SOVIET PHYSICS JETP VOLUME 19, NUMBER 6 DECEMBER, 1964

CROSS SECTION RATIO FOR FORMATION OF THE ISOMER PAIR $Sc^{44,44m}$ *FROM DIRECT-INTERACTION REACTIONS WITH HEAVY IONS*

V. A. FOMICHEV*, B. A. GVOZDEV, and V. V. BREDEL'

Joint Institute for Nuclear Research

Submitted to JETP editor January 19, 1964

J. Exptl. Theoret. Phys. (U.S.S.R.) 46, 2017-2022 (June, 1964)

The Sc^{44m}/Sc^{44} isomer ratio in neutron stripping reactions induced by irradiating Sc with O^{16} or Ne^{22} ions is measured. It is of the order of unity and is independent of energy. It is shown that during many-nucleon transfers (3pn) in the $Al^{27} + Ar^{40} \rightarrow Sc^{44,44m}$ reaction the isomer ratio becomes ~ 6.5, that is, larger than in reactions of complete fusion of nuclei.

1. INTRODUCTION

ONE of the methods of studying the influence of angular momentum, deposited in a nucleus in reactions with heavy ions, on the mechanism of these reactions is the investigation of the energy dependence of the ratio of the cross sections for formation of an isomer pair with a large spin difference. In a previous article [1] we have studied the energy dependence of the formation cross sections of $Sc^{44,44m}$ in heavy ion reactions proceeding via formation of a compound nucleus. The experiments showed that complete fusion of the nuclei occurs only when the angular momentum deposited is less than a certain critical value J_{crit}. In peripheral collisions, when $J > J_{crit}$, centrifugal forces and Coulomb repulsion prevent complete fusion of the nuclei, and in this case a reaction occurs with transfer of some number of nucleons between the incident ion and the target nucleus. The existence of this mechanism of a nuclear reaction with heavy ions is confirmed also by recent theoretical calculations [2,3].

In the present investigation we have studied the energy dependence of the cross sections for formation of the isomer pair $Sc^{44,44m}$ in reactions with heavy ions, when complete fusion of the nuclei does not occur.

2. EXPERIMENTAL METHOD

The isomer pair $Sc^{44,44m}$ was obtained in the one-neutron-transfer reactions:

$$Sc^{45} + O^{16} \rightarrow Sc^{44,\,44\,m},$$
$$Sc^{45} + Ne^{22} \rightarrow Sc^{44,\,44\,m},$$

and also in the many-nucleon-transfer reaction

$$Al^{27} + Ar^{40} \rightarrow Sc^{44,\,44m}.$$

In the experiments with oxygen we irradiated a stack of six 6–8 μ thick aluminum foils on which a layer of scandium oxide (1.1–1.5 mg/cm^2) was deposited. In the neon experiments a scandium oxide layer (2.0–2.8 mg/cm^2) was deposited on 2–2.5 μ nickel foils. It was ascertained beforehand that scandium is not formed in appreciable quantities in the interaction of neon with nickel. For irradiation by argon a stack of aluminum foils 3–8 μ thick served as a target.

The irradiation was carried out in the internal beam of the U-300 cyclotron of the nuclear reactions laboratory at the Joint Institute for Nuclear Research. The ion energy was measured by absorption in aluminum and in some cases with the help of semiconductor detectors [4]. After the irradiation a chemical separation was performed. The target was dissolved in a mixture of hydrochloric and nitric acids in the presence of carriers of the elements formed in the nuclear reactions. In the dissolving of the aluminum targets irradiated by argon ions, a definite quantity of scandium was also added. Then the hydroxides were precipitated by a caustic alkali (for separation from aluminum) or by ammonia (for separation from nickel). A second precipitation of hydroxides was performed with pyridine. By treating the precipitate with ammonium carbonate the scandium was transferred to solution and was separated as the phosphate. The yield of scandium was determined by weight.

The gamma radiation from the specimens was measured in a scintillation spectrometer with an AI-100 100-channel analyzer. The spectrum was

*Deceased.

recorded on a chart recorder, and the area of the γ-line peaks was measured with a planimeter.

Along with Sc^{44}, other scandium isotopes were observed: Sc^{43} (E_γ = 511 keV, T = 3.9 hr), Sc^{46} (E_γ = 1120 keV, T = 84.1 d), Sc^{47} (E_γ = 160 keV, T = 3.4 d). The transition of Sc^{44m} to the ground state occurs with E_γ = 270 keV (T = 59 hr) and Sc^{44} decays mainly with E_γ = 1160 keV (T = 3.9 hr) [5].

The experimental data on the γ-line intensity measurements were analyzed on an electronic computer by the method of least squares in accordance with the relations

$$J = A_1 e^{-\lambda_1 t} + A_2 e^{-\lambda_2 t} + A_3 e^{-\lambda_3 t} \quad \text{for } E_\gamma = 1160 \text{ keV},$$

$$J = A_1 e^{-\lambda_1 t} + A_2 e^{-\lambda_2 t} \quad \text{for } E_\gamma = 511 \text{ keV},$$

where λ_1 = 0.01175 hr^{-1} is the decay probability of Sc^{44m}, λ_2 = 0.178 hr^{-1} is the decay probability of Sc^{44} and Sc^{43}, λ_3 = 0.000343 hr^{-1} is the decay probability of Sc^{46} (the γ-lines 1160 and 1120 keV in the spectrometer were not resolved), and t is the time after the end of the irradiation.

The isomer ratio, and also the relative cross section for formation of the isotopes Sc^{43}, Sc^{44}, and Sc^{44m} were determined in the same way as in our earlier work [1], and for Sc^{46} and Sc^{47} by the corresponding γ-peaks, taking into account the efficiency of the γ-spectrometer.

The experiment on the angular distribution of Sc^{44} and Sc^{44m} in the reaction $Al^{27} + Ar^{40} \rightarrow Sc^{44,44m}$ was performed with a special attachment to the probe. The distance from the target (Al, 0.8 mg/cm²) to the collector was 80 mm.

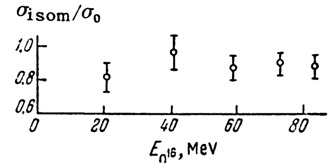

FIG. 1. Energy dependence of the isomer ratio of $Sc^{44,44m}$ in the reaction with O^{16} ions.

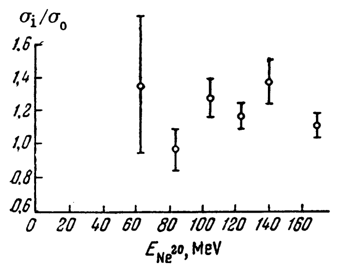

FIG. 2. Energy dependence of the isomer ratio of $Sc^{44,44m}$ in the reaction with Ne^{22} ions.

3. RESULTS AND DISCUSSION

A. One-neutron-transfer reactions. The dependence of the isomer ratio $\sigma(Sc^{44m})/\sigma(Sc^{44})$ on the energy of the incident ion in the reactions $Sc^{45} + O^{16}$ and $Sc^{45} + Ne^{22}$ is presented in Figs. 1 and 2, and the dependence of the relative cross section for formation of the scandium isotopes with mass numbers 43, 44, 46, and 47, in the reaction $Sc^{45} + Ne^{22}$ is given in Fig. 3. It is noteworthy that the isomer ratio, in the removal of one neutron from Sc^{45}, does not depend on the incident ion energy and is ~ 1, being somewhat larger for Ne^{22} ions than for O^{16}.

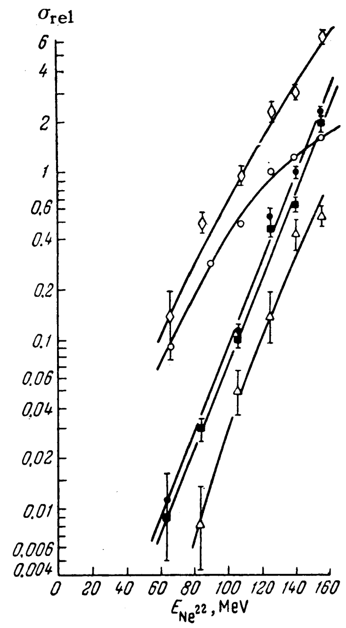

FIG. 3. Energy dependence of the relative cross section for formation of Sc isotopes in neutron-transfer reactions on bombardment of Sc^{45} by Ne^{22} ions: ● – Sc^{44m}(–n), ■ – Sc^{44}(–n), △ – Sc^{43}(–2n), ◇ – Sc^{46}(+n), o – Sc^{47}(+2n).

This value of the isomer ratio evidently indicates that, in a one-neutron-transfer reaction, states with large spin are excited. Calculations of the mean spin value of these excitations by the method of cascade statistics [6] is not possible, since the number of transitions is small and the spins of the Sc^{44} levels lying above the isomeric state are not known.

B. Many-nucleon-transfer reactions. Formation of $Sc^{44,44m}$ in reactions with transfer of many nucleons was achieved by irradiating stacks of aluminum foils by 270 MeV Ar^{40} ions. Picking up three protons and one neutron from the Al^{27} nucleus, Ar is converted into Sc. The relative yield of Sc isotopes with mass numbers 43, 44, 46, and 47 at different depths in the stack of foils is shown in Fig. 4.

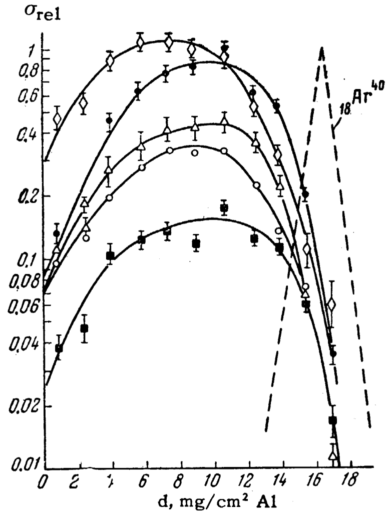

FIG. 4. Relative yield of Sc isotopes in the reaction $Al^{27} + Ar^{40}$ at different depths in the stack of aluminum foils: ● – Sc^{44m} (+3pn), ■ – Sc^{44} (+3pn), △ – Sc^{43} (+3p), ◇ – Sc^{46} (+3p3n), o – Sc^{47} (+3p4n).

To check whether the presence of Sc in the first foils of the stack was due to the presence in the Ar ion beam of a low energy component, a background experiment was performed. A stack of eleven 8.5 μ aluminum foils was irradiated by a beam of 256 MeV Ar ions. The distribution of 1300 keV γ-activity was studied as a function of depth in the stack. This activity decayed with half-lives of T = 14.9 hr, corresponding to the isotope Na^{24}, and T = 1.82 hr,[1)] corresponding to the formation of Ar^{41}. Figure 5 shows curves of the activity distribution. Also shown in Fig. 5 is the range of 256 MeV Ar ions.

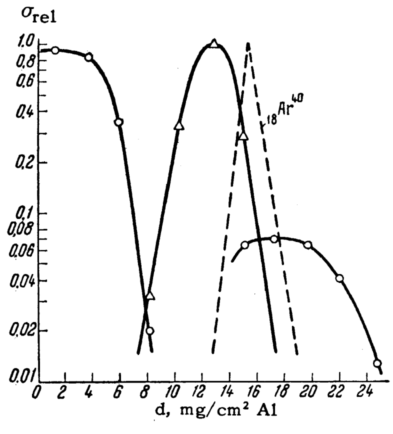

FIG. 5. Relative yield of Na^{24} (o) and Ar^{41} (△) in the reaction $Al^{27} + Ar^{40}$ at different depths in the stack of aluminum foils.

[1)]In addition, an unidentified 11-day activity was present.

The Ar^{41} activity distribution shows that there is no low energy component in the Ar ion beam of any significant intensity. The distribution of Na^{24} nuclei is interesting. These nuclei are formed both by removing two protons and one neutron from Al^{27} nuclei (the short range nuclei) and by removing seven protons and nine neutrons from Ar^{40} ions (the longer range nuclei).

The distribution of the isomer ratio of $Sc^{44,44m}$ in the stack of aluminum foils after irradiation by 270 MeV argon ions is shown in Fig. 6. The large value of the isomer ratio, which reaches ~ 6.5, is striking. We showed earlier [1] that in reactions with complete fusion of the nuclei the maximum value of the isomer ratio $\sigma(Sc^{44m})/\sigma(Sc^{44})$ is ~ 5.

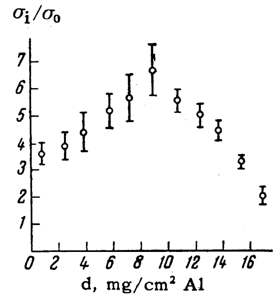

FIG. 6. Distribution of the isomer ratio of $Sc^{44m,44}$ in the reaction $Al^{27} + Ar^{40}$ as a function of depth in the stack of aluminum foils.

With the aid of the cascade statistics method we can show that the isomer ratio can be larger in many-nucleon-transfer reactions than in complete fusion reactions, although the Sc nucleus receives less angular momentum in the first case. In complete fusion reactions Sc nuclei are formed with spins from 0 to some value J, where $J \leq J_{crit}$. In calculation of the isomer ratio according to cascade statistics, it is necessary to average over the cascades of γ-rays emitted by the nuclei with initial spins from 0 to J. Here we must take into account the relative probability with which nuclei with a given angular momentum are formed in the reaction [1]. Because of the contribution of cascades with a low initial spin, the average isomer ratio obtained for complete fusion reactions is relatively small.

In the case of many-nucleon-transfer reactions only peripheral collisions are possible. Therefore in calculation of the isomer ratio it is necessary to consider only cascades with initial spins corresponding to peripheral collisions. In this case the isomer ratio can be comparatively large even for small angular momentum values.

For evaluation of the isomer ratio for the reaction $Al^{27} + Ar^{40} \rightarrow Sc^{44,44m}$ for 270 MeV Ar ions,

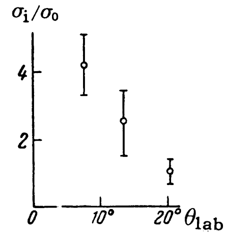

FIG. 7. Angular distribution of the isomer ratio of $Sc^{44m,44}$ in the reaction $Al^{27} + Ar^{40}$ for $E_{Ar} = 270$ MeV.

let us consider a stationary Ar^{40} nucleus into whose periphery are knocked three protons and one neutron with an energy $E_{lab} = 27$ MeV. An angular momentum of $10\hbar$ will be deposited in the Sc^{44} compound nucleus. For the cascade with initial spin $J = 10\hbar$ and for an average number of γ-transitions $N_\gamma = J + 3 = 13$, we obtain for the isomer pair of scandium $\sigma_i/\sigma_0 = 7.3$ (the cutoff parameter for the spins σ was taken as 4). In the calculations we utilized the new spin values (2 for the ground state and 6 for the isomeric state) obtained by Harris and Cullen[7].

According to the treatment described, the peak of the isomer ratio curve at $d = 9.5$ mg/cm^2 Al should correspond to a reaction with transfer of three protons and one neutron, occurring in the first foil of the stack. When a reaction of this type occurs at a greater depth in the stack of aluminum foils, the sum of the ranges of the Ar nucleus before the reaction and the Sc nucleus after the reaction is greater than 9.5 mg/cm^2 Al. The isomer ratio in this case is less than at the peak, because of the reduction in energy of the Ar ions. This can qualitatively explain the drop in the isomer ratio curve at large depths in the foil stack.

The drop in isomer ratio at small thicknesses of the foil stack we can attempt to explain as due to reactions between Ar^{40} and Al^{27} with a smaller impact parameter than in the case discussed earlier. Here argon can capture from aluminum more than three protons and one neutron and then evaporate the excess nucleons. The Ar ions then lose more energy than in the case of four-nucleon transfer, and their range in Al is smaller. Furthermore, the range straggling of Sc nuclei formed in this way will be increased as a result of the nucleon evaporation. All this results in a substantial number of Sc nuclei being found in the first foils of the stack.

The qualitative explanation given agrees also with the angular distribution of the isomer ratio, shown in Fig. 7. Ar^{40} ions which capture three protons and one neutron interact relatively weakly with the Al^{27} nuclei and fly off preferentially forward. The larger values of isomer ratio correspond to this type of reaction. Therefore the isomer ratio for small angles is large. For a closer interaction the deviation of the Sc nuclei from the direction of motion of the Ar ions can be larger, and the isomer ratio is less.

The authors are grateful to G. N. Flerov, S. M. Polikanov, and E. D. Donets for discussion of this work, and to A. N. Filipson and the members of the group directed by him for providing dependable operation of the cyclotron during the irradiations.

[1] Bredel', Gvozdev, and Fomichev, JETP **45**, 904 (1963), Soviet Phys. JETP **18**, 622 (1964).

[2] B. N. Kalinkin and I. Zh. Petkov, Preprint R-1347, Joint Institute for Nuclear Research, Dubna, 1963.

[3] Cohen, Plasil, and Swiatecki, Preprint UCRL-10775, Berkeley, 1963.

[4] Kekk, Mikheev, Pleve, and Fefilov, PTÉ, No. 4, 27 (1963).

[5] B. S. Dzhelepov and L. K. Peker, Skhemy raspada radioaktivnykh yader (Decay Schemes of Radioactive Nuclei), AN SSSR, 1958, p. 91.

[6] J. R. Huizenga and R. Vandenbosch, Phys. Rev. **120**, 1305 (1960). R. Vandenvosch and J. R. Huizenga, Phys. Rev. **120**, 1313 (1960).

[7] D. L. Harris and J. D. Cullen, Phys. Rev. **132**, 310 (1963).

Translated by C. S. Robinson
300