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A Study of the Isomeric Ratio for the (n,2n) and (γ,n) Reactions in Mo92, Zr90, Sr86 and Se74

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Addendum to INDC(VN)-1/L

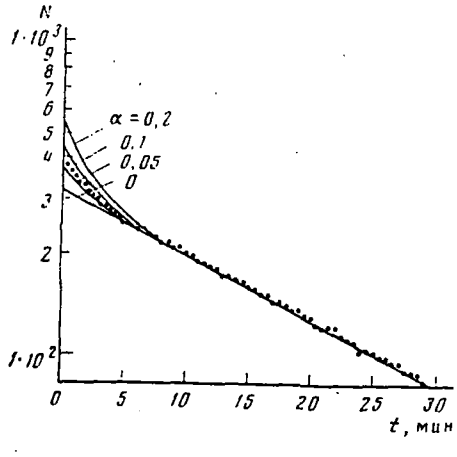

Fig. 1

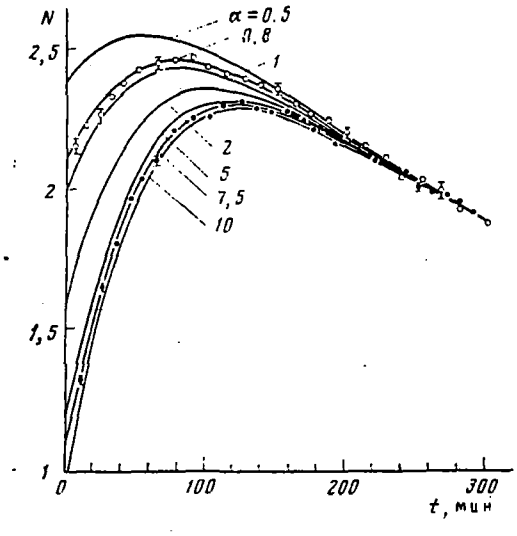

Fig. 2

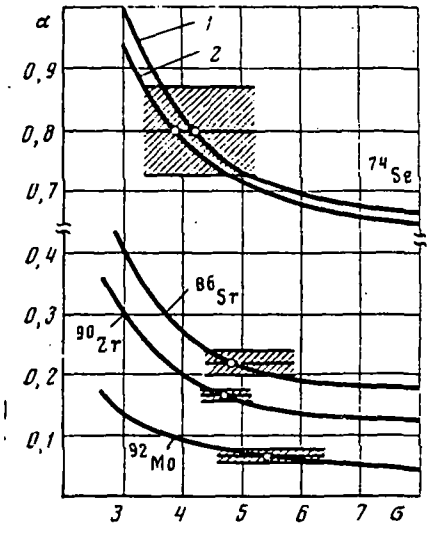

Fig. 3

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A STUDY OF THE ISOMERIC RATIO FOR THE (n,2n) AND (γ,n) REACTIONS ON ^{92}Mo, ^{90}Zr, ^{86}Sr and ^{74}Se

Fam Zui Khien, Ngo Kuang Zui and Nguen Tak An'

[Submitted to "Yadernaya Fizika"]

ABSTRACT

Measurements are made of the isomeric ratio for the (n,2n) and (γ,n) reactions on the neutron-deficient nuclei ^{92}Mo, ^{90}Zr, ^{86}Sr and ^{74}Se. A method is developed for calculating the isomeric ratio for a low excitation energy of the residual nucleus. The good agreement found between experimental results and calculations for the (γ,n) reaction confirms the choices of residual nucleus characteristics, transmission coefficients of neutrons emitted etc. used in the calculations. The results of a study of the (n,2n) reaction were used to find the spin dependences of nuclear level density in the excitation energy region ~14 MeV.

Hanoi, 1981

1. INTRODUCTION

By comparing experimentally found isomeric ratios for nuclear reactions with calculations performed in accordance with the scheme proposed by Huizenga and Vandenbosch [1] information can be obtained about the spin dependence of the nuclear level density (the parameter σ). A considerable number of studies have been devoted to the (n,2n) reaction on the neutron-deficient nuclei ^{92}Mo, ^{90}Zr and ^{86}Sr with the formation of the one-particle states $g_{9/2}$ ($I_g = \frac{9+}{2}$) and $p_{1/2}$ ($I_m = \frac{1-}{2}$). However, there are considerable differences in the experimental data obtained by different authors (see Table 1). On the other hand, in a number of cases the process whereby isomeric and ground states are populated with the emission of a second neutron and subsequent gamma quanta deviates markedly from the statistical rule of distribution in spin used in the calculation scheme of Ref. [1]. This is true of the case examined in the present paper of reactions near the threshold, when the excitation energy of residual nuclei does not exceed 2-3 MeV. A typical example of deviation from the statistical rule of distribution in spin is provided by the reaction ^{74}Se(n,2n)^{73}Se, where the isomeric state ^{73}Se is populated mainly by means of cascade gamma transitions through levels of the rotational band with $K = \frac{1-}{2}$ [2] or $K = \frac{5-}{2}$ [3].

In the present paper experimentally found isomeric ratios are compared with calculations in which the isomeric ratio was found from the probability with which levels of a residual nucleus will be populated up to the maximum excitation energy. In addition to the (n,2n) reaction, a study was also made of the isomeric ratio for the (γ,n) reaction in which, as a result of the small moment introduced with dipole absorption of a gamma quantum by the nucleus, preferential formation of a low-spin isomeric state occurs. Data for the (γ,n) reaction at a gamma-quantum energy $E_\gamma \approx 14.5$ MeV were used to verify the residual nucleus energy-level schemes, neutron transmission coefficients etc. used for the calculations.

2. THE EXPERIMENTS AND THEIR RESULTS

The neutron source used for the experiments was a neutron generator with an output of 10^{10} n/s. The energy of neutrons incident to the target (E_n) was (14.5 $\pm$ 0.2) MeV. The experiment on the (γ,n) reaction was performed on a

microtron with a maximum bremsstrahlung energy (E_γ) of 14.5 MeV. The targets of Mo, Zr and SrO had a natural isotopic composition, whereas for the ^{74}Se reaction an enriched target was used with 41% ^{74}Se.

The isomeric ratio was measured by the activation method. Gamma quanta of reaction products were detected with a semiconductor detector and a multichannel analyser. The target was moved between the neutron generator and the detector by a conveyor tube. The microtron had no conveyor tube, and so after irradiation the target's activity was measured with a delay of 2-3 minutes. In experiments performed in order to determine the isomeric ratio, decay curves were drawn for photopeaks characteristic of the isomeric and ground states of the product nuclei $^{91}Mo^{g,m}$, $^{89}Zr^{g,m}$, $^{85}Sr^{m}$ and $^{73}Se^{g}$. The half-lives obtained in this way agree with those found in the literature and shown in Table 1.

For the $^{92}Mo(n,2n)^{91}Mo$ reaction the isomeric ratio was also determined from the curve of β^+ decay of $^{92}Mo^{(m+g)}$ by detecting the coincidence of annihilation gamma quanta of 511 keV. In this connection, two 76 x 76 mm NaI(Tl) detectors were used which were placed opposite each other and symmetrically with respect to the sample being measured. Between the detectors a lead shield was placed in order to eliminate false coincidences associated with Compton scattering of gamma quanta in the detectors. Pulses from a coincidence unit passed to a multichannel analyser operating in the time analysis mode. Figure 1 shows the time dependence of β^+ decay of $^{92}Mo^{(m+g)}$ measured by the cyclical activation method on a neutron generator. In each cycle the irradiation time was one minute. Curves were calculated with the spectroscopic data of Table 1. The best agreement between experimental and theoretical data is found for $\alpha = 0.065 \pm 0.005$, which is confirmed by independent measurements of the intensity of photopeaks at 658 keV ($^{91}Mo^{m}$) and 511 keV on a semiconductor detector ($\alpha = 0.051 \pm 0.06$).

For determining the isomeric ratio for the ^{74}Se reactions the annihilation photopeak at 511 keV was not used as in other experiments [11, 14], but the accumulation and decay curve for the photopeak at 361 keV was recorded. The advantage of this technique consists in the fact that the experimental results are affected to a minimal extent by errors associated with the relative yield of characteristic gamma transitions occurring with the decay of the product nucleus ^{73}Se and those associated with the determination of detector efficiency.

Figure 2 shows experimental data together with accumulation and decay curves for the photopeak at 361 keV calculated as a function of the isomeric ratio. The irradiation time was the same for the (n,2n) and (γ,n) reactions, that is 30 min. The theoretical curves were normalized in such a way that where $t >> T_{\frac{1}{2}}$ ($^{73}Se^{m}$) the intensity of the photopeak at 361 keV was the same irrespective of the isomeric ratio.

Tables 2 and 3 show the experimental results, and results from other papers are given for purposes of comparison. It will be seen from Table 2 that, except as regards ^{90}Zr, the data in the literature are highly contradictory. For the $^{90}Zr(n,2n)^{89}Zr$ reaction the results from most papers are in the range α = 0.20–0.25, whereas we obtained the value $\alpha = 0.166 \pm 0.004$. It should be mentioned that the experimental errors in our paper represented an improvement on other findings for ^{90}Zr and ^{74}Se.

Data on the (γ,n) reaction are very scarce and a comparison between them and our experimental results would scarcely be meaningful because of the great difference in the maximum energy of incident gamma quanta.

3. DERIVATION OF BASIC FORMULAE FOR CALCULATING THE ISOMERIC RATIO

The isomeric ratio was calculated within the framework of the compound nucleus formation and decay model. In the case examined, residual nuclei are formed in the excitation energy region $\lesssim$ 2–3 MeV, for which the concept of level density cannot be used. At the same time, the isomeric ratio should be determined on the basis of a calculation of the population of all energetically accessible levels in the region of the discrete spectrum of the residual nucleus. For the (n,2n) reaction the population of a level with energy E_f, spin I_f and parity π_f was calculated in accordance with the formula

$$P(E_f, I_f, \pi_f) = \sum_{E,I,\pi} P_1(E,I,\pi) \frac{\Gamma_n(EI\pi \to E_f I_f \pi_f)}{\sum_i \Gamma_n(EI\pi \to E_i I_i \pi_i) + \Gamma_\gamma(EI\pi)} \quad (I)$$

where $P_1(E,I,\pi)$ is the population of the unbound state (E,I,π) formed as a result of the emission of the first neutron and $\Gamma_n(EI\pi \to E_f I_f \pi_f)$ is the partial neutron width corresponding with the transition between the states (E,I,π) and (E_f,I_f,π_f). The denominator in the right-hand part of Eq. (1) is the total width of the unboud state (E,I,π) in which, in addition to the

total neutron width $\sum_i \Gamma_n(E I\pi \to E_i I_i \pi_i)$, account is taken of the radiation width $\Gamma_\gamma(E,I,\pi)$. The partial neutron width has the following form:

$$\Gamma_n(EI\pi \to E_f I_f \pi_f) = \frac{1}{\rho(E,I,\pi)} R(\varepsilon_{nf} I\pi, I_f \pi_f) \qquad (2)$$

where ρ is the nuclear level density and

$$R(\varepsilon_{nf}, I, \pi, I_f \pi_f) = \frac{1}{2} \sum_{S=|I_f - \frac{1}{2}|}^{I_f + \frac{1}{2}} \sum_{l=|S-I|}^{S+I} T_l(\varepsilon_{nf})\left[1 + (-1)^l \pi \pi_f\right], \qquad (3)$$

where $T_\ell(\varepsilon_{nf})$ is the transmission coefficient of a neutron with energy $\varepsilon_{nf} = E - E_f - B_n$ and B_n is the separation energy of the neutron. The summation in the denominator of Eq. (1) is performed over all energetically accessible levels $(E_i I_i \pi_i)$ of the residual nucleus at a given unbound state energy E. For the radiation width the dipole approximation was used:

$$\Gamma_\gamma(E,I,\pi) = \frac{C A^{2/3}}{\rho(E,I,\pi)} \sum_{I'=|I-1|}^{I+1} \int_0^E E_\gamma^3 \rho(E - E_\gamma, I', -\pi) dE_\gamma \qquad (4)$$

where C is a coefficient found by comparing Eq. (4) with experimental radiation widths. The level density in Eqs (2) and (4) was calculated in accordance with the Fermi-gas model with pairing taken into account:

$$\rho(E,I) = \frac{1}{24\sqrt{2}} \frac{2I+1}{\sigma^3 a^{1/4}} \frac{\exp\left[2(a(E-\Delta))^{\frac{1}{2}} - I(I+1)/2\sigma^2\right]}{(E - \Delta + t)^{5/4}} \qquad (5)$$

where a is the level density parameter, $\sigma^2 = \frac{Jt}{\hbar^2}$, J is the inertia moment of the nucleus, t is the thermodynamic temperature determined by the relationship $E - \Delta = at^2 - t$ and Δ is the pairing energy.

The value $\underline{P}_1(E,I,\pi)$ in Eq. (1) was calculated in the same way as in other papers (e.g. Refs [1, 5]).

For the (γ,n) reaction, instead of Eq. (1) the following formula was used to calculate the population $\underline{P}(E_f, I_f, \pi_f)$:

$$P(E_f, I_f, \pi_f) \sim \int \varphi(E_\gamma)\sigma_{\gamma n}(E_\gamma) \frac{R(\varepsilon_{nf}, 1^-, I_f, \pi_f)}{\sum_i R(\varepsilon_{ni}, 1, I_i, \pi_i)} \quad (6)$$

where $\sigma_{n\gamma}(E_\gamma)$ is the cross-section of the (γ,n) reaction and integration is performed over the bremsstrahlung spectrum of the microtron $\phi(E_\gamma)$ from $E_{min} = E_f + B_n$ up to the maximum energy. R was also calculated from Eq. (3), whereby $\varepsilon_{nf} = E_\gamma - B_n - E_f$ and the summation in the right-hand part of Eq. (6) is performed over all the energetically accessible levels of the residual nucleus in accordance with the incident gamma quantum theory applied. The absorption of the gamma quantum in Eq. (6) is described in the dipole approximation, whereby with an even-even target nucleus the compound state is formed with spin 1^-.

4. NUMERICAL CALCULATIONS

For the numerical calculations of Eq. (6) the spectrum of microtron bremsstrahlung was taken from Ref. [16] and the excitation function of the (γ,n) reaction for ^{92}Mo and ^{90}Zr from Refs [17] and [18]. Since we have no data on the (γ,n) reaction cross-section for ^{74}Se and ^{86}Sr, for these nuclei the form of the excitation function $\sigma_{\gamma n}(E_\gamma)$ in the threshold region was taken to be the same as that for the (γ,n) reaction for ^{76}As [19] and ^{90}Zr [17]. The energy, spin and parity of final nuclear levels of ^{91}Mo, ^{89}Zr, ^{85}Sr and ^{73}Se were taken from Refs [20, 2, 3]. In the high excitation energy region individual spin and parity values have not been unequivocally identified for a number of levels and Ref. [20] gives only possible values of I_f and π_f. For such levels the population was taken to be equal to $\underline{P}(E_f, I_f, \pi_f)$. This assumption will not greatly affect the accuracy with which isomeric ratios are determined, since the population of a residual nuclear level decreases quickly as the excitation energy increases. A different situation arises with the product nucleus ^{73}Se, for which individual spin values have not yet been identified for most levels (including the isomeric and ground states). According to Ref. [2] the spins of the ground and isomeric states of ^{73}Se are $\frac{7}{2}^+$ and $\frac{1}{2}^-$ respectively, whereas Ref. [3] gives the spins for these states as $\frac{9}{2}^+$ and $\frac{3}{2}^-$. In Ref. [2] the isomeric state is the very lowest component of the rotational band with $K = \frac{1}{2}^-$, while in Ref. [3] this rotational band is placed above the level $\frac{5}{2}^-$ ($K = \frac{5}{2}^-$) and has different spin values. The use of these two energy-level schemes for nuclear levels of ^{73}Se has given different results in calculations (see Table 2).

Table 3 shows calculated isomeric ratios for the (γ,n) reaction. These calculations are highly sensitive to the neutron transmission coefficients $T_\ell(\varepsilon_n)$ used. Good agreement between experimental and theoretical data was found when the neutron transmission coefficients calculated in Ref. [21] were used. The calculated isomeric ratios for the (γ,n) reaction are considerably (up to several times) higher if the coefficients $T_\ell(\varepsilon_n)$ are taken from Ref. [22], where the optical potential was used with parameters differing somewhat from those of Ref. [21].

The neutron transmission coefficients $T_\ell(\varepsilon_n)$ given in Ref. [21] were thus chosen from the results of a study of the (γ,n) reaction for calculating the isomeric ratio in the (n,2n) reaction. In the numerical calculations of Eqs (1-5) the parameters a and σ varied, while the pairing energy Δ was taken from Ref. [24]. The coefficient C in the radiation width formula (4) was found by comparisons with experimental data (e.g. those of Ref. [24]). As compared with the one-particle evaluation of Weisskopf, these data show a reduction in the probability of radiative transitions of 0.003. However, the coefficient C used was lower by a factor of three than that of Ref. [25], where a study was made of the influence of the competition of gamma decay of unbound states on the (n,n') and (n,2n) reaction cross-sections.

The results of the numerical calculations have shown that the isomeric ratio varies very little with the variation in the parameter a within reasonable limits ($a = \frac{A}{8} - \frac{A}{12}$). The competition of gamma decay of unbound states has a greater influence on the absolute (n,2n) reaction cross-section than on the isomeric ratio. For example, for the $^{92}Mo(n,2n)^{91}Mo$ reaction, in which the excitation energy of the residual nucleus does not exceed 2 MeV, the use of the radiation width in Eq. (1) produced a 20% reduction in the cross-section and a 7% increase in the isomeric ratio. The influence of the competition of gamma decay proves to be even more insignificant if instead of Eq. (4) a formula for radiation width is used taking account of the energy dependence in the form of a giant resonance (see, for example, Ref. [25]).

The results of the numerical calculations of the dependence of the isomeric ratio for the (n,2n) reaction on the parameter σ (with $a = \frac{A}{10}$) and a comparison thereof with experimental data are shown in Fig. 3. For ^{74}Se the results of both types of calculation using the energy level schemes for ^{73}Se in Refs [2] amd [3] are given.

The spin dependences of level density obtained (σ) are shown in Table 3. These results are relatively close to rigid-body maximum values.

5. DISCUSSION

Instead of using the traditional statistical method of calculating the isomeric ratio proposed by Huizenga and Vandenbosch [1], in the present paper experimental data are compared with calculations in which the isomeric ratio was determined from the population probability of discrete levels of a residual nucleus (Eq. (1)). For these numerical calculations, in addition to level densities, neutron transmission coefficients etc., use was made of the spectroscopic characteristics of levels up to an excitation energy of 2–3 MeV. The good agreement found between experimental and theoretical results for the (γ,n) reaction on ^{92}Mo, ^{90}Zr and ^{86}Sr justified the use of the neutron transmission coefficients of Ref. [21] and the energy-level schemes given in Ref. [20]. The experimental data for the ^{74}Se(γ,n)^{73}Se reaction would appear to provide support for the energy-level scheme proposed in Ref. [3] ($I_g = \frac{9+}{2}$, $I_m = \frac{3-}{2}$). The use of data from a study on the (γ,n) reaction thus made it considerably easier to choose the initial data for calculating the isomeric ratio for the (n,2n) reaction. Moreover, unlike the (n,2n) reaction cross-section [5] the isomeric ratio is relatively insensitive to variations in the level density parameter a (Eq. (5)).

All these circumstances indicate the correctness of the theoretical curves in Fig. 3, and thus the accuracy with which the parameter σ is determined depends mainly on the accuracy of experimentally found isomeric ratios. The parameter σ derived in the present paper relates to the excitation energy region of the target nuclei $E \simeq 11$–14 MeV. The near-unity values of σ/σ_{rig} show that the superfluidity effect plays an unimportant part in the determination of the effective moment of inertia of a nucleus in this excitation energy region (see, for example, Ref. [26]).

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TABLE 1

Spectroscopic data used for determining the isomeric ratio

Product nucleus	Spin	$T_{1/2}$	E_γ(keV)	No. of quanta/decay
^{91m}Mo	$\frac{1}{2}^-$	65,5 s	511 658	0,756 0,55
^{91g}Mo	$\frac{9}{2}^+$	15,5 min	511	1,88
^{89m}Zr	$\frac{1}{2}^-$	4,18 min	588	0,94
^{89g}Zr	$\frac{9}{2}^+$	78,43 h	908	1
^{85m}Sr	$\frac{1}{2}^-$	69,5 min	237	0,87
^{85g}Sr	$\frac{9}{2}^+$	65,19 d	514	1
^{73m}Se	$(\frac{1}{2}^-),(\frac{3}{2}^-)$	38,9 min	361	73% transition
^{73g}Se	$(\frac{7}{2}^+),(\frac{9}{2}^+)$	7,1 h	351	$^{73m}Se \rightarrow {}^{73g}Se$

TABLE 2

Experimental isomeric ratios(α) for the (n,2n) reaction and the parameter of nuclear level density spin dependence (σ)

Target nuclei and neutron separation energy (MeV)	$\alpha = \frac{\sigma_m}{\sigma_g}$	$\sigma(\hbar)$	σ/σ_{rig}	Data[1] in literature	
^{91}Mo (12,7)	0,063±0,006	5,4±0,8	0,98	0,04±0,01 (14,7)	[4]
				0,067±0,007 (14,8)	[5]
				0,094±0,003 (14,8)	[6]
				1,08±0,1 (14,8)	[7]
				1,04±0,01 (14,5)	[8]
^{90}Zr (12,1)	0,166±0,004	4,7±0,4	0,87	0,25±0,05 (14,7)	[4]
				0,198±0,02 (14,8)	[5]
				0,22±0,05 (14,8)	[6]
				0,22±0,02 (14,8)	[8]
				0,22±0,007 (14,52)	[11]
				0,300±0,035 (14,8)	[12]
^{86}Sr (11)	0,22±0,02	4,8±0,7	0,9	0,24±0,05 (14,7)	[4]
				0,201±0,023 (14,8)	[12]
				0,40±0,08	[13]
				0,402±0,053 (14,06)	[14]
				0,44±0,05 (15,62)	[14]
^{74}Se	0,80±0,07	4,2±0,8[2)] [3)]	0,87	0,22±0,07 (14,4)	[6]
				0,175±0,021 (14,17)	[11]
				1,15±0,29 (14,82)	[14]

1) Incident neutron energies are shown in brackets.

2) The energy level scheme for ^{73}Se in Ref. [2] ($I_g = \frac{7^+}{2}, I_m = \frac{1^-}{2}$) was used.

3) The energy level scheme for ^{73}Se in Ref. [3] ($I_g = \frac{9^+}{2}, I_m = \frac{3^-}{2}$) was used.

TABLE 3

The isomeric ratio for the (γ ,n) reaction

Target nucleus	α_{exp}	α_{theor}	Data[1] in literature
^{92}Mo	I,54±0,I5	I,36	I,32±0,I5 (70) [9] I,03±0,2I [10] 0,35±0,07 (30) [15]
^{90}Zr	I,52±0,04	I,49	0,50±0,I5 (30) [15]
^{86}Sr	0,70±0,07	0,86	0,63±0,I4 (30) [15]
^{74}Se	7,5±I,0	I0,5 [2] 8,6 [3]	

1) Maximum bremsstrahlung energies are shown in brackets.

2) The energy level scheme for ^{73}Se in Ref. [2] ($I_g = \frac{7+}{2}, I_m = \frac{1-}{2}$) was used.

3) the energy level scheme for ^{73}Se in Ref. [3] ($I_g = \frac{9+}{2}, I_m = \frac{3-}{2}$) was used.

Figure captions

Fig. 1. β^+ decay of $^{91}Mo^{(m+g)}$. $^{92}Mo(n,2n)^{91}Mo$ reaction, irradiation time 1 min.

Fig. 2. Accumulation and decay of the intensity of the photopeak at 361 keV for ^{73}Se formed from the (n,2n) () and (γ,n) () reactions in ^{74}Se. The relative unit is shown on the ordinate (see explanation in text).

Fig. 3. Dependence of the isomeric ratio for the (n,2n) reaction on the parameter of level density spin dependence σ (1) in accordance with the ^{73}Se energy-level scheme in Ref. [2] and (2) in accordance with the ^{73}Se energy-level scheme in Ref. [3].