PHYSICAL REVIEW C **93**, 054614 (2016)

# Isomer production in intermediate-energy deuteron-induced reactions on a gold target

A. R. Balabekyan,[1] G. S. Karapetyan,[2] N. A. Demekhina,[3,4] D. R. Drnoyan,[4] V. I. Zhemenik,[4] J. Adam,[5] L. Zavorka,[5] A. A. Solnyshkin,[5] V. M. Tsoupko-Sitnikov,[5] V. Guimarães,[2] and A. Deppman[2]

[1]*Yerevan State University A. Manoogian, 1, 025, Yerevan, Armenia*

[2]*Instituto de Fisica, Universidade de São Paulo Rua do Matao, Travessa R 187, 05508-900 São Paulo, SP, Brazil*

[3]*Yerevan Physics Institute, Alikhanyan Brothers 2, Yerevan 0036, Armenia*

[4]*Joint Institute for Nuclear Research (JINR), Flerov Laboratory of Nuclear Reactions (LNR), Joliot-Curie 6, Dubna 141980, Moscow region, Russia*

[5]*Joint Institute for Nuclear Research (JINR), Laboratory of Nuclear Problems (LNP), Joliot-Curie 6, Dubna 141980, Moscow region, Russia*

(Received 15 January 2016; published 18 May 2016)

Residual nuclei formed at ground and isomeric states from the interaction of 4.4 GeV deuteron with a gold target have been measured and investigated by the induced-activity method. Eight isomeric and ground-state pairs of target residues in the mass range of $44 < A < 198$ were identified by off-line $\gamma$-spectroscopy analysis and their isomer ratios were obtained from the cross-section production. From the isomer ratio data of the formed $^{196}$Au and $^{197}$Hg nuclei, the average intrinsic angular momentum of the composite system was estimated by means of a simple statistical model based on the formalism developed by Huizenga and Vandenbosch.

DOI: 10.1103/PhysRevC.93.054614

## I. INTRODUCTION

As is well known, an isomeric state is a long-lived excited state (metastable state) of an atom's nucleus, in which the decay to the nuclear ground state is inhibited by the spin-parity combination of the excited and ground states. A nucleus in an isomeric state can hold an enormous amount of energy which is released when the transition from the highly excited state to the ground state occurs, with the emission of a $\gamma$ ray. The formation of high-spin isomers by a nuclear reaction is associated with the transfer of a large amount of angular momentum. Actually, the population of a nucleus in the ground ($\sigma_g$) and metastable ($\sigma_m$) states, from a reaction, depends on the angular momentum in the entrance channel, on the excitation energy of the residual nucleus before evaporation, and on the type of particles emitted during the deexcitation stage. The production of isomer can, thus, provide information to the study of the collective rotational degrees of the reaction remnant. By its turn, the study of the angular momenta of the reaction fragments can provide insight into the configuration of the nuclear system at high excitation energies. The angular-momentum transfer in nuclear reactions can also influence, for instance, the fissility of an excited fissioning nucleus since the fission barrier should decrease monotonically, and eventually vanishes, as the transferred angular momentum increases [1,2]. Thus, the interpretation of the high-spin-state population is important for understanding the mechanism of intermediate- and high-energy particle interaction with nuclei.

The measurements of high-state isomers produced in nuclear reactions are a challenge for experiments and for the theoretical point of view, and data on isomers produced by nuclear reactions are very scarce. Some experiments aimed to get isomer ratios from reactions induced by photons [3], protons [4,5], and heavy ions [6,7] at the intermediate-energy range have been reported. However, no measurement of independent isomer-yield ratios for a gold target at intermediate and high energies has yet been reported. In this work we report the independent cross-section ratios for pairs of reaction products with isomeric metastable and ground states from the interaction of a 4.4 GeV deuteron beam on a gold target. The deuteron-induced reaction is the transition between small, as for nucleon-nucleus reaction, and large angular-momentum transfer, as for heavy-ion reactions. The objective of our experiment is to investigate general regularities of the phenomenon of isomer production in deuteron-induced reactions at high energies. The interpretation of results can be important for the understanding of the mechanism of intermediate-energy particle interaction with nuclei. This paper is a sequel of the previous two works [8,9], where we reported the fragment kinematic features and mass distribution for the target residuals from the deuteron interaction with a gold target.

We applied the induced-activity method to investigate the production of nuclei in the isomer state from the interaction of a 4.4 GeV deuteron beam with a gold target. This method, in combination with appropriated nuclear properties, allows us to identify as well as determine the production cross sections of the reaction products in isomeric states. The information about the primary angular momenta of the fragments can also be obtained from the measurements of independent isomer ratio, $IR = \sigma(I_h)/\sigma(I_l)$, where $\sigma(I_h)$ is the production cross section of a specific reaction product at high spin $I_h$, and $\sigma(I_l)$ is the analogous quantity at low-spin $I_l$. This technique, however, imposes some restrictions on the measurements of the independent cross sections due to the contribution from the $\beta^{\pm}$ decays of neighboring unstable isobars, i.e., the cumulativity of their production. Thus, only a few part of the experimental data can be used to determine the characteristics of the reaction under investigation. Deexcitation of primary products takes place by the emission of prompt neutrons and $\gamma$ rays until the final state is populated. Neutrons and $\gamma$ rays carry away different amounts of energy and angular momentum; thus changing the initial distribution of the primary products. As a result, the primary products, originating from reaction remnants, have a wide range of angular momenta and excitation energies. The comparison of the measured isomer cross-section ratios with different statistical models [4,10] can provide a way to estimate the spin associated with the reaction products from different exit channels.

## II. EXPERIMENTAL PROCEDURE

The 4.4 GeV deuteron beam from the Nuclotron of the Laboratory of High Energies (LHE), Joint Institute for Nuclear Research (JINR), Dubna, was used to irradiate a 39.13-mg/cm$^2$-thick gold target. The target consisted of a stack of 15 gold foils of $20 \times 20$ mm$^2$ in size surrounded by Mylar catcher foils of the same size. The Mylar foils in contact with the gold served as forward and backward catchers. The total irradiation time was 28.6 hours with a total beam intensity integration of $6.43 \times 10^{12}$ deuterons. The $\gamma$ rays from the decay of the reaction residues formed in the target were measured with high-purity germanium (HpGe) detectors. The detectors, with 28% relative efficiency, had an energy resolution of 2 keV ($^{60}$Co at 1332 keV). The energy-dependent efficiency of the HpGe detectors was measured with standard calibration sources of $^{54}$Mn, $^{57,60}$Co, $^{137}$Cs, $^{154}$Eu, $^{152}$Eu, and $^{133}$Ba. The $\gamma$-ray spectra were evaluated in an off-line analysis with the code package DEIMOS32 [11] and the radioactive nuclei were identified by the energy and intensity of their characteristic $\gamma$ lines as well as by their respective half-lives, using information from the literature [12].

The isomer ratios of a particular nucleus can be calculated from the measured yields of its metastable and ground states. A nucleus in its ground state can be formed directly from the reaction with the target and/or can be formed indirectly through the decay of a formed nucleus in a metastable state. The yield production of a given isomeric pair during the activation time $t_i$ can be obtained by solving the following two differential equations:

$$\frac{dN_\mathrm{m}}{dt} = N_\mathrm{n}\Phi\sigma_\mathrm{m} - \lambda_\mathrm{m}N_\mathrm{m}, \tag{1}$$

$$\frac{dN_\mathrm{g}}{dt} = N_\mathrm{n}\Phi\sigma_\mathrm{g} - \lambda_\mathrm{g}N_\mathrm{g} + p\lambda_\mathrm{m}N_\mathrm{m}, \tag{2}$$

where $N_\mathrm{n}$ is the number of nucleus of the target, $\Phi$ is the intensity of the beam, $N_i$ is the numbers of product nuclei for $i = \mathrm{g}$ (m) state, $\lambda_\mathrm{g}$ and $\lambda_\mathrm{m}$ are the decay constants of these states, respectively, and $p$ is the contribution from the metastable state to the ground state.

Solving Eqs. (1) and (2) in the three time intervals, the irradiation time $t_1$; the time of exposure between the end of the irradiation and the beginning of the measurement $t_2$ and the time of measurement $t_3$, we can estimate the yields in the total absorption photopeak and derive the isomer ratio [13,14]:

$$\frac{\sigma_\mathrm{m}}{\sigma_\mathrm{g}} = \left[\frac{\lambda_\mathrm{g}(1-e^{\lambda_\mathrm{m}t_1})e^{\lambda_\mathrm{m}t_2}(1-e^{\lambda_\mathrm{m}t_3})}{\lambda_\mathrm{g}(1-e^{\lambda_\mathrm{m}t_1})e^{\lambda_\mathrm{m}t_2}(1-e^{\lambda_\mathrm{m}t_3})} \times \left(\frac{k_\mathrm{m}N_\mathrm{g}\eta_\mathrm{m}\epsilon_\mathrm{m}}{k_\mathrm{g}N_\mathrm{m}\eta_\mathrm{g}\epsilon_\mathrm{g}} - p\frac{\lambda_\mathrm{g}}{\lambda_\mathrm{g}-\lambda_\mathrm{m}}\right) + p\frac{\lambda_\mathrm{m}}{\lambda_\mathrm{g}-\lambda_\mathrm{m}}\right]^{-1}, \tag{3}$$

Here, $N$ is the yield under the photopeak with energy $E_\gamma$, $\lambda$ is the decay constant (min$^{-1}$), $\eta$ is the intensity of $\gamma$ transitions, $k$ is the total coefficient of $\gamma$-ray absorption in the target and in the detector materials, $\epsilon$ is the $\gamma$-ray-detection efficiency, and $p$ is the contribution from the metastable state to the ground state. The subscripts $m$ and $g$ refer to the metastable and the ground states, respectively.

The isomer ratios for eight nuclides were calculated by using Eq. (3) and the results are listed in Table I. To improve the accuracy of the calculations, the independent production cross sections of the isotopes were determined by using Eqs. (5) and (7) from Ref. [15]. The considerations taken into account to obtain these cross sections are described below:

(i) The cross section for the isomeric state of $^{44\mathrm{m}}$Sc ($T_{1/2} = 58.6$ h) was obtained by considering the yields of the $\gamma$ transition with energy $E_\gamma =$ 271.13 keV. The cross section for the ground state, $^{44\mathrm{g}}$Sc ($T_{1/2} = 3.93$ h), which $\beta$ decays to $^{44}$Ca, was obtained by using the $\gamma$ transition with energy $E_\gamma = 1157.03$ keV. The contribution $f_{ij} = 1.0$ of parent isotope $^{44}$Ti was considered negligible. The contribution from the metastable state to the ground state, used in Eq. (3), is $p = 0.98$.

(ii) The cross section of the isomeric state of $^{95\mathrm{m}}$Nb ($T_{1/2} = 86.64$ h) was obtained by considering the yields of the $\gamma$ transition with energy $E_\gamma =$ 235.68 keV. The contribution $f_{ij} = 0.0088$ of the parent isotope $^{95}$Zr ($T_{1/2} = 64.02$ d) was taken into account. The cross section of ground state $^{95\mathrm{g}}$Nb ($T_{1/2} = 34.98$ d), which decays to $^{95}$Mo, was obtained by using the $\gamma$ transition with energy $E_\gamma =$ 766.0 keV, and it was calculated with the contribution $f_{ij} = 0.991$ of parent isotope $^{95}$Zr ($T_{1/2} = 64.02$ d).

TABLE I. The production cross sections of ground and metastable states and the corresponding isomeric ratio of nuclide formed by the reaction of 4.4 GeV deuterons with a $^{197}$Au target.

| Element | State (spin) | $\sigma_\mathrm{m}$ (mb) | $\sigma_\mathrm{g}$ (mb) | $\sigma(I_\mathrm{h})/\sigma(I_\mathrm{l})$ |
|---|---|---|---|---|
| $^{44}$Sc | $\mathrm{m}(6^+) \to \mathrm{g}(2^+)$ | $0.45 \pm 0.16$ | $1.76 \pm 0.70$ | $0.26 \pm 0.09$ |
| $^{95}$Nb | $\mathrm{m}(1/2^-) \to \mathrm{g}(9/2^+)$ | $0.35 \pm 0.03$ | $1.09 \pm 0.30$ | $3.11 \pm 0.87$ |
| $^{95}$Tc | $\mathrm{m}(1/2^-) \to \mathrm{g}(9/2^+)$ | $1.92 \pm 0.5$ | $9.67 \pm 1.5$ | $5.03 \pm 0.87$ |
| $^{102}$Rh | $\mathrm{m}(6^+) \to \mathrm{g}(2^-)$ | $13.15 \pm 0.23$ | $3.85 \pm 0.60$ | $3.41 \pm 0.87$ |
| $^{184}$Re | $\mathrm{m}(8^+) \to \mathrm{g}(3^-)$ | $4.09 \pm 0.25$ | $0.92 \pm 0.18$ | $4.45 \pm 1.11$ |
| $^{193}$Hg | $\mathrm{m}(13/2^+) \to \mathrm{g}(3/2^-)$ | $7.19 \pm 0.80$ | $3.3 \pm 1.1$ | $2.12 \pm 0.73$ |
| $^{196}$Au | $\mathrm{m}(12^-) \to \mathrm{g}(2^-)$ | $5.56 \pm 0.30$ | $135 \pm 14$ | $0.041 \pm 0.005$ |
| $^{197}$Hg | $\mathrm{m}(13/2^+) \to \mathrm{g}(3/2^-)$ | $2.63 \pm 0.20$ | $12.10 \pm 0.40$ | $0.217 \pm 0.018$ |

The isomer ratio was calculated with contribution from the metastable state to the ground state $p = 0.976$.

(iii) The cross section of isomeric state $^{95m}$Tc ($T_{1/2} =$ 61.0 d) was obtained by considering the yields of the $\gamma$ transition with energy $E_\gamma = 204.11$ keV. The cross section of ground state $^{95g}$Tc ($T_{1/2} = 20.0$ h), which decays to $^{95}$Mo, was obtained using the $\gamma$ transition with energy $E_\gamma = 765.79$ keV, The contribution of parent isotope $^{95}$Ru is the same for both states of the isomeric pair. The isomer ratio was calculated with the contribution from the metastable state to the ground state $p = 0.038$.

(iv) The cross section of isomeric state $^{102}$Rh$^{m}$ ($T_{1/2} =$ 2.9 y) was obtained by considering the yields of the $\gamma$ transition with energy $E_\gamma = 475.1$ keV. The contribution $f_{ij} = 0.42$ of the isotope $^{144}$Pm ($T_{1/2} =$ 363.0 d), which also have a $\gamma$ transition with energy $E_\gamma = 475.1$ keV, was taken into account. The cross section of ground state $^{102}$Rh$^{g}$ ($T_{1/2} = 207.0$ d), which decays to $^{102}$Pd, was obtained by using the $\gamma$ transition with energy $E_\gamma = 556.41$ keV. The isomer ratio was calculated with contribution from the metastable state to the ground state $p = 0.0023$.

(v) The cross section of the isomeric state $^{184m}$Re ($T_{1/2} =$ 169.0 d) was obtained by considering the yields of the $\gamma$ transition with energy $E_\gamma = 216.55$ keV. The cross section of the ground state $^{184g}$Re ($T_{1/2} = 38.0$ d), which decays to $^{184}$W, was obtained by using the $\gamma$ transitions with energy $E_\gamma = 792.07$ keV and 903.28 keV. The isomer ratio was calculated with a contribution from the metastable state to the ground state $p = 0.754$.

(vi) The cross section of isomeric state $^{193m}$Hg ($T_{1/2} =$ 11.8 h) was obtained by considering the yields of the $\gamma$ transition with energy $E_\gamma = 1241$ keV. The cross section of the ground state $^{193g}$Hg ($T_{1/2} = 3.8$ h), which decays to $^{193}$Au, was obtained by using the $\gamma$ transitions with energy $E_\gamma = 861$ keV. The isomer ratio was calculated with contribution from the metastable to the ground state $p = 0.071$.

(vii) The cross section of isomeric state $^{196m}$Au ($T_{1/2} =$ 9.7 h) was obtained by considering the yields of the $\gamma$ transition with energy $E_\gamma = 147.8$ keV. The cross section of the ground state $^{196g}$Au ($T_{1/2} =$ 6.183 d), which decays to $^{196}$Hg, was obtained by using the $\gamma$ transitions with energy $E_\gamma = 355.68$ and 332.98 keV, with the contribution of the parent isotope $^{196m}$Au $f_{ij} = 1.0$. The isomer ratio was calculated with the contribution from the metastable state to the ground state $p = 1.0$.

(viii) The cross section of the isomeric state $^{197m}$Hg ($T_{1/2} = 23.8$ h) was obtained by considering the yields of the $\gamma$ transition with energy $E_\gamma =$ 133.9 keV. The cross section of ground state $^{197g}$Hg ($T_{1/2} = 64.14$ h), which decays to $^{197}$Au, was obtained by using the $\gamma$ transitions with energy $E_\gamma =$ 191.44 keV. The isomer ratio was calculated with the contribution from the metastable state to the ground state $p = 0.914$.

## III. RESULTS AND DISCUSSION

### A. Isomer ratio

The isomer ratio of eight residual nuclei, which have been successfully detected, are listed in Table I. The production cross sections of all isotopes were determined as independent yields after the subtraction of the contribution from electron capture (EC) and $\beta$ decays of the corresponding parent isotopes. The main sources of uncertainties in these cross sections were the statistical error, the detection efficiency error, uncertainties in the geometry of the target position during the irradiation and measurement, and the errors of the nuclear data used in the calculation, such as decay half-life of the radioactive isotopes and $\gamma$-ray intensities.

As is well known, the fragments formed in high-energy nuclear collisions are basically produced by spallation, fission, and multifragmentation processes [8,9]. According to Hufner [16], spallation is the process in which only one heavy fragment with mass close to the target mass $A_T$ is formed (a special case of spallation is the so-called deep spallation where the number of fragments $M$ is also equal to one, but with $50 < A < 2A_T/3$); fission is the process which leads to two heavy fragments in the mass range around $A = A_T/2$; and multifragmentation is the process leading to the formation of several (more than two) fragments with $A <$ 40–50. During a peripheral collision, which usually takes place at relativistic velocities of the projectile, such processes can be described by the two-step abrasion-ablation model [16]. In this model the nucleons are removed from the projectile and target during the interaction (abrasion). As a result, highly excited projectile- and target-like prefragments are formed. The abrasion phase is viewed as participant-spectator model where the majority of the projectile-target interaction occurs within a narrow region of overlap of the colliding nuclei. Prefragments may then evaporate nucleons and/or light particles (ablation), losing a large amount of their excitation energy. The final residual nuclei are formed with different spin states whose distribution depends on the angular-momentum transfer from the incident particle. Isomer production at intermediate energy, which would correspond to the production of fragments with high-spin states, can be related to the above-mentioned processes.

The variation of isomer ratio ($IR$) obtained in the present work with the product mass $A$ is shown in Fig. 1, with the exception of the data for the $^{196}$Au and $^{197}$Hg nuclei which will be discussed separately at the end of this section. In the figure, the dashed curve is the result of an exponential fit plotted just to represent the trend of the data. As one can see in this figure, the $IR$ increases rapidly with mass of the product, going from 0.26 for $^{44}$Sc, which can be formed in multifragmentation process [8,9], to a plateau in the mass region $90 < A < 200$. The transition region ($A \sim$ 60–65) could also have a contribution from the fission process. With further increase in mass ($A > 190$) of the residuals, going into the deep-spallation and near-target product regions, the $IR$ values drop down again. Such behavior suggests some

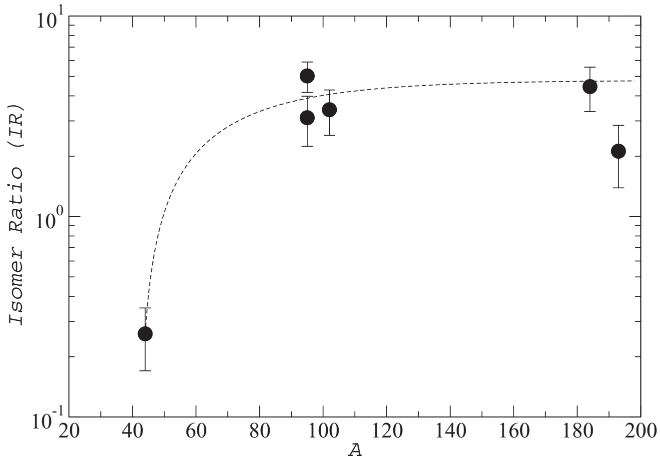


FIG. 1. Isomer ratios $IR$ versus mass number $A$ of the reaction products. The dashed line shows the general trend of $IR$.

dependence of the population of high-spin state with the mass of the fragments. The saturation of isomer ratios for the heavy fragment masses can be understood as the increasing of light-fragment cross-section production in this high-incident-energy regime and by the competition from different reaction channels such as multifragmentation. In this energy regime, the energy transfer to the after-cascade remnants promotes the opening of several new reaction channels. As also observed in Table I, in the plateau range of the $IR$, the difference between high- and low-spin states ($I_h - I_l$) increases from $4\hbar$ to $10\hbar$. Such behavior indicates a saturation of high-spin-state population for heavy fragment masses.

The variation of isomer ratios with relative transfer of linear momentum $p/p_{cn}$ determined in our previous work [8] can be seen in Fig. 2. The linear momenta $p$ and $p_{cn}$ are the momentum of the fragment and the momentum of a hypothetical compound nucleus, respectively. From this figure it is clear the tendency of the isomer ratio is to decrease with

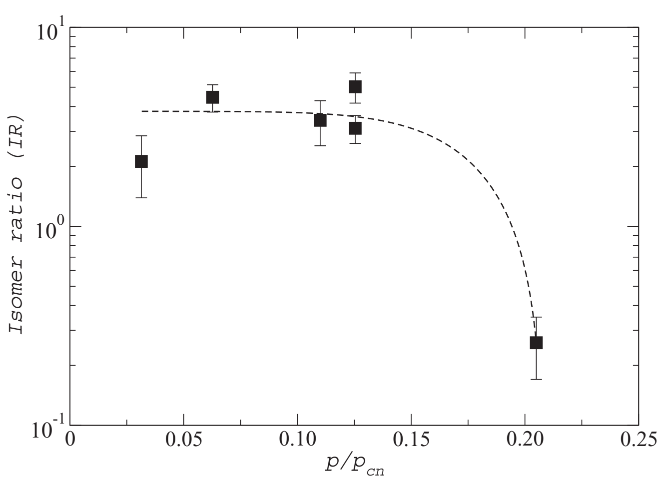


FIG. 2. Isomeric ratios $IR$ versus the fractional momentum transfer of residual nuclei $p/p_{cn}$ from Ref. [8]. The dashed line shows the general trend of $IR$.

the increase in the transfer of linear momentum. Such behavior is expected since the probability of high-spin-state population is associated with transfer of high angular momentum to the target from different processes in the first abrasion step of the reaction. The transfer of angular momentum $l$ is determined by the impact parameter of the collision, $b$, and by the linear momentum of the projectile. The linear momentum of the projectile can be completely absorbed in a head-on collision ($b \approx 0$), and it does not produce large angular momentum since $\mathbf{l} = [\mathbf{p} \times \mathbf{b}]$. On the other hand, for a peripheral collision at high energy with $b_{max} = (R_p + R_T)$, where $R_p$ and $R_T$ are the radii of projectile and target, respectively, the probability to transfer the linear momentum is low, but it can impart a large angular momentum to the final fragments. According to our recent result based on the estimation of the total reaction cross section in Ref. [8], the impact parameter in deuteron-induced reaction of gold at 4.4 GeV is $b = 8.37$ fm, which corresponds to a peripheral collision. Also, as was shown in Ref. [9], the maximum linear momentum $p/p_{cn} \sim 0.37$ can be released in the case of the production of light nuclei with masses $A < 40$, probably in the process of multifragmentation of gold. We can estimate that during the interaction of 4.4 GeV deuteron with gold target a maximum angular momentum of about $63\hbar$ can be imparted in the reaction. As already mentioned, the isotopes $^{44}$Sc, $^{95}$Nb, $^{95}$Tc, and $^{102}$Rh, which are in the mass range $40 < A < 120$, can be formed by fission or multifragmentation processes. Actually, the mass yields of both processes overlap and we cannot disentangle them with the activation method used in the present work. The average transfer of fractional momentum in such a mass range is $\sim$0.13 with $\langle l \rangle \sim 22\hbar$. The heavy-mass fragments ($A > 131$), such as $^{184}$Re and $^{193}$Hg, are formed by the spallation process of the gold target. In this mass region the products have the lowest value of energy transfer, linear momentum ($p/p_{cn} \sim 0.085$), and angular momentum ($\langle l \rangle \sim 14.5\hbar$). Thus, the spallation products are most probably formed in peripheral collisions with large impact parameter.

In conclusion we can say that the isomer production follows basically the processes of fragment production in the 4.4 GeV deuteron interaction with gold, where the majority of the total reaction cross section corresponds to spallation, deep spallation, and fission-like processes [8]. This means that, at such an energy regime, the population of high-spin isomeric states prevails for the reaction products formed mainly by fission-like and/or deep spallation and spallation processes over the fragmentation at the same excitation-energy regime. It can be suggested that fragmentation requires more excitation energy for the higher probability of formation of fragments.

The exception to the above picture is the production of isomers of $^{196}$Au and $^{197}$Hg nuclei. The $IR$ for these nuclei, also listed in Table I, are less than unity, indicating that the mechanism of their formation is other than spallation and/or fission of the gold target. We suggest that these nuclei have been formed via direct reaction with the target, neutron pickup reaction for the $^{196}$Au and charge-exchange mechanism induced by the proton from the breakup of the beam to form $^{197}$Hg. In a direct process a small amount of angular momentum should be transferred to produce the high-spin isomer state in $^{196}$Au and therefore we can expect that the probability of the formation this nucleus in its ground state should be higher. This effect results in a small isomer ratio, $0.041 \pm 0.005$, for the $^{196}$Au isotope. The production cross sections of the two isomer isotopes $^{193m}$Hg and $^{197m}$Hg are $\sigma = 7.19 \pm 0.80$ and $\sigma = 2.63 \pm 0.20$, respectively. The fact that production cross sections are higher for the $^{193m}$Hg isotope indicates that, when more neutrons are emitted from the composite remnant nucleus, high-spin-state isotopes are more likely to form in the final residue.

### B. Angular momentum: model calculation

The relative cross-section production of a nucleus in its ground and metastable states, at intermediate energy,-depends strongly on the excitation energy and angular momentum distribution of the remnants as well as on the type of particles that are emitted during its deexcitation, since different particles can carry away different amounts of energy and angular momentum. Also, the orbital angular momentum transferred in the entrance channel plays a major role in the population of the residual nuclei.

In the present work we determine the probability of population of the ground and metastable states of the residual nuclei pairs $^{196g,m}$Au and $^{197g,m}$Hg. These nuclei seem to be formed from direct reactions in peripheral interactions. The average initial angular momentum of the reaction's remnant can be deduced from the measured cross sections by considering the concepts of the statistical model. The formalism of these calculations was first introduced by Huizenga and Vandenbosch [17] and the main ingredient is the probability distribution of initial angular momentum, which can be represented by the following equation:

$$P(J_i) \sim (2J_i + 1)\exp[-J_i(J_i + 1)/B^2], \qquad (4)$$

where $P(J_i)$ is the probability distribution over spin $J$, and $B$ is a parameter which defines the width of the distribution. The root-mean-square angular momentum $(\bar{J^2})^{1/2}$ of the primary product is equal to $B$ for large values:

$$(\bar{J^2})^{1/2} \cong B. \qquad (5)$$

In the reaction of 4.4 GeV deuterons with a gold target, the prefragment excitation energies $E^*$ were estimated on the basis of linear momentum transfer from the projectile [8]. The effective excitation energy of the residual nucleus after emission of nucleons is calculated by using the following expression:

$$E^*_{\text{eff}} = E^* - E_{\text{Coul}} - E_p - E_{\text{KE}}, \qquad (6)$$

where $E_{\text{Coul}}$ is the Coulomb barrier for the emitted proton, $E_p$ is the binding energy of a proton inside a nucleus, and $E_{\text{KE}}$ is the mean kinetic energy of the proton.

According to the evaporation model, the nucleons are emitted by the excited nucleus with a mean energy $E_{\text{KE}} = 2T$, where $T$ is the nuclear temperature which is determined by the expression [18]

$$aT^2 - 4T = E^*_{\text{eff}}, \qquad (7)$$

where $a$ is the level-density parameter $a = A/10\ \text{MeV}^{-1}$.

At the stage involving the cascade of $\gamma$ transitions, eventually leading to the metastable or ground states, the spin distribution of the nuclear levels determines the probability of population of intermediate nuclear states. In the calculations, we used the spin's part of the Bethe–Bloch formula given by

$$P(J) \sim (2J + 1)\exp[-(J + 0.5)^2/2\sigma^2], \qquad (8)$$

where $P(J)$ is the probability distribution of levels with spin $J$ and $\sigma$ is the spin cutoff parameter which characterizes the angular-momentum distribution of the level density and is related to the moment of inertia and to the temperature of the excited nucleus and is given by $\sigma^2 = 0.00889\sqrt{aE^*_{\text{eff}}}A^{2/3}$.

The average energy and number of prompt $\gamma$ rays emitted from the nucleus with the initial excitation energy $E^*_{\text{eff}}$ can be estimated by means of the following equation from Ref. [19]:

$$\bar{E_\gamma} = 4\left(\frac{E^*_{\text{eff}}}{a} - \frac{5}{a^2}\right)^{1/2}. \qquad (9)$$

The energy of each succeeding $\gamma$ ray is found by computing the new excitation energy and by subtracting the average energy of the $\gamma$ ray, calculated by using Eq. (9), from the residual excitation energy.

In these calculations we used both the dipole's $E1$ and the quadrupole's $E2$ multipolarity of $\gamma$ transitions. However, as was shown in Ref. [6], the relative sharing of the quadrupole transitions in the deexcitation process does not exceed 10%.

The excitation energy $E^*_{\text{eff}}$ and, accordingly, the energy $E_\gamma$ of emitted photons, are determined at each stage of the cascade. The last level from which the population of the ground or the isomeric states occurs is characterized by an excitation energy no higher than 2 MeV.

The results of these calculations for the angular momentum induced to the composite nucleus from which $^{196g,m}$Au and $^{197g,m}$Hg have been formed were $B = 17 \pm 1.5\hbar$ and $B = 19.5 \pm 2.0\hbar$, respectively. The uncertainties have been determined from the statistical errors in the measurements of activity and the uncertainty in our knowledge of the deexcitation cascade. Thus, the average spin of composite nucleus after interaction of 4.4 GeV deuteron with $^{197}$Au target was considered to increase up to $19.5\hbar$. This result indicates that a considerable part of the intrinsic angular momentum can be imparted in the first step of the reaction with the gold target at high energies.

## IV. CONCLUSION

In the present paper we report the isomer ratios for eight nuclides produced by deuteron-induced reactions on a gold target at intermediate energy. The dependence of experimental isomer ratios on the mass of the target residues and on the fractional momentum transfer of residuals was investigated. Based on the experimental results, a qualitative explanation of the observed regularities is suggested. It was found that there is a competition of different processes during the population of metastable and ground states and that the main contribution comes from the spallation and/or fission channels. The average angular momenta of the composite nucleus was calculated within the framework of the statistical model and we conclude that it could have been increased up to $19.5\hbar$ for the interaction of high-energy deuterium with a gold target.

## ACKNOWLEDGMENTS

G.K. is grateful to CNPq (Grant No. 112986/2015-3), to the International Centre for Theoretical Physics (ICTP) under the Associate Grant Scheme, and to the Sao Paulo Research Foundation (FAPESP) (Grant No. 2014/00284-1). V.G. would like to thank the São Paulo Research Foundation (FAPESP) (Grant No. 2014/14432-2) and the Conselho Nacional de Desenvolvimento Científico (CNPq) (Grant No. 302969/2013-6) for financial support.

[1] A. J. Sierk, Phys. Rev. C **33**, 2039 (1986).
[2] O. A. Capurro *et al.*, Phys. Rev. C **55**, 766 (1997).
[3] N. A. Demekhina, A. S. Danagulyan, and G. S. Karapetyan, Phys. At. Nucl. **65**, 365 (2002).
[4] B. L. Zhuikov, M. V. Mebel, V. M. Kokhanyuk, A. S. Iljinov, A. Y. Zyuzin, and J. Vincent, Phys. Rev. C **68**, 054611 (2003).
[5] C. J. Orth, W. R. Daniels, B. J. Dropesky, R. A. Williams, G. C. Giesler, and J. N. Ginocchio, Phys. Rev. C **21**, 2524 (1980).
[6] D. C. Aumann *et al.*, Phys. Rev. C **16**, 254 (1977).
[7] A. M. Denis Bacelar *et al.*, Phys. Lett. B **723**, 302 (2013).
[8] A. R. Balabekyan *et al.*, Phys. Rev. C **90**, 054612 (2014).
[9] A. R. Balabekyan *et al.*, Phys. Rev. C **89**, 054604 (2014).
[10] N. Patronis *et al.*, Phys. Rev. C **75**, 034607 (2007).
[11] J. Frána, J. Radioanal. Nucl. Chem. **257**, 583 (2003).
[12] R. B. Firestone, in *Tables of Isotopes*, 8th ed., update with CD ROM, edited by S. Y. Frank Chu (CD-ROMeditor) and C. M. Baglin (Wiley Interscience, New York, 1998).
[13] R. Vanska and R. Rieppo, Nucl. Instrum. Methods **179**, 525 (1981).
[14] D. Kolev, E. Dobreva, N. Nenov, and V. Todorov, Nucl. Instrum. Methods Phys. Res., Sect. A **356**, 390 (1995).
[15] G. Karapetyan, Eur. Phys. J. Plus **130**, 180 (2015).
[16] J. Hufner, Phys. Rep. **125**, 129 (1985); J. Phys. G **38**, 115006 (2011).
[17] J. R. Huizenga and R. Vandenbosch, Phys. Rev. **120**, 1305 (1960).
[18] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (Wiley, New York, 1952; Inostrannaya Literatura, Moscow, 1954).
[19] H. K. Vonach, R. Vandenbosch, and J. R. Huizenga, Nucl. Phys. **60**, 70 (1964).