RATIO OF CROSS SECTIONS FOR THE PRODUCTION OF THE Sc^{44} *AND* Sc^{44m} *ISOMER PAIR IN HEAVY ION REACTIONS*

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The energy dependence of the ratios of the cross sections for formation of the isomer pair $Sc^{44,44m}$ in the reactions $Al^{27}(Ne^{20}, 2pn)$, $Al^{27}(Ne^{22}, \alpha n + 2p3n)$ and $S^{32}(O^{16}, 3pn)$ is measured. The excitation functions for reactions leading to the formation of Sc^{44m} and Sc^{44} and also Sc^{43} and Sc^{46} have a form which is characteristic of reactions occurring via a compound nucleus. On the basis of the isomer ratio energy dependence, it is concluded that scandium isotopes are produced in reactions with collision parameters corresponding to angular momenta $< 25\hbar$.

1. INTRODUCTION

THE investigation of the energy dependence of the ratio of the cross sections for the production of an isomer pair with a large spin difference is a promising method for the study of the mechanism of nuclear reactions. The value of this ratio should depend appreciably on the angular momentum transferred to the nucleus by the incoming particle. The angular momentum is determined, in turn, by the energy and mass of the incoming particles and by the mechanism of the nuclear reaction.

In the case of reactions that proceed via a compound nucleus, the angular momentum introduced increases with increasing energy of the incoming particle. This should lead to an increase in the isomer ratio, that is, the ratio of the cross section for the production of the isomer with the larger spin to the cross section for the production of the isomer with the smaller spin. In direct nuclear interactions, the nucleus acquires a smaller angular momentum at the same incoming-particle energy. In this case a lower value of the isomer ratio is to be expected.

In reactions with heavy ions, the angular momentum introduced into the nucleus can, in accordance with theoretical estimates, be appreciable and equal to several times 10 $\hbar$ units. So large an angular momentum should exert an appreciable influence on the mechanism of the nuclear reactions with heavy ions.

We have investigated the isomer ratio $\sigma(Sc^{44m})/\sigma(Sc^{44})$ in reactions with heavy ions. The isomer pair $Sc^{44,44m}$ is convenient for the performance of the experiment, and the corresponding isomer ratio was investigated many times in reactions with light particles [1-4] and low-energy heavy ions [5-7]. In reactions with light particles one observes in all cases an initial increase in the isomer ratio with energy of the incoming particles, which is interpreted as the consequence of the formation of a compound nucleus. At high energies, a decrease is observed in the isomer ratio, indicating an increasing role of the mechanism of direct knock-on of the nucleons at these energies. In reactions with nitrogen ions with maximum energy 28 MeV, an increase is observed in the isomer ratio with increasing energy.

2. EXPERIMENTAL PROCEDURE

The scandium isotopes were obtained in the following reactions:

$$Al^{27}(Ne^{20}, 2pn)\,Sc^{44,44m},$$
$$Al^{27}(Ne^{22}, \alpha n + 2p3n)\,Sc^{44,44m},$$
$$S^{32}(O^{16}, 3pn)\,Sc^{44,44m},$$

and also

$$Al^{27}(Ne^{20}, \alpha + 2p2n)\,Sc^{43},$$
$$Al^{27}(Ne^{22}, \alpha 2n + 2p4n)\,Sc^{43},$$
$$S^{32}(O^{16}, \alpha p + 3p2n)\,Sc^{43},$$
$$Al^{27}(Ne^{22}, 2pn)\,Sc^{46}.$$

In the experiments with neon, stacks of 6—12 aluminum foils from 3 to 9 μ thick were irradiated. In the experiments with oxygen, stacks of aluminum foil 6 μ thick were used, each foil being coated with 0.6—0.7 mg/cm² of sulfur.

*Deceased.

The bombardment was by the internal beam of the U-300 cyclotron of the Laboratory for Nuclear Reactions of the Joint Institute for Nuclear Research. The ion current ranged from 0.1 to 2 μA in the various experiments, the ion energy from 40 to 175 MeV, and the bombardment time from 15 minutes to 2 hours.

In most cases, the scandium was chemically separated after the bombardment. The bombarded targets were dissolved in a mixture of hydrochloric and nitric acids in the presence of carriers of scandium and other elements, produced as a result of the nuclear reactions. Caustic alkali was used to precipitate the hydroxides, and then the scandium was converted into solution by treating the precipitate with ammonium carbonate. The scandium was separated from the solution in phosphate form. The yield of the scandium was determined by weighing.

The γ radiation from the specimens was measured with a scintillation spectrometer and a 100-channel AI-100 pulse-height analyzer. The information from the analyzer was recorded automatically on a chart. The area under the peaks of the γ lines was measured with a planimeter.

The decay scheme of the isomer pair $Sc^{44,44m}$ is shown in Fig. 1 [8]. As follows from the scheme, the decay of the isomer and ground states proceeds essentially via the 1160-keV level of Ca^{44}. From the change in the intensity of this γ line with time it is possible to determine the isomer ratio, without introducing additional corrections for the counting efficiency for γ rays of different energy.

The curves showing the time variation of the intensity of the γ line with E_γ = 1160 keV and the annihilation line with E_γ = 510 keV satisfied to a good degree, in all the experiments, the relation

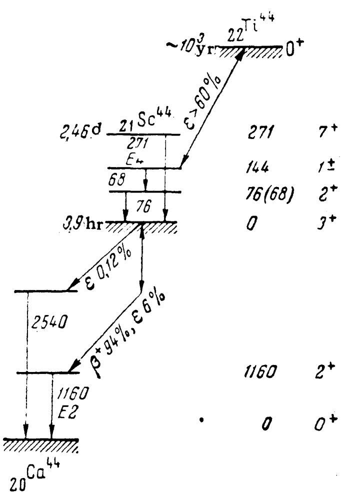

FIG. 1. Level scheme for the decay of the isomer pair $Sc^{44,44m}$.

$$J = A_1 e^{-\lambda_1 t} + A_2 e^{-\lambda_2 t},$$

where $\lambda_1 = 0.01175\ hr^{-1}$ — probability of Sc^{44m} decay, $\lambda_2 = 0.178\ hr^{-1}$ — probability of Sc^{44} and Sc^{43} decay, t — time following the end of the bombardment. The factors A_1^{1160}, A_2^{1160}, A_1^{510}, and A_2^{510} preceding the exponentials were determined by approximating the experimental point to this function by least squares, using the M-20 electronic computer.

The isomer ratio was determined from the formula

$$\sigma_m/\sigma_0 = \left[\frac{\lambda_2-\lambda_1}{\lambda_2}\frac{1-\exp(-\lambda_2 t_1)}{1-\exp(-\lambda_1 t_1)}\right] \Big/ \left[\frac{A_2^{1160}}{A_1^{1160}} + \frac{\lambda_1}{\lambda_2}\frac{1-\exp(-\lambda_2 t_1)}{1-\exp(-\lambda_1 t_1)}\right],$$

where t_1 — duration of the bombardment.

From the values of A_1^{520} we plotted the excitation function of the reaction leading to Sc^{44m}. The corresponding excitation functions for Sc^{44} and Sc^{45} were plotted from values of A_1^{510} with account of the isomer ratios for Sc^{44} and in accordance with the expression

$$\left(A_2^{510} - A_1^{510}\frac{A_2^{1160}}{A_1^{1160}}\right)\frac{1-\exp(-\lambda_1 t_1)}{1-\exp(-\lambda_2 t_1)}\frac{\lambda_2}{\lambda_2-\lambda_1}$$

for Sc^{43}. The excitation function for Sc^{46} was determined from the 890-keV γ line with account of the γ spectrometer efficiency.

The excitation function was corrected for the range of the recoil nuclei. Special experiments were carried out on the determination of the dependence of the range of the recoil nuclei in $S^{32}(O^{16}, 3pn)Sc^{44m}$ on the energy. In these experiments, the target was made up of four layers of sulfur 0.6—0.7 mg/cm² thick, with five aluminum foils 0.6—0.9 mg/cm² placed between each layer to serve as absorbers. The distribution of the activity of Sc^{44m} in the absorbers was used to determine the average ranges of the recoil nuclei Sc^{44m} in aluminum, up to values corresponding to 30 MeV (Fig. 2). The range-energy relation was linear in this energy region. The range of the scandium nuclei in aluminum at energies up to 70 MeV was determined by linear extrapolation.

It must be noted that the measured ranges were approximately one-sixth those calculated by the Bohr formula [9] and about one-third of the ranges obtained by Matsuo and Sugihara [3]. The reason for the discrepancy between our data and those of Matsuo and Sugihara is not clear.

3. RESULTS AND DISCUSSION

The excitation functions for the reactions $Al^{27} + Ne^{20}$, $Al^{27} + Ne^{22}$, and $S^{32} + O^{16}$ are shown in

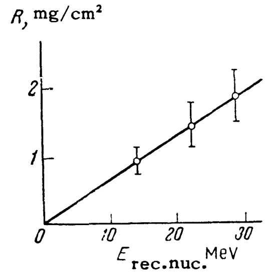

FIG. 2. Range of Sc^{44m} nuclei vs. recoil energy in the reaction $S^{32}(O^{16}, 3pn)Sc^{44m}$.

Figs. 3a, b, and c. They all have the form characteristic of the reactions proceeding via a compound nucleus. In those cases when reactions (αxn) and (αxp) are possible in addition to the evaporation of free nucleons, the excitation function has two maxima. What is striking is that Sc^{43} is obtained in the reactions $Al^{27} + Ne^{22}$ and S^{32} and O^{16} essentially because of evaporation of an α particle and two neutrons or a proton.

The absolute values of the reaction cross sections were not determined. According to crude estimates they amount to several times 10 millibarns at the maximum of the Sc^{44m} excitation curves.

The isomer ratios for $Sc^{44,44m}$ are plotted against the excitation energy for different reactions in Fig. 4. It is difficult to attribute the cessation in the growth of the isomer ratio with increasing energy at $E^* \sim 55$ MeV to direct knock-on processes, as in reactions with light particles. The form of the excitation functions indicates that at excitation energies exceeding 55 MeV the isomer pair of scandium is produced via a compound nucleus.

The dependence of the isomer ratio on the energy can be explained by assuming that the formation of the isomer pair of scandium proceeds via a compound nucleus with angular momentum not exceeding a critical value J_{cr}. The cessation in the growth of the isomer ratio at an energy ~ 55 MeV indicates that J_{cr} has an approximate value $25\hbar$. The presence of a critical angular momentum should lead to a decrease in the cross section for the production of scandium isotopes at higher energies. This agrees with the small value of the absolute cross section, which follows from our estimates. The hypothesis of existence of a critical value of angular momentum also agrees with the results of the experiments of Anderson et al [10]. These authors have shown that in the $Al^{27} + O^{16}$ reaction at 116 MeV the greater part of the total cross section (0.5—1 b) goes to reactions that lead to the formation of heavy fragments (F, O, N, C).

An attempt was made to calculate the energy variation of the isomer ratio, using the cascade statistics proposed previously [11], modified as applied to our reactions. Although good agreement with the experimental data was obtained (see the solid curves of Fig. 4), this agreement must not be overrated, since several non-rigorous assumptions had to be made (particularly concerning the multipolarity and the number of emitted γ quanta).

The calculations for the reaction $Al^{27} + Ne^{20}$ reduced essentially to the following items.

1. Cascade statistics and an M-20 electronic computer were used to calculate the γ-transition cascades. The transitions were assumed to be dipole, and the parameter σ [1)] was chosen equal to 4. Unlike the data of Huizenga and Vandenbosch [11], the forbidenness of the transitions between the states with spin zero was taken into account.

2. The distribution of the weights of the compound-nucleus spins to the cross section for its production was chosen proportional to the spin up to a value J_{max}, determined from the semiclassical formula.

3. The number of γ transitions in the cascade was taken to equal $J + 3$.

4. The isomer ratio was plotted against the maximum spin introduced into the compound nucleus (5).

5. The value of J_{cr} was chosen equal to $25\hbar$.

6. The average angular momentum l carried away by the three evaporated nucleons at the given excitation energy was calculated.

7. The difference $J_{max} - l$ was used to determine the corresponding isomer ratio from the curve of Fig. 5.

The fall-off of the isomer ratio curve was due to the fact that at large excitation energies the evaporating nucleons carry away a large angular momentum from the compound nucleus. The agreement with the experimental data in the excitation energy region 30—40 MeV can be improved by introducing corrections for the penetration through the Coulomb barrier.

Analogous calculations were made also for the reaction $Al^{27} + Ne^{22}$ with $J_{cr} = 26\hbar$. At low excitation energies, account was taken of the evaporation of the α particle and the neutron, while at larger ones—of the evaporation of two protons and three neutrons. In the energy region 70—80 MeV, the calculated values should be averaged with account of the weights of the overlapping excitation functions of the (αn) and (2p3n) reactions.

1)σ – cutoff parameter in the spin dependence of the nuclear level density.

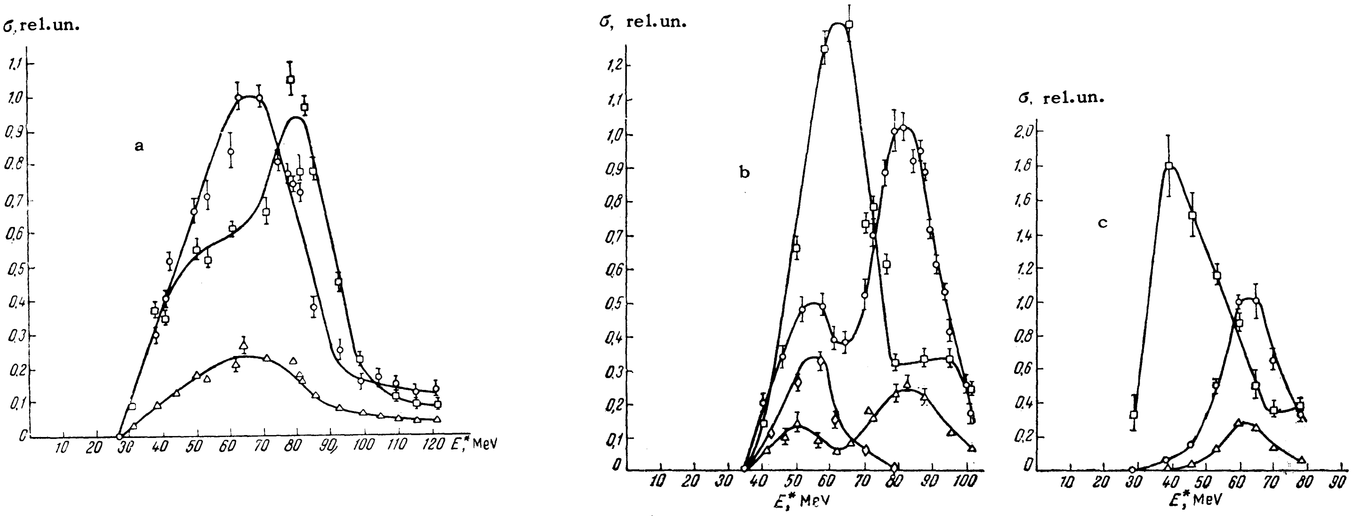

FIG. 3. Excitation functions of the reactions $Al^{27} + Ne^{20}$ (a), $Al^{27} + Ne^{22}$ (b) and $S^{32} + O^{16}$ (c), which lead to the following scandium isotopes: Sc^{44m} (o), Sc^{44} (△), Sc^{43} (□) and Sc^{46} (◇).

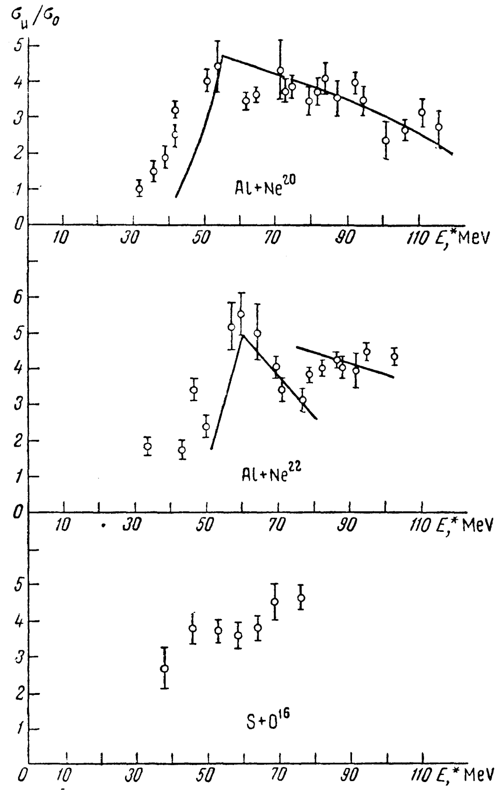

FIG. 4. Energy dependence of the isomer ratio in reactions with heavy ions. The continuous lines are the theoretical curves.

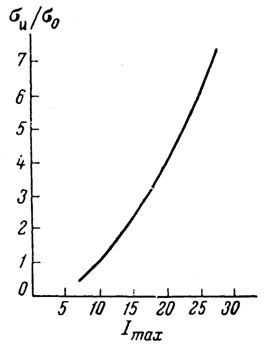

FIG. 5. Dependence of the isomer ratio on the maximum spin of the compound nucleus, calculated from cascade statistics.

No calculations were made for the isomer ratios in the reaction $S^{32} + O^{16}$. The slight rise in the isomer ratio at the high excitation energies is apparently due to the (αpn) reaction with the S^{34} impurity (4%).

It is difficult to draw from our experimental data any conclusions with respect to the cause of occurrence of the critical value of the angular momentum in the production of the compound nucleus. It can be assumed that the mechanism of grazing collisions proposed by Kaufmann and Wolfgang[12] sets in when the centrifugal forces prevent complete coalescence of the nuclei at large collision parameters.

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