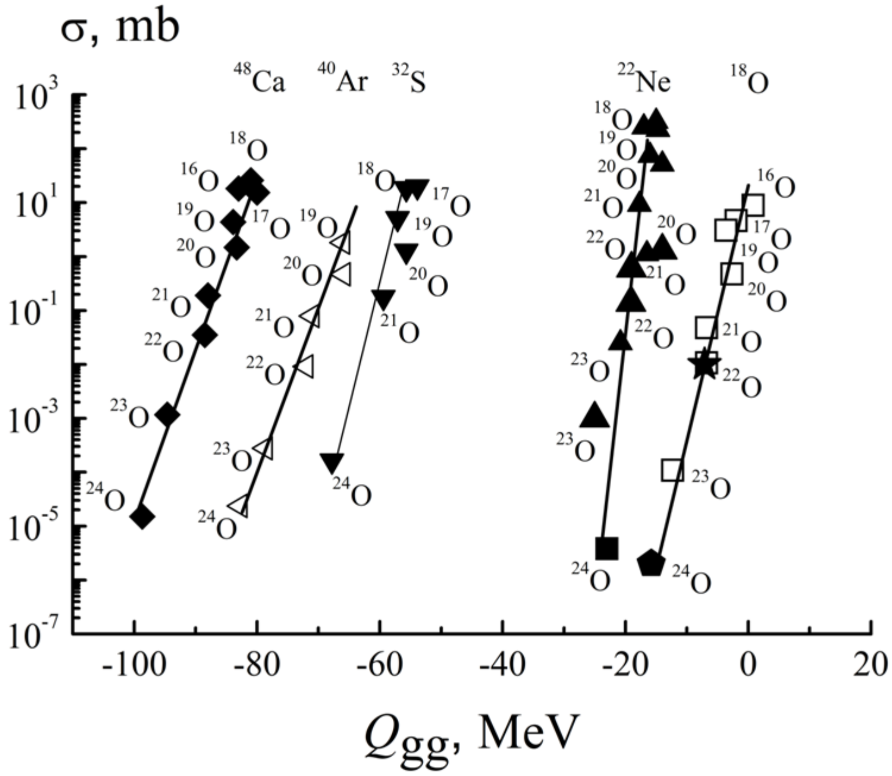

Figure 3. Q_{gg}-systematics for the production of oxygen isotopes, obtained in various reactions: ♦ for ^{48}Ca + Ta reaction [11], ◄ for ^{40}Ar + Be reaction [12], ▼ for ^{36}S + Au reaction [4], ▲ for reaction ^{22}Ne + Ta [13], □ for reaction ^{18}O + Ta, present measurement for energy 10 MeV/nucleon at 12° in laboratory system. Calculated cross section for ^{24}O according to [5] is denoted by ★ symbol. Extrapolations for ^{24}O (^{22}Ne , ^{18}O + Ta) are denoted by ■ and filled pentagon symbols.

We figured that the cross-sections of unmeasured neutron-rich oxygen isotopes could be extrapolated using a systematic trend involving the Q_{gg} energy as in formula (2). For instance, we estimated that the production cross section for ^{24}O was about $6 \cdot 10^{-5}, 3 \cdot 10^{-5}, 2 \cdot 10^{-5}$ mb for ^{48}Ca + Ta, ^{36}S + Au and ^{18}O + Ta reaction, respectively. This value is much less than that predicted by V. Zagrebaev [5]. The extrapolated cross-sections will be very useful in planning experiments with neutron-rich isotopes produced from projectile fragmentation or multinucleon transfer reaction.

Obtained differential cross sections for oxygen isotopes were analyzed by GRAZING code [7]. Figure 4 shows the comparison of the present experimental differential cross section (related to the ^{18}O + Ta reaction) and the data obtained in the reaction ^{18}O on U target [6]. Further data analyze is in progress.

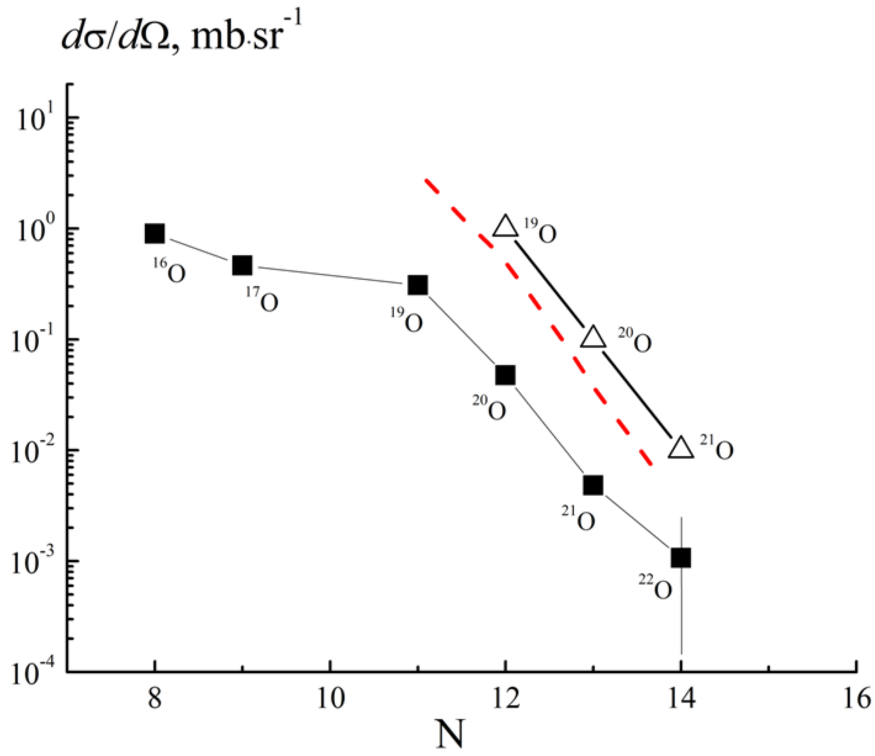

Figure 4. Comparison of the present experimental differential cross section related to the ^{18}O + Ta (■) reaction for energy 10 MeV/nucleon at 12° in laboratory system and the data obtained in the reaction ^{18}O on U target [6] (Δ) depending on the number of neutrons. Differential cross sections for oxygen isotopes calculated by GRAZING code [7] is shown by dashed curve.

Another point of view is the production yield of the neutron-rich isotopes in the case of the U-target [6] is higher than that in the case of the Ta-target (our present data) with the same projectile.

Conclusion

In summary, we measured the differential production cross sections for the B, C, N and O isotopes in the reaction ^{18}O + Ta with the beam energy at 10 MeV/nucleon by multinucleon transfer process being a promising approach. The measured differential cross section of the products follows to the Q_{gg}-systematics. The total production cross-sections transformed from differential cross sections were obtained by integrating over the momentum distributions of isotopes with $Z = 8$ (oxygen). According to the trend of Q_{gg}-values, the total cross-sections of unmeasured neutron-rich oxygen isotopes could be extrapolated which guided to estimate the production cross section of ^{24}O, for instance, being much less than that in ref. [5] in the comparison. Further, there was a fairly good agreement in production cross sections for oxygen isotopes between the experimental data and that of theoretical prediction [14], based on the frame of a Langevin-type approach. Last but not least, the dependence of O isotope production yields on the various targets has been concerned.

Acknowledgments

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