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Spallation of ^{197}Au with 4.4-GeV deuterons

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Abstract. A comprehensive set of 110 radioactive nuclide cross sections with mass numbers $22 \leq A \leq 198$ amu in the interaction of 4.4-GeV deuterons with ^{197}Au have been measured for the first time. The results including charge distributions have been parameterized in term of a 3-parameter equation in order to reproduces the isobaric distributions. Using data from the charge distributions, the total mass-yield distribution was obtained. The new experimental data of the recoil properties of reaction products were also obtained. Kinematical characteristics of the reaction products obtained from measurements of the residuals emitted in the forward and backward directions exhibit different behavior depending on the mass region. The kinematical features of reaction products have been analyzed on the basis of the two-step model of high-energy nuclear reactions and discussed in terms of the different reaction mechanisms.

1 Introduction

Spallation reactions with Au target have been investigated for many years but have not been precisely described yet. Only a few data have been accumulated for the production of reaction products in the energy range around a few GeV, mostly from proton- [1, 2] and heavy-ion-nucleus collisions [3, 4]. The studies of deuteron-induced processes are very scattered. The experiments with deuterons collisions are additionally a source that is also extremely important for scientific and technological applications. The knowledge of cross sections for different reaction channels is crucial for testing the theoretical models and codes. Investigation of deuteron-nucleus collisions is important since the deuteron represents is the lightest weakly bounded system. During the interaction with a heavy nucleus, the difference between a whole nucleus and distinct nucleons can be studied. The absence of a satisfactory theoretical description to predict isotope yields as well as the need for experimental fragment mass and charge distributions forms the motivation for this work. This experiment was performed with activation methods of the measurement of products formed in the interaction of an Au target with deuterons. The recoil data provide in addition valuable information, such as angular distributions and kinetic energies of product nuclei as well. Furthermore they deepen our understanding of the reaction mechanism.

The goal of the present work was to complete the existing data with those which are still necessary to obtain a consistent set of benchmark data for Au, namely, the determination of the isobaric-and mass-yield distribution of the reaction products. The obtained experimental data allowed one to estimate the contribution of the different reaction channels such as fragmentation, spallation and fission-like processes, and to make comparisons with the earlier studies of the proton-induced reaction.

2 Experimental Procedure

A beam of 4.4 GeV deuterons from the Nuclotron of the HEBL, JINR was used to irradiate gold a target. The target consisted of a high-purity target metal foil of size 20x20 mm^2 sandwiched exactly by one pair of Mylar foils of the same size, which collected the recoil nuclei in the forward or backward directions with respect to the beam. The thickness of each target foil was 39.13 mg/cm^2 and the Mylar foil thickness was 7.0 mg/cm^2. To improve the statistics 15 target piles were used. The irradiation time was 28.6 hours at an ion beam total intensity of about $6.43 \cdot 10^{12}$ deuterons. The residual nuclei were identified by the energy and intensity of characteristic γ-lines and by the respective half-lives of nuclei. Nuclear properties used for isotope identification were taken from literature [5]. The experiment in question was described in detail elsewhere [6]. The measurements regarding recoil nuclei were transformed into kinematical quantities using the two-step vector model of high energy nuclear reactions [7]. According to [7], the first stage of areaction involves the formation of the remnant nuclei after cascade having an excitation energy E^* and a velocity $\vec{v}$ (or the momentum $\vec{p}$) along the beam direction. In the second stage of reaction, the evaporation of nucleons and light nuclei occurs and an additional velocity $\vec{V}$ is acquired by teh residual nucleus. Thus, the velocity $\vec{V_l}$ of a recoil nuclide in the laboratory system is the sum of two vectors $\vec{V_l} = \vec{v} + \vec{V}$.

In terms of this model it was assumed that: (1) there is no correlation between the velocity $\vec{v}$ of the excited nucleus and $\vec{V}$; (2) the angular distribution of fragments in the moving frame is isotropic; (3) the mean range in the laboratory system is proportional to the fragment speed; (4) $v_\perp$ is zero.

The mathematical formalism developed in [7] makes it possible to calculate, on the basis of experimental results of the nuclides recoil out of a target in the forward and backward directions, parameters that characterize the first ($\vec{v}$, E^*) and the second stage of the interaction (R and T), where R is the range of a recoiling nucleus in the target material and T is its kinetic energy.

3 Results and Discussion

As a result of the measurements, 110 radioactive nuclide cross sections with mass number $22 \leq A \leq 198$ amu were obtained. In order to obtain a complete picture of the mass distribution of the reaction products, it is necessary to estimate the cross sections of isotopes immeasurable by the induced-activity method. In the present work the analysis of the charge distributions were obtained as the function of [1]:

$$\sigma(Z, A) = \sigma(A) \exp\left(-R \left|Z - SA + TA^2\right|^{3/2}\right), \tag{1}$$

where $\sigma(Z, A)$ is the independent cross section for a given nuclide production with atomic charge Z and mass number A; $\sigma(A)$ is the total isobaric cross section of the mass chain A. The parameter R defines the width parameter of the charge distribution and parameters S and T define the most probable charge (Z_p) for a given isobar chain A.

The values of these parameters for 4.4-GeV deuterons are

$$R = 30A^{-0.79}, \qquad S = 0.47, \qquad T = 2.3 \times 10^{-4}. \tag{2}$$

An interesting feature is that the width of charge distribution of the present work is the same as for the system ^{197}Au+p at 1.0-3.0 GeV [1], but in the present work the center of the charge distribution is shifted towards the neutron deficient side of the valley of beta-stability. There is also good agreement with the parameters $S = 0,477$ and $T = 2.4\times10^{-4}$ for the system ^{2}H+^{181}Ta at the deuterons energy of 7.3 GeV [3]. It can be proposed that the charge distributions of the fragments are mainly determined by the properties of the residual nuclei and don't depend on the way they are formed in the initial interaction.

The mass-yield obtained in this manner is shown as the solid squares in Fig. 1. The smooth curve in the Fig. 1 indicates the best fit for the mass numbers $40 \leq A \leq 198$ amu based on the experimental data, depending on the contribution from different processes such as spallation, deep spallation or fission-like binary decay and fragmentation or multifragmentation.

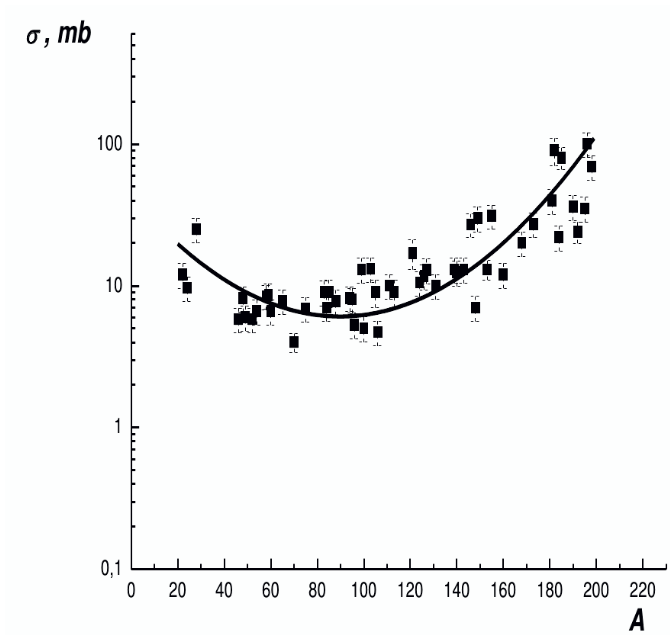

Figure 1. Mass-yield distribution at 4.4 GeV. Solid squares indicate estimated total isobaric cross sections. The solid line is the best fit through the experimental cross sections of the reaction fragments.

Integration of the mass-yield curves over mass number gives the cross section for the production of target residues 2.20±0.44 b.

Knowing the total reaction cross section the impact parameter can be estimated from the overlap parameter $b_{Tp} = 0.97$ fm calculated according to the experimental total reaction cross section using the hard sphere model [8]:

$$\sigma_R = \pi r_0^2 (A_T^{1/3} + A_p^{1/3} - b_{Tp})^2 fm^2, \tag{3}$$

where A_T and A_p are the mass numbers of the target and beam nuclei, respectively; r_0 is the constant of proportionality, b_{Tp} is the overlap parameter.

The value of the impact parameter b in this work was equal to 8.37 fm. Since, the value of the impact parameter lies in the range $1/2(R_p+R_T) \leq b \leq (R_p+R_T)$ [4], we can conclude that the collision is peripheral in most cases. It can be suggested that in peripheral collisions at large impact parameter, the probability of the whole deuteron interaction is very low. Taking into account the low binding energy of the deuteron (2.22 MeV), it can be presented that in this case the deuteron can break up and that only one participant nucleon interacts with the target [9].

Some general kinematic features for deuteron-induced reaction can be obtained directly from experiment. The F/B values represent in a sense the extent of forward peaking of the recoil and thus are a measure of the forward momentum transferred to the target nucleus in the reaction which resulted in that recoil being formed. The variation of F/B with product mass A is shown in Fig. 2.

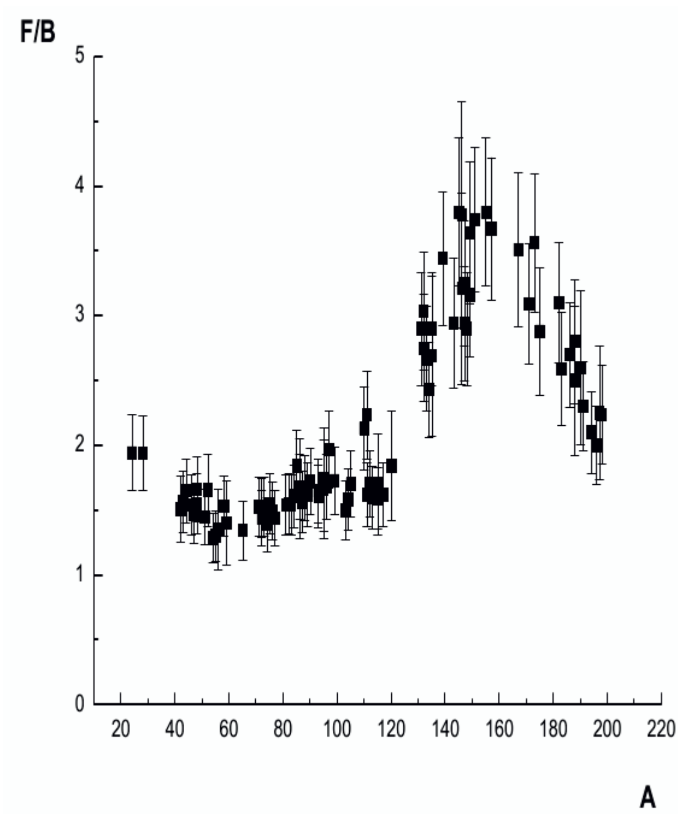

Figure 2. The dependence of F/B on product mass number.

From Fig. 2 it can be seen that F/B shows a rapid increase in forward peaking with increasing mass loss from the compound nucleus until about 20 nucleons have been lost. With further mass loss, going into the deep spallation region, the F/B values level off and then decrease. There is a broad minimum in the mass region $A = 45 - 75$, and then an increase as one goes to the light fragment region. As shown in Fig. 3, the ratios F/B are of the order of ~ 2 - 3 for heavy product nuclei

(A > 130) and decrease to about ∼ 1.6 for light residuals (40 < A < 120). Heavy residual nuclei produced mainly via spallation mechanism are preferably emitted in the forward direction, preserving the incident particle direction. Light products have a more isotropic distribution in the target rest frame. Such a dependence could be explained by different mechanisms for the production of nuclei in different mass regions. The isotropic distribution of light nuclei may be due to deep spallation, multifragmantation or fission-like processes where the memory of the initial interaction is lost. In light mass nuclei, the fragmentation processes can produce the contribution and define the forward direction.

In Fig. 3 we show a comparison between the target fragment recoil properties for the reaction of 4.4 GeV deuterons and similar measurements for the same products from the reaction of 1.0-11.5 GeV protons with ^{197}Au [10].

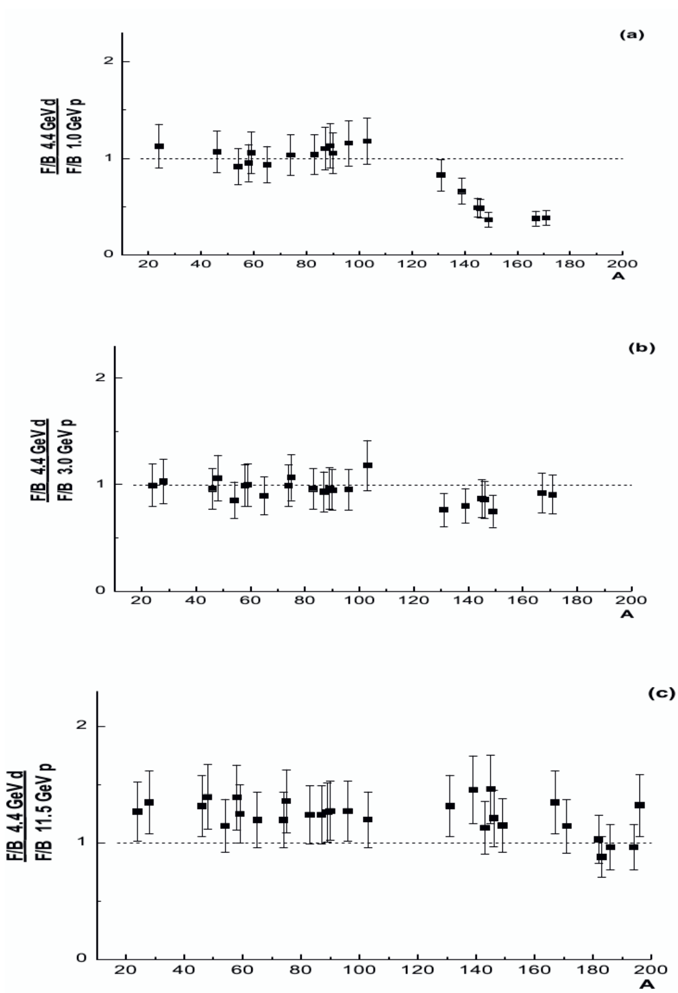

Figure 3. The ratio of target fragment F/B values to those measured for the reaction of protons [10] at (a) 1.0 GeV, (b) 3.0 GeV and (c) 11.5 GeV.

One can see in Fig. 3 that at a proton energy of 1.0 GeV, the F/B values for the fragments formed in deep spallation reactionsare in general in agreement with data for reactions with deuterons, excepting the spallation products in the heavy mass range probably formed in peripheral collisions. As is well known spallation products and heavy nuclei are formed with high probability at not high excitation energies. With the increase of the projectile energy new channels are opened and the spallation contribution decreases [10]. Therefore in Fig. 3a for the mass range $140 < A < 180$ a fall of the ratio F/B is observed. With increasing proton bombarding energy this difference is smoothed over: the F/B values of fragments formed in the 3.0 GeV proton-induced and 4.4 GeV deuteron-induced reaction within experimental error are generally similar, with no obvious systematic differences between them for the entire range of product masses and no dependence on the projectile. This fact serves to justify the representation of the equivalent trends for different system data sets at almost the same total energy and was confirmed by theoretical calculations [9]. We can say that target fragment kinematic properties from deuteron-induced reaction mostly resemble those from the reaction induced by protons of the same total projectile energy.

When proton energy is further increased, at 11.5 GeV, the ratio of F/B values is slightly larger than unity. A systematically large F/B ratio of the experiment in relation to the proton-induced reactions at 11.5 GeV can be explained by the domination ofnon-peripheral collisions with a smaller impact parameter.

The dependence of the parallel component of the cascade velocity of the recoiling nuclei on the product mass losses from a hypothetical compound nucleus formed in a complete fusion ΔA together with those from the reaction of protons 1.0, 3.0 and 11.5 GeV [10] are shown in Fig. 4. As we can see from Fig. 4, a gradual decrease of the linear velocity with increasing total projectile energy is observed. Our data well describe the general tendency of the $v_{\|}$ value for protons and can serve to improve the similarity of the picture after the first step of the reaction for different kind of incident particles at incident energy about 3 GeV. We can conclude that for the Au target, the distribution from the relativistic deuteron reaction is generally similar to the distributions produced in reactions induced by protons of the same total kinetic energy.

The two-step vector model approach allows us to estimate the linear momentum transferred to an intermediate nucleus in the first cascade step ($p_{\|}$) and the mean excitation energy of the residual cascade nucleus (E^{*}). The mean values of the relative linear momentum transfer $p_{\|}/p_{CN}$, where p_{CN} is the momentum of a hypothetical compound nucleus formed in a complete fusion, for the fragments representing different reaction mechanisms, are: 0.47±0.10 ($A < 40$); 0.16±0.03 ($42 \leq A \leq 59$); 0.12±0.02 ($65 \leq A \leq 120$); 0.09±0.02 ($A \geq 131$).

The mean excitation energies for the different product mass ranges are: 1416.0±283.0 MeV (A < 40); 472.0±95.0 MeV ($42 \leq A \leq 59$); 353.0±71.0 MeV ($65 \leq A \leq 120$); 264.0±53.0 MeV (A ≥ 131). To explain this pattern, one can assume that a few sources having different excitations can take part in the formation of the residual nuclei [11].

4 Conclusion

Cross sections of a number of deuteron-induced reactions on ^{197}Au have been measured at an energy of 4.4 GeV. The charge and mass distributions were analyzed in the term of a 3-parameter equation. The charge distributions of the fragments were found to be mainly determined by the properties of the residual nuclei and to not depend on the manner of their formation. The mass yield distribution of target residues has been determined by integration of the cross sections for fragments. The calculation of the impact parameter indicates that the considered reactions of 4.4 GeV deuterons with gold in most cases may be realized through peripheral collisions. The investigation of kinematical properties

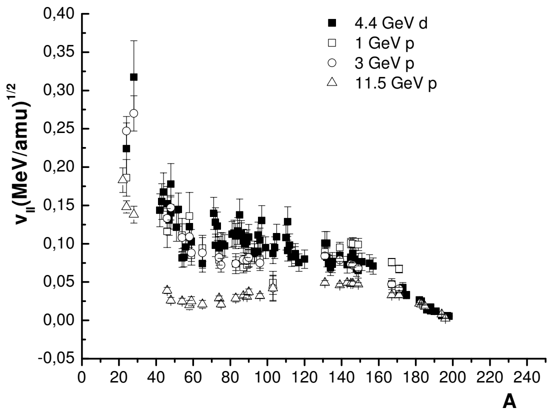

Figure 4. Dependence of the longitudinal velocity of residual cascade nuclei $\upsilon_{||}$ on the product mass losses from a hypothetical compound nucleus formed in a complete fusion ΔA. Open symbols are data for proton-induced reaction of Au [10]: □ – E_p = 1.0 GeV; ○ – E_p = 3.0 GeV; △ – E_p = 11.5 GeV; ■ – data of this work.

of the reaction products have been analyzed on the basis of the two-step vector model. The results are analyzed and discussed in terms of the different reaction mechanisms, spallation, fission/deep spallation and fragmentation. The dependence of recoil properties on the mass number of the products has been studied and compared to those for reactions of energetic protons with gold. The similarity of the main features in the collision with high-energy protons and deuterons at the similar total kinetic energy of the projectile allows one to exclude the additivity of two nucleons in the deuteron during interaction with a nucleus. The deuteron, as a weakly bound system, can decay and undergo a one nucleon collision in most cases of interaction.

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