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The ^{181}Ta(^{7}Li,5n)^{183}Os reaction: Measurement and analysis of the excitation function and isomeric cross-section ratios

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Excitation function and isomeric cross-section ratios for the production of ^{183}Os^{m,g} by ^{7}Li-induced reactions on ^{181}Ta are obtained from the measurements of the residual activities by the conventional stacked-foils technique from threshold to 50 MeV. The excitation function and isomeric cross-section ratios for nuclear reaction ^{181}Ta(^{7}Li,5n)^{183}Os^{m,g} are compared with the theoretical statistical model calculation by using the ALICE/91, STAPRE, and CASCADE codes. In the energy range of the present measurement the excitation functions are fitted fairly well by both the geometry dependent hybrid (GDH) model and the hybrid model of Blann with initial exciton number $n_0=7$ ($n_n=4$, $n_p=3$, $n_h=0$) using the ALICE/91 code. The experimental isomeric cross-section ratios are also reproduced fairly well by the calculation using the STAPRE code. However, the CASCADE code calculations slightly underpredict the cross section but reproduce the shape. In general, the statistical model under a suitable set of global assumptions, can reproduce the excitation function as well as isomeric cross-section ratios. [S0556-2813(98)02503-5]

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I. INTRODUCTION

For many years there has been great interest in studying the reaction mechanism in medium-energy heavy-ion-induced reactions. Most of the earlier studies have concentrated on studying the energy, angular momentum, and charge distribution of the products emitted in heavy-ion reactions, while others are focused on multifragmentation which is intimately connected with that of a complex fragment or intermediate mass fragments. In recent years there has been considerable interest in the study of fusion and incomplete fusion (ICF) in heavy-ion reactions at a projectile energy range of 5–10 MeV/nucleon. The motivation for this work is to use the ^{7}Li ions and other heavy-ion beams from the BARC-TIFR Pelletron Accelerator Facility to study the fusion and incomplete fusion reaction mechanism by measuring the cross-section and isomeric cross-section ratios. In the case of a fusion reaction the highly excited nuclear system decays by evaporating low-energy nucleons and α particles at the equilibrium stage. In the case of the ICF reaction only a part of the projectile fuses with the target nucleus and the other part moves in beam direction with almost the same velocity as that of incident ion beam. The excitation functions and isomeric cross-section studies are significant for the investigation of the mechanism of nuclear reactions. The excitation function and isomeric cross-section ratios of nuclei produced in the ^{7}Li-induced reactions on a ^{181}Ta target were measured by the conventional stacked foil technique for bombarding energies $E \leqslant 50$ MeV for the ^{7}Li ion beam. The experiments were performed at the BARC-TIFR (14-UD Pelletron) Medium Energy Heavy Ion Accelerator Facility in Bombay.

The isomeric cross section ratios for a pair of isomeric states are known to depend strongly on the spins of the isomers concerned as well as on the spins of the higher lying levels populating the isomers. Experimental and theoretical studies on the isomeric cross-section ratios, especially as a function of incident particle energy, should therefore lead to useful information on the spin-cutoff parameter as well as on the level structure of the residual nuclei. The present work on ^{7}Li-induced reactions on the target nucleus ^{181}Ta will supply some new data in the ^{7}Li energy range from threshold to 50.0 MeV. In this work, calculations in the framework of the equilibrium statistical model and preequilibrium model using the codes ALICE/91 [1], STAPRE [2], and CASCADE [3] were performed and the results are compared with experimental excitation functions and isomeric cross-section ratios.

II. EXPERIMENTAL PROCEDURE

The targets were commercially available thin self-supporting foils. The average thickness of the target foils was determined by weighing. Each foil was cut out into a square shape and pasted on a annular aluminum holder having 21.0 mm as the outer diameter and 15 mm as the inner diameter. There were six targets in the stack for the excitation function measurement. The stacks were irradiated in a chamber specially constructed for this purpose by the Radio-Chemistry Division of BARC Bombay, able to suppress electrons in the Faraday cup by applying negative bias. The beam spot on the targets was limited to 5.0 mm in diameter by using a stainless steel collimator in front of the targets. The stacks were exposed to the analyzed beam from the 14UD Tandem Pelletron Accelerator Facility at TIFR Bombay. The beam current on the targets was about $\cong 200$ enA. The total ^{7}Li beam was collected and measured using a calibrated current integrator.

The mean beam energy at half thickness in each foil of a stacked foil assembly was calculated from energy degradation of the initial beam energy using the coefficients obtained from fitting the stopping power data for different materials. The α-stopping power tables of Williamson *et al.* [4] were used for fitting. Then the stopping power S for a given combination of stopping medium and the heavy-ion beam and

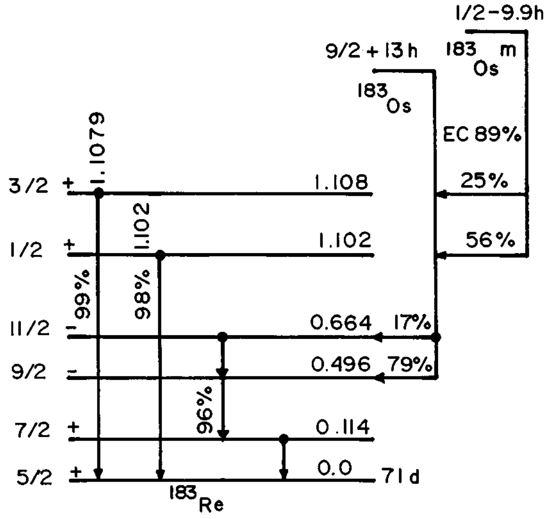

FIG. 1. Simplified level scheme of the isomeric pair ^{183}Os^{m,g}.

velocity is calculated by means of the well-known scaling law

$$S/(\gamma Z_1)^2 = S_{\text{ref}}/Z_{\text{ref}}^2, \quad (1)$$

in which (γZ_1) is the heavy-ion effective charge (Z_1 being its atomic number) and S_{ref} is the stopping power of the same medium for a reference ion (α ion) of the same velocity and of effective charge Z_{ref}. The tabulation is then generated based on the arguments of the effective charge parameter γ $(Z_1, E/A, Z_2)$ given by Hubert, Bimbot, and Gavin [5]. The stopping power generated in this way is very similar to that generated by the code TRIM.

Figure 1 gives the simplified level schemes of the isomeric pair involved in the product nucleus ^{183}Os^{m,g}. The separation energy between the isomeric levels concerned is small ($\cong$0.171 MeV) but the spins differ considerably. In ^{183}Os the ground state has a higher spin than the metastable state. The excitation functions for ^{7}Li-induced reactions on ^{181}Ta were determined using the absolute yields of characteristic delayed γ rays pertaining to the decay of each radioactive residual nuclei as usually done in the stacked foil technique (for details see Ismail [6]). The measurement of ^{183}Os^{m,g} radioactivities presented no difficulty since the decay scheme of each of them is very simple as shown in Fig. 1 and the delayed γ-ray spectrum shown in Figs. 2(a) and 2(b). The calculation of the isomeric cross-section ratio σ_m/σ_g for the isomeric pair ^{183}Os^{m,g} was straightforward since σ_m and σ_g were determined independently of each other.

The delayed γ rays emitted by the irradiated target foils were detected with the HPGe detectors available at TIFR (Bombay) as well as VECC at Calcutta. The efficiency calibrations of the detector were done with a standard ^{152}Eu radioactive source. The γ rays used in the yield determination (listed in Table I and displayed in Fig. 2) stand out very prominently in the spectra and did not pose any identification problem. The γ-ray spectra from the HPGe spectrometers were recorded on 3.5 in. diskettes by using a PC-based data acquisition system. The spectra were later analyzed by personal and super-32 computers at our center. The methods of analysis of the γ-ray spectra and the efficiency calibrations of the detector were the same as reported in Ref. [6].

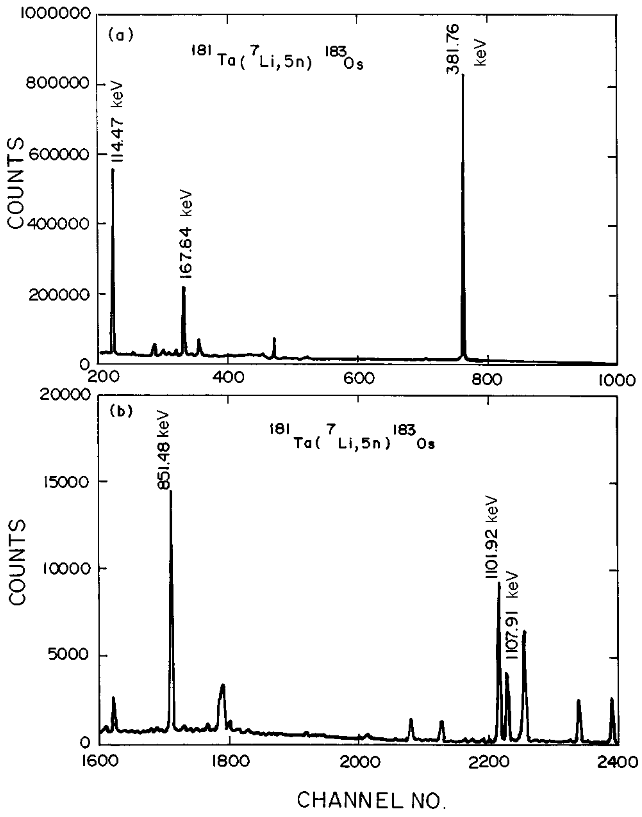

FIG. 2. Offline γ-ray spectrum obtained with a high purity germanium (HPGe) intrinsic detector for ^{7}Li+^{181}Ta at the highest laboratory bombarding energy (48.17 MeV). Showing the relevant delayed γ rays emitted from the radioactive residues.

The nuclear data necessary for the evaluation of the cross sections are presented in Table I. The half-lives of the radioactive atoms are taken from the chart of nuclides, the γ-rays energies, and branching ratios are taken from the table of isotopes (Lederer and Shirley [7]). In Table I only those γ rays are listed which were chosen for the calculation of the cross sections. The Q values was calculated by using the atomic mass table of Wapstra and Audi [8].

III. EXPERIMENTAL RESULTS

The cross section and their ratios for the isomer pair ^{183}Os^{m,g} produced by the reaction ^{181}Ta(^{7}Li,5n)^{183}Os^{m,g} are presented in Table II and Figs. 3(a) and 3(b) as a function of ^{7}Li-ion bombarding energy. The experimental cross sections are in millibarns and presented along with an absolute error of only $\cong$10%. The absolute errors are also shown as error bars in Figs. 3(a) and 3(b). For most of the data points, the error bars are the same size as the symbols. The absolute error consists of uncertainties due to target foil thickness ($\pm$3%), the beam current integration ($\pm$5%), the detector efficiency ($\pm$5%), and the analysis of the γ-ray spectra (statistical uncertainty), generally ($\leqslant$2%). The uncertainties caused by the large size of the irradiation area and the non-uniformities of the target contribute about ($\pm$5%) to the average error of the cross section. The percentage of the

TABLE I. Half-lives, γ-energies, and branching ratios of the γ decays and Q values for ^{7}Li-induced reactions on ^{181}Ta.

Nuclide	Half-life	E_γ (keV)	I_γ (%)	Reaction	Q values (MeV)
^{183}Os^m	9.90 h	1101.93	49.01	^{181}Ta(^{7}Li,5n)^{183}Os	−30.385
		1107.91	22.40		
^{183}Os^g	13.01 h	114.47	20.60	^{181}Ta(^{7}Li,5n)^{183}Os	−30.385
		167.84	8.81		
		381.76	89.61		
		851.48	4.56		

absolute errors ($\cong 7\%$) for the isomeric cross-section ratios are smaller than those for the cross section because errors due to target foil thickness, target nonuniformities, and the beam charge integration do not enter into the isomeric cross section ratio calculation. The uncertainties given for the energy values are those of target thickness only. The reaction cross-section and isomeric cross-section ratios were measured for the first time, therefore, no comparison could be made.

IV. NUCLEAR MODEL CALCULATION

It is well known that the compound statistical model gives a correct overall description of the excitation functions and particle energy spectra in nuclear reactions at medium energies ($E \leqslant 10$ MeV/nucleon). However, the calculations fail to account for all details such as the exact position of the maximum or the slope of the ascending and descending parts of the excitation functions. The high-energy part of the excitation functions are dominated by preequilibrium reaction mechanism whereas the low-energy parts are dominated by evaporation with its characteristic peak. We have investigated the nuclear mechanism of the nuclear reaction ^{181}Ta+^{7}Li by using the three computer codes ALICE/91 [1], STAPRE [2], and CASCADE [3] which are based on compound statistical model.

A. ALICE/91 code calculation

The ALICE/91 code [1] describes the process of equilibrium evaporation of particles and γ rays in terms of the Weisskopf and Ewing model [9] and the preequilibrium reaction mechanism according to the hybrid and geometry-dependent hybrid model (GDH) [10]. The statistical part of ALICE/91 [1] can account for a large variety of reaction types.

TABLE II. Experimental cross section for the ^{7}Li-induced reaction with ^{181}Ta.

S. No.	Energy in (Mev)	Cross section of the product in mb		
		^{183}Os^g	^{183}Os^m	σ_m/σ_g
1	48.17±1.83	1161.67±92.93	113.41±9.07	0.098±0.007
2	44.38±1.92	772.83±61.83	92.74±7.42	0.120±0.008
3	40.37±2.03	259.64±20.77	40.43±3.23	0.156±0.011
4	36.25±2.15	24.16± 1.93	4.49±0.36	0.186±0.013
5	31.79±2.31	0.05± 0.01	0.01±0.01	0.20 ±0.08

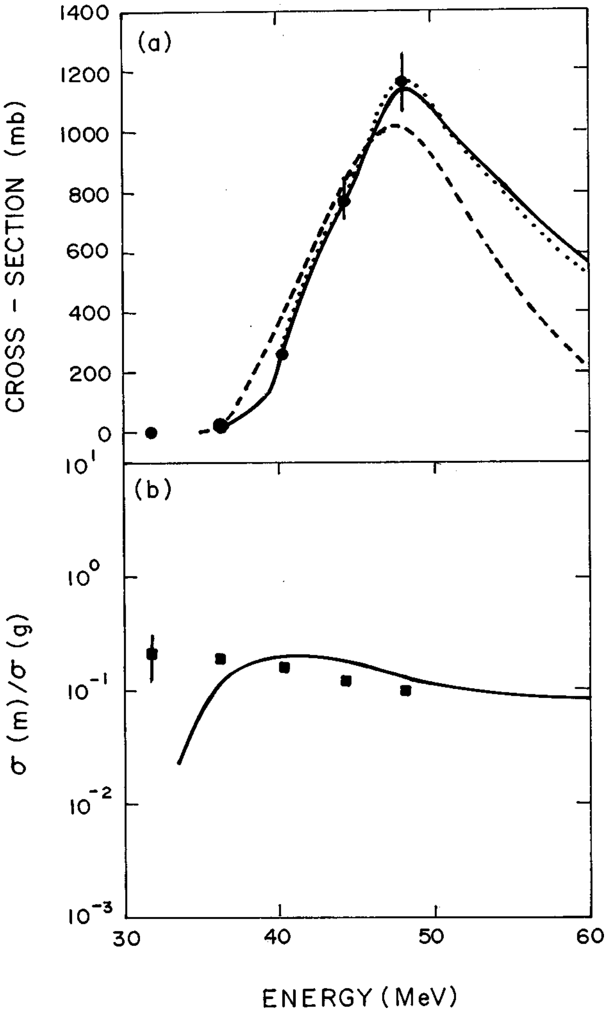

FIG. 3. (a) The total residual production cross section in mb for the reaction ^{181}Ta(^{7}Li,5n)^{183}Os (●) are plotted as a function of ^{7}Li-ion bombarding energy. The solid and dotted lines are, respectively, the geometry-dependent hybrid model and the hybrid model fits using the code ALICE/91 with $N_o=7$, $N_n=4$, $N_p=3$, and $N_h=0$. The dashed line is the CASCADE code calculation. (b) The isomeric cross-section ratios for the isomer pair ^{183}Os^{m,g} plotted (■) as a function of ^{7}Li-ion bombarding energy. The solid curve is the STAPRE code calculation with FM=500 MeV^3 and $\eta=1.0$. The curves with other sets of parameters (see Sec. IV B) are indistinguishable with the plotted solid curve.

The evaporation of neutrons, protons, and clusters such as deuteron and α particles were considered (Weisskopf and Ewing [9]). The binding energies and Q values used in the present code are based on experimental masses (Wapstra and Audi [8]). The ALICE/91 code [1] stores experimental masses in a data file. Whenever the nuclear masses are not available in the data file they are calculated from the Myers and Swiatecki mass formula [11] (liquid drop masses with pairing). We have used the option in the default version of GDH whereby only the first collision is localized according to the impact parameter (Blann and Vonach [12]) with all the higher order precompound terms being treated by the hybrid model, i.e., using nuclear densities averaged over the nucleus and independent of the impact parameter. This is reasonable because the excitons can sample nearly the entire nuclear volume after a single scattering since the mean free path (MFP) values are $\cong$4.74 fm. The inverse cross sections were calculated using the optical model subroutine of ALICE/91 [1], where the optical model parameters were those of Becchetti and Greenlees [13]. The Fermi level density used is of the form $\rho(u)=(\sqrt{\pi}/12)(u-\delta)^{-5/4}a^{-1/4}\exp[2\sqrt{a(u-\delta)}]$, where u is residual nucleus excitation, a is the level density parameter taken as $A/9\ \mathrm{MeV}^{-1}$, which is the default option of the code, and $\delta=11/\sqrt{A}$ MeV the pairing energy shift, with either a back shifted or standard pairing shift option. We have used the standard option. In the *a priori* formulation of the hybrid and geometry-dependent hybrid model, the intranuclear transition rates are calculated either from the imaginary part of the optical model or from the free nucleon-nucleon scattering cross section [12]. We have used only the optical model option for calculating the intranuclear transition rates.

We have taken an initial exciton configuration $n_0=7$ ($n_n=4$, $n_p=3$, $n_h=0$) which is equivalent to a break-up of the incoming ^{7}Li ion in the field of the nucleus and the nucleons occupying excited states above the Fermi energy gives a better description of the excitation function compared to other configurations for the ^{7}Li-ion bombarding energies up to 60.0 MeV. In Fig. 3(a) the total residual production cross section in mb for the sum of isomeric cross sections for the reaction ^{181}Ta(^{7}Li,5n)^{183}Os (closed circles) are plotted as a function of the ^{7}Li-ion bombarding energy. The solid and dotted lines are, respectively, the geometry-dependent hybrid and hybrid model fits.

In the energy range of the measurement both the geometry-dependent hybrid model and the hybrid model fit the excitation functions reasonably well taking limitations of the calculations into account. Considering the multitudes of uncertainties in preequilibrium calculations such as (i) the range of equilibrium and preequilibrium reaction cross sections involved, and (ii) in parameters such as the inverse reaction cross sections and level densities, etc. Blann [10] considered that a result which is within a factor of 2 of the experimental result in the absolute cross section and which generally has the correct spectral shape and variation of yield with excitation energy is an encouraging result.

B. STAPRE code calculation

In the STAPRE code the evaporation of particles and γ rays are treated in the framework of the statistical model with consideration of angular momentum and parity using the Hauser-Feshbach formalism [14]. For the emission of the first particle preequilibrium decay is also taken into account. The preequilibrium emission of the particles were treated in the framework of the exciton model [10]. The STAPRE code [2] has been used to calculate the isomeric cross section ratios for ^{7}Li-induced reactions which can take into account up to six sequential evaporation of particles and γ rays. Each evaporation step is treated within the framework of the statistical model with the consideration of angular momentum and parity using the Hauser-Feshbach formalism [14]. Direct interactions were not considered.

The parameters used in the code STAPRE [2] were generally the accepted ones. For the calculation of the transmission coefficients of various particles (such as neutron, proton, α, and ^{7}Li) the default global set of the optical model (OM) parameters of the TLCALC subroutine of the CASCADE code [3] were used. For the neutron, the OM parameter set of Rapaport [15] and Wilmore and Hodgson [16] was used, while for proton, the OM parameter set of Becchetti and Greenlees [13] was used. In the case of α particle, the OM parameter sets of Satchler [17], McFadden and Satchler [18], and Huizenga and Igo [19] were used. And for ^{7}Li, the general heavy-ion OM potential parameter set obtained from Voos *et al.* [20] was used. The transmission coefficients for γ rays with transition energy ε_γ are expressed by the γ-ray strength function $f_{XL}(\varepsilon_\gamma)$ for the multipole radiation of type XL. For the $E1$ strength function the Brink-Axel [21] model with global parameters was used and for $M1$, $E2$, $M2$, $E3$, and $M3$ radiations, the Weisskopf model [22] was used. For energies, spins, and parities of the discrete levels of the residual nuclei, the lowest 15–20 levels in Ref. [7] were used. The level density formalism of the back-shifted Fermi gas model expressed by Lang [23] was used for the continuum excitation energy region. The level density parameter $a=A/9$ was used for all nuclei, where A is the mass number of the nucleus. The spin distribution of the level density was characterized by the effective moment of inertia Θ_{eff} or better by its ratio to rigid body moment of inertia Θ_{rig} ($\eta=\Theta_{\mathrm{eff}}/\Theta_{\mathrm{rig}}$). Since isomeric cross-section ratios are expected to depend strongly on the effective moment of inertia, all the calculations were performed for $\eta=0.5$ and $\eta=1.0$. In the STAPRE code the preequilibrium emission of the particles were treated in the framework of the exciton model [10] having the following ingredients. For the initial exciton configurations (p_0h_0) we used (7,0) for ^{7}Li ions. The transition rates were calculated using the formulas of the William-Cline model [24]. The average residual two-body matrix element that appears in the transitions rates λ_+, λ_0, and λ_- formulas as a function of mass and energy (proposed by Kalbach-Cline [25]) is expressed as

$$|M|^2=FMA^{-3}E^{-1}, \tag{2}$$

where E is the excitation energy of the composite system. The quantity FM is a constant with the dimension of $(\mathrm{MeV})^3$ and generally treated as a free parameter so as to get a good fit to the experimental data. The values used for the ^{7}Li-ion-induced reactions were in the range of $FM=(500-1000)\ (\mathrm{MeV})^3$.

In Fig. 3(b) and Table II the isomeric cross sections ratios (closed squares) are presented along with their absolute errors ($\cong 7\%$). The experimental isomeric cross-section ratio is practically constant within experimental errors (generally $\cong 7\%$, except for the energy value of 31.79 MeV, where the error is $\cong 40\%$) through out the bombarding energy range without showing any tendency to decrease or increase, which means no preference for any of the states to populate. The calculations for cross-section and isomeric cross-section ratios have been done for the following sets of parameters: (i) $FM = 500\,(\mathrm{MeV})^3$, $\eta = 0.5$, (ii) $FM = 500\,(\mathrm{MeV})^3$, $\eta = 1.0$, (iii) $FM = 1000\,(\mathrm{MeV})^3$, $\eta = 0.5$, (iv) $FM = 1000\,(\mathrm{MeV})^3$, $\eta = 1.0$. Since in the energy range of the present experiment the preequilibrium emission is not very significant, all the four sets of the calculations are within 20% of each other. Hence the calculations for set (ii) $FM = 500\,(\mathrm{MeV})^3$, $\eta = 1.0$ are being presented in Fig. 3(b). The experimental isomeric cross section ratios are reproduced fairly well by the calculation.

C. CASCADE code calculation

The CASCADE code is based on the assumption that the projectile and target form a compound nucleus in statistical equilibrium and the Hauser-Feshbach formula together with the statistical nuclear model are applied in order to calculate the intensities of the various decay chains and thus the excitation functions of the reactions. In Fig. 3(a) the short dashed curve is the CASCADE code calculation with transmission coefficients of evaporated particles (neutron, proton, and α particles) calculated using the default global set of optical model parameters of the TLCALC subroutine of the CASCADE code [3] as mentioned in Sec. IV B. However, the CASCADE code slightly underpredicts the cross sections.

V. CONCLUSION

In the energy range of the measurement, both the geometry-dependent hybrid model and the hybrid model (ALICE/91 code calculations) fit the excitation functions reasonably well taking limitations of the calculations into account. The experimental isomeric cross-section ratios (STAPRE code calculation) are reproduced fairly well by the calculation by the set (ii) $FM = 500\,(\mathrm{MeV})^3$, $\eta = 1.0$. However, the CASCADE code calculations slightly underpredicts the measured cross sections. Considering the multitudes of uncertainties and limitations of the calculations into account, the statistical model in the range of the present experiment can reproduce fairly well the excitation function and isomeric cross-section ratios.

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