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SPIN CUT-OFF FACTORS FROM (n,2n) REACTIONS OF NUCLEI WITH $N < 50$

By

D. HORVÁTH* and A. KISS

DEPARTMENT OF ATOMIC PHYSICS, ROLAND EÖTVÖS UNIVERSITY, BUDAPEST

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The available experimental data on isomeric ratios measured in (n,2n) reactions are re-evaluated using a method based on the HUIZENGA—VANDENBOSCH assumptions. So far only the experimental values of isomeric (n,2n) cross section ratios reported for nuclei with $N < 50$ at 14 MeV have been re-analysed. The dependence of the extracted spin cut-off factors on the parameters used is discussed, and the latter are compared with the values predicted by the Fermi gas model; their ratios are found to be about 0.5.

Introduction

In recent years many isomeric ratios measured in (n,2n) reactions at 14 MeV have been evaluated by means of the HUIZENGA—VANDENBOSCH method [1]. However, the spin cut-off factors obtained by different authors are not comparable, as different adaptations of the method, employing various approximations and data for nuclear temperature, transmission coefficients, level density parameters, pairing energies and gamma multiplicities have been applied. Re-analysis of the available experimental data utilizing the same sources for the parameters might make it possible to investigate the dependence of the spin cut-off factors on the choice of models. It is the aim of the authors to perform this task along the lines of a recent study of (n,gamma) reactions [2]. As a first step, data for the $N < 50$ "island of isomerism" were re-evaluated.

The main features of the calculation for extracting the spin cut-off factors from (n, 2n) isomeric cross-section ratios are essentially the same as described elsewhere [10].

The nuclear level density adopted is

$$\varrho(U, J) \propto (2J + 1) \exp\left\{ 2\sqrt{aU} - \left(J + \frac{1}{2}\right)^2 \Big/ 2\sigma^2 \right\},$$

where a is the zero spin level density parameter, σ the spin cut-off factor, and J the angular momentum. The effective excitation energy is $U = E - \varepsilon\delta$,

* Present address: Central Research Institute for Physics, Budapest.

where E is the incident neutron energy in CM system, $\delta = 16/a$ is the pairing energy of one nucleon, and ε is the parity factor:

$$\varepsilon = \begin{Bmatrix} 2 & \text{for even} \\ 1 & \text{for odd-mass} \\ 0 & \text{for odd} \end{Bmatrix} \text{nuclei}$$

The mean energy of the emitted neutrons is assumed to be twice the nuclear temperature, T, given by $U = T^2 - 4T$. For the zero-spin level density parameter a we have applied Newton's formula $a = 0.095 \cdot (j_N + j_Z + 1) \cdot A^{2/3}$. The values for the averaged shell spins j_N and j_Z were taken from [2].

Assuming there are dipole radiations only, the mean number of emitted photons is $1/2 \sqrt{aU'}$, where U' is the average excitation energy after the second neutron emission.

The calculated zero-spin level density parameters, pairing corrections, mean neutron energies and average numbers of emitted photons are shown in Table I. The isomeric ratios examined and the spin cut-off factors calculated from them are displayed in Table II. In some cases only a lower limit for

Table I

Actual values of reaction parameters

E is the bombarding energy in CM system, a the zero-spin level density parameter, δ the pairing energy correction, E_1 and E_2 the energies of the evaporating neutrons, n the average γ multiplicity

Target	E	Target		Residual		E_1	E_2	n
		a	δ	a	δ			
^{70}Zn	14.5	12.38	2.6	11.19	1.4	2.1	1.2	2
^{74}Se	13.9	12.29	2.6	11.07	1.4	2.1	0	0
^{76}Ge	13.8	13.06	2.4	12.95	1.2	2.0	0.7	1
^{78}Se	14.5	12.72	2.6	12.60	1.3	2.1	0.6	0
^{80}Se	14.5	12.93	2.4	12.82	1.3	2.1	0.8	2
^{81}Br	14.8	13.62	1.17	13.52	0	2.24	1.00	2
	14.3					2.20	0.91	2
	13.8					2.17	0.81	1
	13.3					2.13	0.70	1
^{82}Se	14.2	10.76	3.0	13.04	1.2	2.2	0.8	2
^{85}Rb	13.9	11.62	1.4	13.97	0	2.3	0.8	1
^{86}Sr	14.5	12.95	2.4	15.30	1.1	2.1	0	0
^{87}Rb	14.5	12.43	1.3	11.41	0	2.2	1.1	2
^{88}Sr	14.5	13.77	2.4	12.75	1.3	2.0	0	0
^{90}Zr	14.0	17.17	1.8	16.09	1.0	1.8	0	0
^{92}Mo	14.5	17.43	1.8	16.34	1.0	1.9	0	0

Table II

Cross-section ratios and spin cut-off factors

The reactions are considered at the bombarding energies reported in Table I. The numbers in parentheses after the data refer to the literature. Isomeric ratios marked "*" were obtained by dividing the experimental isomeric cross-section with a computed ground-state one. "*" means that the measured isomeric ratio cannot be compared with the calculated one

Residual nucleus	Isomeric ratio measurement				Calculated spin cut-off factors		
	E	R	σ	Ref.	our	other's	Ref.
^{69}Zn	14.7	0.56(11)	2.8(3)	[10]	$2.6^{+1.7}_{-0.6}$	—	
^{73}Se	14.1	0.86(8)	—	[5]	$3.8^{+\infty}_{-1.6}$	2.9	[6]
	14.4	0.82(5)	—	[17]	3.3 ± 1.2	2.7	[6]
						4.2 ± 0.5	[10]
^{75}Ge	14.8	0.62(8)	3(1)	[12]	2.1 ± 0.2	$4.8^{+1.8}_{-0.8}$	[6]
	14.5	0.42(8)	1.80(15)	[9]	1.7 ± 0.2	—	
	15.0	0.74(5)	—	[15]	2.5 ± 0.3	6.0	[6]
^{77}Se	14.7	0.51*	2.7	[13]	1.6	—	
^{79}Se	14.7	0.83*	3.3	[13]	3	—	
^{80}Br	13.5	0.623(36)	—	[15]	3.9 ± 0.5	—	
	13.9	0.635(51)	—	[15]	$3.9^{+0.9}_{-0.4}$	—	
	14.0	0.52(4)	4.4(3)	[8]	$3\ \pm0.3$	—	
	14.6	0.637(34)	—	[15]	$4\ \pm0.4$	—	
		0.58(7)	—	[18]	3.5 ± 0.5	$6\ \pm1$	[12]
						$4.9^{+1.2}_{-0.6}$	[6]
	14.7	0.72(8)	$6\ \pm1$	[14]	$5.6^{+\infty}_{-1.5}$	—	
	14.9	0.635(30)	—	[15]	3.9 ± 0.3	5.6 ± 0.8	[6]
		0.62(2)	5.4(3)	[6]	3.7 ± 0.3	—	
^{81}Se	14.4	0.80(5)	—	[17]	3.1 ± 0.4	$4.6^{+0.9}_{-0.5}$	[6]
						2.9 ± 0.2	[10]
	14.7	0.74(2)	3.0(5)	[13]	3.6 ± 0.1	4.0 ± 0.2	[6]
^{84}Rb	14.1	0.52(5)	3.96(6)	[11]	4.2 ± 0.6	—	
	14.7	0.55(20)	4.9(5)	[14]	$4.6^{+\infty}_{-1.6}$	—	
^{85}Sr	14.6	0.47(5)	—	[18]	4.6 ± 1.5	2.3 ± 0.1	[6]
						2.5 ± 0.5	[12]
	14.7	0.80(15)	3.0(5)	[14]	?	—	
^{86}Rb	14.7	0.37(12)	2.9(5)	[14]	$3\ \pm0.5$	—	
^{87}Sr	14.7	0.74*		[14]	3.5	—	
^{89}Zr	14.7	0.80(17)	3.5 ± 0.5	[14]	$3.4^{+\infty}_{-1.5}$	—	
	14.8	0.72(8)	5.5 ± 1	[12]	$2.4^{+1.0}_{-0.5}$	$2.2^{+0.9}_{-0.4}$	[6]
		0.82(16)	4.2(3)	[10]	$4.2^{+\infty}_{-2.3}$	—	
^{91}Mo	14.7	0.96(38)	6(1)	[14]	?	—	
	14.8	0.91(18)	6	[10]	?	—	
		0.80(10)	8.5(15)	[16]	3.4 ± 1.2	2.0	[6]
	14.9	0.82(1)	3.5(4)	[6]	3.8 ± 0.4	—	

the σ-value could be determined (an example is presented in Fig. 3). The transmission coefficients were taken from [3], the neutron binding energies and nuclear level spins from [4].

Discussion

Because expressions for the level densities of both the target and residual nuclei are used in the calculations, it must first be decided which of the two nuclei involved in the (n,2n) reaction is characterized by the extracted spin cut-off parameter. The case of the ^{86}Sr (n,2n) ^{85}Sr^{m,g} reaction, illustrated in Fig. 1, provides a typical example. The Figure clearly shows that the first

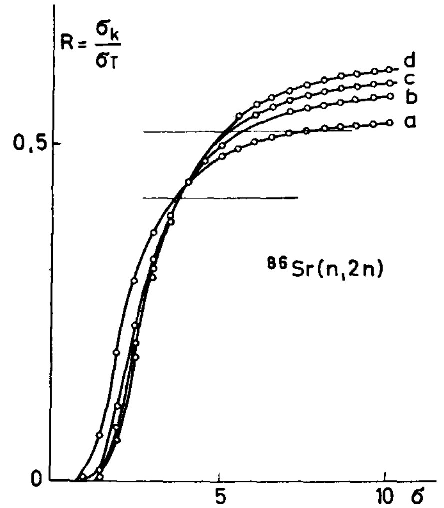

Fig. 1. Calculated isomeric ratio curves for the ^{86}Sr (n, 2n) reaction after the emission of (a) 1 neutron; (b) 2 neutrons; (c) 2 neutrons and 1 photon; (d) 2 neutrons and 2 photons. The shaded area corresponds to isomeric ratio measured by STROHAL et al. [18]

neutron evaporation process plays the most important role in determining the isomeric ratio. This reflects the fact that the second neutron to be emitted does not carry away much orbital momentum and thus does not considerably alter the spin distribution. The gamma multiplicity is low for the same reason. This conclusion is generally valid in (n, 2n) reactions at about 14 MeV, which means that the σ-values obtained belong primarily to the target nucleus.

The energy dependence of the calculated isomeric ratios is shown in Fig. 2. The ratios seem to be insensitive to small changes of the energy of the incident neutron beam around 14 MeV (the investigated region is 13—15 MeV).

Although the transmission coefficients are strongly dependent on mass number, orbital momentum and the form and parameters selected for the optical potential, the calculated isomeric ratios are not sensitive to them. The differences of about 1% between the isomeric ratio curves for the Se isotopes, which have the same data except for mass number and neutron binding energy, corresponds to the differences in the transmission coefficients of the isotopes.

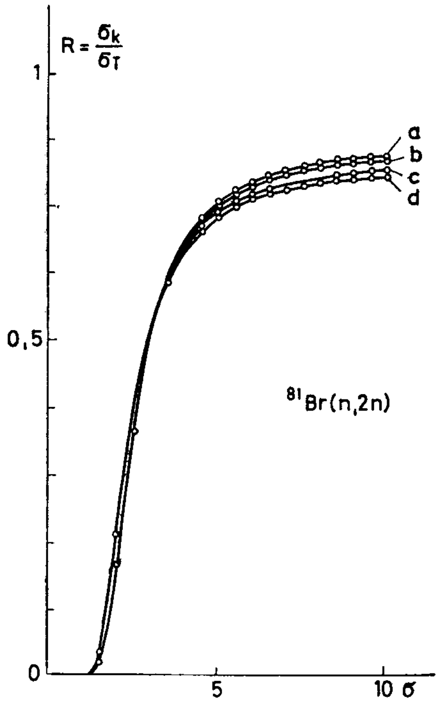

Fig. 2. Calculated isomeric ratio curves for the ^{81}Br(n, 2n) reaction at (a) 14.8; (b) 14.3; (c) 13.8; (d) 13.3 MeV incident neutron energy (in CM system)

The spin cut-off factor and the inertia momentum of nuclei are related by the expression $\sigma^2 = \Theta \cdot T/\hbar^2$. In the energy region examined the Fermi gas model predicts a rigid-body momentum of Θ_R, whereas pairing models predict values $\Theta_P < \Theta_R$. The Θ/Θ_R ratios are plotted against mass numbers in Fig. 4.

All the ratios are far below unity, as predicted by the pairing models.

Table III

Spin cut-off factors for the reaction ^{86}Sr(n,2n) with the measured isomeric ratio of [18] after emitting (a) 1 neutron; (b) 2 neutrons; (c) 2 neutrons and 1 photon; (d) 2 neutrons and 2 photons

a	*b*	*c*	*d*
4.6	4.5	4.4±0.6	4.3±0.5

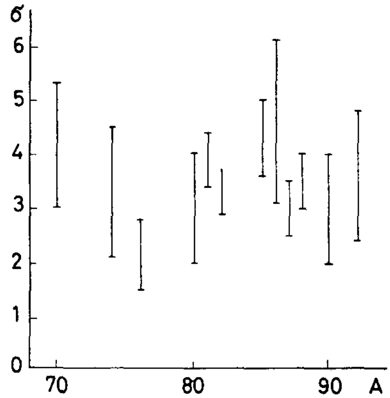

Fig. 3. Plot of spin cut-off factors against mass numbers

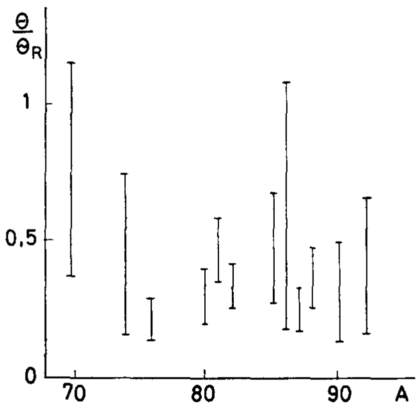

Fig. 4. Ratio of "measured" and rigid-body moments of inertia of nuclei vs mass number

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СПИНОВЫЕ КОЭФФИЦИЕНТЫ ОБРЕЗАНИЯ ДЛЯ ЯДЕР $N < 50$ ПО РЕАКЦИЯМ (n, 2n)

Д. ХОРВАТ и А. КИШ

Резюме

Проведен пересмотр экспериментальных данных по изомерным отношениям, полученных из измерений реакций типа (n, 2n). Для этого используется метод, основанный на предположениях Гюйзенги-Ванденбоша.

До сих пор такой пересмотр был проведен только в случае экспериментальных значений отношений изомерных сечений (n, 2n), относящихся к ядрам $N < 50$ при энергии 14 MeV. Рассматривается зависимость извлеченных спиновых коэффициентов обрезания от использованных параметров и параметры спинового обрезания сравниваются со значениями, предсказанными моделью Ферми—газа; оказывается, что их отношения приблизительно равны 0,5.