SOVIET PHYSICS JETP

A translation of the Zhurnal Éksperimental'noĭ i Teoreticheskoĭ Fiziki

Vol. 20, No. 2, pp. 259-525 (Russ. Orig. Vol. 47, No. 2, pp. 393-785, August 1964) February 1965

EXCITATION FUNCTIONS OF THE (α, γ) AND (α, n) REACTIONS OF TIN ISOTOPES

D. E. KHULELIDZE, V. L. CHIKHLADZE, M. Z. MAKSIMOV, and V. G. ONUFRIEV

Submitted to JETP editor August 13, 1963

J. Exptl. Theoret. Phys. (U.S.S.R.) 47, 393-399 (August, 1964)

The excitation functions for the $Sn^{112}(\alpha, \gamma)Te^{116}$, $Sn^{112}(\alpha, n)Te^{115}$, and $Sn^{114}(\alpha, n)Te^{117}$ reactions are measured for particle energies between 10 and 20 MeV. The peak values of the cross sections are respectively 8, 54 and 290 mb. The cross sections for the (α, γ) reaction are very large. The cross sections are calculated on the basis of the compound nucleus model. The probability for γ-quantum emission is calculated in the single particle approximation as well as with the aid of formulas that take the structure of the giant resonance into account. In the latter case the agreement with the experiments is much better.

INTRODUCTION

In the study of the mechanisms governing the course of nuclear reactions induced by bombarding particles of medium energy, the emission of γ quanta is frequently neglected. Such an assumption is not always valid. Consequently knowledge of the dependence of the relative probability of γ-quantum emission on the energy of the incident particles is one of the important aspects in the comparison of any theory of nuclear reactions with experiment, particularly near threshold.

In addition, the study of the radiative capture of particles by nuclei is of interest in itself, since the mechanism of this process still remains unclear [1]. Reactions of this type have been studied most thoroughly with protons and neutrons of energy up to 4-5 MeV. On the other hand, relatively few investigations have been made of radiative capture of nucleons with higher energies (deuterons, α particles, etc.), or heavier particles. This is perfectly understandable, since the cross sections of such processes increase abruptly with increasing energy, either because of the competition of particle emission, or because of the decrease in the interaction time. It has thus been shown by several investigations [2-4] that at α-particle energies larger than 10—12 MeV the ratio $\sigma(\alpha, \gamma)/\sigma_{tot}$ of the radiative-capture cross section to the total cross section is $\leq 10^{-3}$. The absolute values of the cross sections $\sigma(\alpha, \gamma)$ at the maximum amount only to several hundred microbarns.

In many cases, however, the cross section of such a process is sufficiently large. In particular, when we investigated [5] the decay scheme of Te^{115}, we noted in the γ spectrum an intense line with $E_\gamma = 94$ keV, occurring in the decay of Te^{116}. Preliminary experimental estimates have shown that the cross section of the $Sn^{112}(\alpha, \gamma)Te^{116}$ reaction reaches several millibarns, which at first glance appears to be unexpected. In this connection we set up special experiments to determine, using a compound of Sn^{112}, the cross sections of the reactions (α, γ) and (α, n) as functions of the α-particle energy.

EXPERIMENTAL PROCEDURE AND RESULTS

As already mentioned, we investigated the γ spectrum of Te^{115} ($T_{1/2} = 7$ minutes). To this end, α particles of energy $E_\alpha = 21$ MeV were used to bombard a tin compound enriched to 60% Sn^{112}. A line with $E_\gamma = 94$ keV was observed in the γ spectrum of the chemically separated tellurium fraction. Its intensity decreased with a half-life $T_{1/2} = 2.5$ hours. The value of the internal conversion coefficient as measured with a β spectrometer, $\alpha_K = 1.5 \pm 0.3$, and the ratio $\alpha_K/\alpha_L = 2.3 \pm 0.2$ show that this transition is E2. We separated the antimony from the tellurium fraction chemically. The γ spectrum of the antimony fraction exhibited annihilation radiation and a γ line with $E_\gamma = 1280$ keV, the intensity of which decreased with a half-life of 16 minutes. It was shown by the fractional separation method that the parent tellurium decays with a half-life of 2.5 hours. It follows from these experimental data that the γ transition with $E_\gamma = 94$ keV belongs to the well investigated isotope Te^{116}. This is seen from the decay schemes (Fig. 1) compiled on the basis of the literature data[5-8].

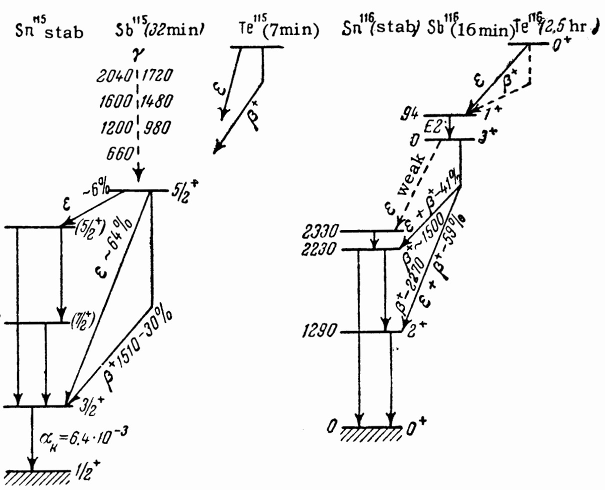

FIG. 1. Decay schemes of Te^{115} and Te^{116} (for the transition $E_\gamma = 94$ keV, value of $\alpha_K = 1.4$, and K : L : M = 0.40 : 0.14 : 0.036).

In our case Te^{116} could be produced in accordance with two reactions, namely:

$$Sn^{112}(\alpha, \gamma)Te^{116}, \qquad Sn^{114}(\alpha, 2n)Te^{116}$$

(the Sn^{114} contamination of our compound was $\sim 2\%$). To clarify the method of formation of Te^{116}, a special experiment was set up. Alpha particles were used to irradiate a tin compound enriched to 57% Sn^{114}, and the tellurium fraction was separated chemically. The intensity of the 94-keV γ transition decreased sharply (by a factor ~25—30) compared with the intensity observed in the irradiation of the Sn^{112} compound. Complete vanishing of the 94-keV line could not be observed, since the Sn^{114} compound contained an admixture of Sn^{112} ($\sim 1.5\%$). It was thus shown unequivocally that Te^{116} is produced by the reaction

$$Sn^{112}(\alpha, \gamma)Te^{116}.$$

It is seen from Fig. 1 that in order to determine the yield ratio $B(\alpha, n)/B(\alpha, \gamma)$ it is sufficient to measure the ratio of the intensities of the 499-keV (Sb^{115}, $T_{1/2} = 32$ minutes) and 94-keV (Te^{116}, $T_{1/2} = 2.5$ hours) transitions. To this end a compound of $Sn^{112} \sim 40$ mg/cm^2 thick was bombarded with α particles (current 0.85 μA) for 50—60 minutes. The tellurium fraction was separated from the tin target chromatographically, and a β spectrometer was used to measure the ratio of the intensities of the conversion lines belonging to the transitions with energies 94 and 499 keV. Simple calculations yielded a value $B(\alpha, n)/B(\alpha, \gamma) = 11.3 \pm 1.5$. The γ spectrometer was used to determine the absolute value of the yield: $B(\alpha, \gamma) = (5.5 \pm 1.2) \times 10^{-7}$.

To plot the cross sections $\sigma(\alpha, \gamma)$ and $\sigma(\alpha, n)$, the method of foil stacks was used. To this end, the Sn^{112} compound was rolled to a thickness 5 mg/cm^2. The energy of the particles incident on each foil was determined from the range-energy ratio [9]. The foil was bombarded on the internal target of the cyclotron with 0.44 μA of α particles for 40 minutes. The initial α-particle energy was reduced to ~20 MeV by varying the final cyclotron radius, since the threshold of the reaction $Sn^{114}(\alpha, 2n)Te^{116}$ is 19.7 MeV [10,11]. The tellurium fraction was rapidly separated from the tin target together with the carrier (separation coefficient ~90%). A scintillation spectrometer was used to measure the intensity of the 94- and 511-keV γ transitions. Measurement of the 94-keV γ transition entailed no difficulty, since there are no γ lines to interfere with the measurement, but the measurement of the annihilation radiation was made difficult by the β^+ transitions in Te^{117} ($T_{1/2} = 1$ hour) and by the radioactive chain

$$Te^{116} \xrightarrow{\varepsilon} Sb^{116} \xrightarrow{\beta+} Sn^{116}.$$

Therefore the error in the measurement of $\sigma(\alpha, n)$ is somewhat larger than the error in the measurement of $\sigma(\alpha, \gamma)$. The results are given in Figs. 2a and b.

During the course of the experiments we measured also the cross section of the reaction $Sn^{114}(\alpha, n)Te^{117}$. The experimental data were obtained by measuring with the scintillation spectrometer the absolute intensities of the γ transitions with $E_\gamma = 160$ keV, occurring during

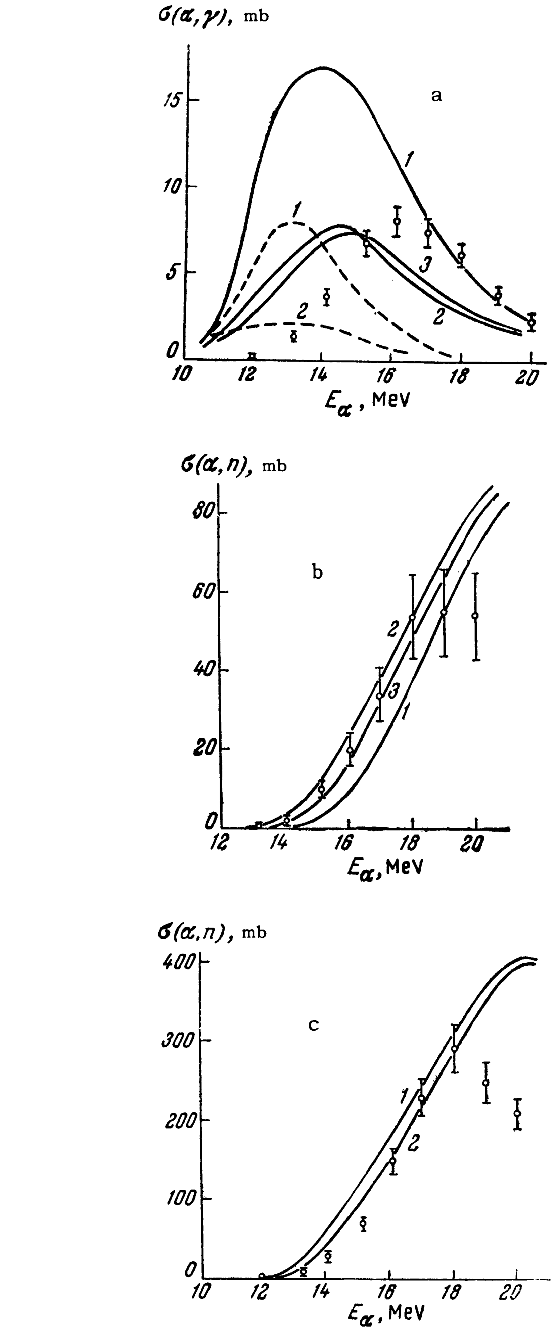

FIG. 2. Cross section of the following reactions: a – $Sn^{112}(\alpha,\gamma)Te^{116}$, b – $Sn^{112}(\alpha, n)Te^{115}$, c – $Sn^{114}(\alpha, n)Te^{117}$, as a function of the α-particle energy (l.s.).

the Te^{117} decay. The decay scheme of the radioactive chain $Te^{117} \rightarrow Sb^{117} \rightarrow Sn^{117}$ was taken from [6,12]. The results are given in Fig. 2c.

As already mentioned in the introduction, reactions of the (α, γ) type have been studied very little. In [2-4] the reaction (α, γ) was observed on three isotopes: Ni^{58}, Zn^{64}, and Xe^{136}. The cross section vs. α-particle energy curve is of the giant resonance type. The maxima of the cross sections lie in the α-particle energy region $E_\alpha \approx 14-18$ MeV, and the values of the cross section $\sigma_{max}(\alpha, \gamma)$ are 0.4, 0.9, and 0.06 mb respectively. In all three cases the ratio $\sigma(\alpha, n)/\sigma(\alpha, \gamma) \geq 5 \times 10^2$ in the energy region $E_\alpha \approx 14-18$ MeV.

In our case, however, the cross section $\sigma_{max}(\alpha, \gamma)$ reaches $\sim$ 8 mb, and the ratio $\sigma(\alpha, n)/\sigma(\alpha, \gamma) \leq 10$ in the same α-particle energy region. We have attempted to explain theoretically these experimental results, which at first glance are unexpected.

CALCULATION OF THE CROSS SECTIONS OF THE REACTIONS (α, n) AND (α, γ)

In accordance with the compound-nucleus model, the cross section for the reaction with emission of one particle b, is of the form [13,14]

$$\sigma_b(E_a) = \sigma_c(E_a)\{I_b(E_a - Q_b) - \sum_{\mu\neq\gamma} I_{b\mu}(E_a - Q_{b\mu})\} \equiv \sigma(E_a)\, I_{b\gamma}(E_a - Q_b), \qquad (1)$$

where E_a—energy of the incident particle in the center-of-mass system and Q_b and $Q_{b\mu}$—thresholds of the corresponding reactions; the summation in the second term corresponds to the possible emission of secondary particles (μ = n, p, α); $\sigma_c(E_a)$—cross section for the production of a compound nucleus, and $I_{b\gamma}$—probability of its decay with emission of first a particle b and then a γ quantum, i.e., the production probability of of the given isotope. The details of the calculations of these functions are given in the paper of Maksimov [14]. We merely note here that, unlike Maksimov and many others, we determined the cross section for the production of compound nuclei in both direct and inverse reactions using the formulas

$$\frac{\sigma_c}{\pi R_a^2} = D_a(x) = \begin{cases} \alpha_a x^{-1} \exp\{-2g_a f(x)\} & \text{for } x < 1 \\ 1 - (1 - \alpha_a)/x & \text{for } x > 1, \\ 1 & \text{for neutrons} \end{cases} \qquad (2)$$

where $x = E_a/B_a$, $f(x) = x^{-1/2}\cos^{-1}x^{1/2} - (1 - x)^{1/2}$, B_a—Coulomb barrier, $R_a = R_A + \rho_a$—radius of interaction of particles with the nucleus, $R_A = r_0A^{1/3} + r_1$, and ρ_a—radial parameter which takes into account the structure of the incident particles: $\rho_n \approx \rho_p \approx 0$, $\rho_\alpha \approx \rho_d \approx \rho_t \approx 1.2$ F. In all the calculations we took into account also the possibility of emission of dipole γ quanta, using the semiempirical result of Caryer and Jones [15]. In this case we have in formula (2) $\pi R_a^2 = Z(1.7/E_\gamma)(1 - Z/A)[F^2]$ and $D(x)$ takes the form

$$D(x) = \alpha_\gamma x^3 / [(x^2 - 1)^2 + \alpha_\gamma^2 x^2], \qquad (3)$$

where $\alpha_\gamma = \Delta_\gamma / B_\gamma$; $x = E_\gamma / B_\gamma$; $\Delta_\gamma = 5.5-6$ MeV—half-width of giant resonance for the absorption of dipole γ quanta, and $B_\gamma \approx 21.5 \exp(0.00274A)$ [MeV]—energy at the maximum of the resonance[16].

In calculating the possibility of emission of different particles, we used the ordinary dependence of the level density $\omega(U)$ on the excitation energy and on the mass number

$$\omega(U) = G \exp(\Lambda\sqrt{U}), \quad \Lambda \approx 0.55\sqrt{A}, \quad G \approx 2J + 1. \qquad (4)$$

For the radiation widths we used along with (3) also the formulas in the single-particle approximation [13], but with parameter $D_0 = 100$ MeV, obtained from an analysis of the cross sections of the reactions (n, γ) on slow neutrons [14]. In this case

$$D(x) = x^2, \qquad x = E_\gamma / 20;$$

$$\pi R_\alpha^2 \approx 5 \cdot 10^{-3} R_\gamma^2, \qquad R_\gamma \approx 1.2 A^{1/3} \text{ [F]}. \qquad (5)$$

The results of the calculations in accordance with the indicated formulas are shown in Fig. 2, and the thresholds of the nuclear reactions were calculated from the tables of [10,11]. Since the thickness of the foils was ~ 5 mg/cm^2 in our experiments (losses ~ 0.7 MeV for α particles with energy 10—20 MeV), the results of the calculations were averaged also over the corresponding energy interval with allowance for the slowing down of the α particles.

DISCUSSION OF THE RESULTS

Let us consider in greater detail the results of the experimental measurements and the theoretical calculations.

A. The reaction $Sn^{112}(\alpha, \gamma)Te^{116}$. Figure 2a gives the experimental and theoretical data for this reaction. The continuous curves correspond to the calculation of the γ-widths by formula (3), while the dashed ones—to formula (5). Inasmuch as the Te^{115} and Te^{116} masses have not been measured experimentally with sufficient accuracy [5,6], we used the semiempirical tables of Cameron [10] to calculate the thresholds of the corresponding reactions. These tables give in some cases deviations up to 1—1.5 MeV from the real values. Therefore in calculating the cross section $\sigma(\alpha, \gamma)$ we took two values of the binding energy of the α particles in the Te^{116} nucleus: $\epsilon_\alpha = 1.84$ MeV (after Cameron; curves 1) and $\epsilon_\alpha = 0.84$ MeV (presumed, curves 2). It is seen from Fig. 2a that the cross section of the (α, γ) reaction is very sensitive to a change in the binding energy of the particles in the nucleus. Therefore by suitable choice of this quantity we can improve somewhat the agreement between theory and experiment. In addition, we see that the calculations with the aid of formulas (3) are in better agreement with experiment, and this is perfectly understandable, since these semiempirical formulas represent the structure of the "giant resonance." The agreement is somewhat further improved if account is taken of the finite thickness of the bombarding target. Calculations with the aid of the single-particle approximation (by formulas (5), dashed curves 1 and 2) are on the other hand is much poorer agreement with the experimental data.

The anomalously large value of the cross section of the $Sn^{112}(\alpha, \gamma)Te^{116}$ reaction can be explained qualitatively within the framework of the compound-nucleus model. In this case the competing reactions are (α, γ), (α, α), (α, n), and (α, p). However, owing to the large threshold (~ 13 MeV) of the (α, n) reaction, the competition takes place principally between the reactions $(\alpha, \gamma)(\alpha, \alpha)$, and (α, p). But the probabilities of emission of a proton and an α particle are under-valued by the influence of the Coulomb barrier. Nevertheless, it is difficult to obtain a complete explanation and agreement with experiment within the framework of this model, let alone with the single-particle approximation. An account of the cascade emission of the γ quanta would perhaps improve this agreement, but we did not make such calculations in view of their complexity.

B. The reaction $Sn^{112}(\alpha, n)Te^{115}$. Data on this reaction are given in Fig. 2b. Here, as in Fig. 2a, curve 1 corresponds to an α-particle binding energy 1.84 MeV, and curve 2 to 0.84 MeV. Curve 3 was obtained by averaging curve 2 over the thickness of the bombarding target. The calculations were made in accordance with the compound-nucleus model. It is seen from the figure that, within the framework of this model, the agreement between theory and experiment is satisfactory. The low value of this cross section is due to the high threshold of the reaction and to the strong competition of the (α, p) reaction.

C. The reaction $Sn^{114}(\alpha, n)Te^{117}$. The experimental and theoretical data are given in Fig. 2c. The values of the corresponding binding energies are known experimentally and were taken from the tables of [11]. Curve 2 was obtained by averaging curve 1 over the thickness of the bombarded target. We see that in this case, too, the agreement is satisfactory.

Thus, the cross sections we measured for the nuclear reactions (α, γ) and (α, n) on tin isotopes in the medium-energy region are explained qualitatively and sometimes also quantitatively, with the aid of a mechanism wherein the nuclear reaction proceeds via a compound nucleus.

In conclusion the authors express deep gratitude to corresponding member of the USSR Academy of Sciences B. S. Dzhelepov for useful advice and for continuous interest in the work.

[1] A. M. Lane and I. E. Lynn, Nucl. Phys. **11**, 625, 646 (1959).

[2] H. Morinaga, Phys. Rev. **101**, 100 (1956).

[3] Ball, Fairhall, and Halpern, Phys. Rev. **114**, 304 (1959).

[4] N. T. Porile, Phys. Rev. **115**, 939 (1959).

[5] Khulelidze, Chikhladze, and Ryukhin, Program and Topics of Papers at the Thirteenth Annual Conference on Nuclear Spectroscopy, AN SSSR, 1963.

[6] Fink, Andersson, and Katele, Ark. Fysik **14**, 323 (1961).

[7] Selinov, Chikhladze, Khulelidze, and Vartanov, Izv. AN SSSR ser. fiz. **25**, 848 (1961), Columbia Tech. Transl. p. 857.

[8] M. L. Sehgyl, Phys. Rev. **125**, 968 (1962).

[9] M. Z. Maksimov, JETP **37**, 127 (1959), Soviet Phys. JETP **10**, 90 (1960).

[10] A. G. W. Cameron, A Revised Semi-empirical Atomic Mass Formula, Chalk River, Ontario, (1957).

[11] Konig, Mattauch, and Wapstra, Nucl. Phys. **31**, 1 (1962).

[12] Khulelidze, Chikhladze, Vartanov, and Ryukhin, Izv. AN SSSR ser. fiz. **26**, 1036 (1962), Columbia Tech. Transl. p. 1044.

[13] J. M. Blatt and V. F. Weisskopf, Theoretical Nuclear Physics, Wiley, N. Y., 1952.

[14] M. Z. Maksimov, JETP **33**, 1411 (1957), Soviet Phys. JETP **6**, 1085 (1958).

[15] J. H. Caryer and G. A. Jones, Nucl. Phys. **11**, 400 (1959) and **24**, 607 (1961).

[16] A. G. Cameron, Phys. Rev. **82**, 272 (1951).

Translated by J. G. Adashko
58