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Systematic Trends in the Analysis of Photonuclear Cross Section Ratios

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Isomeric cross section ratios were measured for the photonuclear reactions ^{100}Mo(γ, n) ^{99m_1,m_2,g}Mo and ^{102}Ru(γ, p) ^{101m,g}Tc. Using the Huizenga-Vandenbosch-method spin cut-off parameters were deduced. The applicability of this statistical procedure is discussed. A systematic analysis of all known (γ, xn) isomeric ratio-measurements shows a linear correlation between derived spin cut-off parameters and the mean value of the spins of the isomeric pair.

1. Introduction

Isomeric cross section ratios for photonuclear reactions can be calculated within the statistical model by a procedure proposed by Huizenga and Vandenbosch [1–3]. Comparing experimental and theoretical results for the isomeric ratios, the spin cut-off parameter σ (SCOP), describing the spin dependent level density $\rho(I) \propto \rho_0(2I+1) \cdot \exp(-I(I+1)/2\sigma^2)$, can be derived. This SCOP is related to the nuclear moment of inertia.

A presentation and a first discussion of the applicability of the Huizenga-Vandenbosch-method (HVM) to the analysis of photonuclear and $(n, 2n)$-reactions has recently been reported [4]. The most important results were:

i) For (γ, xn)- and $(n, 2n)$-reactions the SCOP, derived from the HVM, often agrees with the centre of spins (COS), which is the mean value of the spins of the isomeric pair.

ii) The simple decision model for the population of the isomeric and the groundstate is a lower order approximation of the realistic decay modes. Therefore the HVM and especially the decision model is applicable only to "model nuclei" with decay schemes according to the assumptions of the HVM.

iii) For (γ, n)-reactions on neutron magic nuclei non-statistical contributions are to be expected. Therefore a statistical model analysis of cross section ratios within the Huizenga-Vandenbosch procedure seems to be unreasonable.

A critical test of the decision model of the HVM is the analysis of cross section ratios for nuclei with more than one isomer, where multiple isomeric ratios can be evaluated. In this work we, therefore, investigated experimentally a further reaction of this type (^{100}Mo(γ, n)) as well as the (γ, p)-reaction on ^{102}Ru.

In order to test the supposed correlation between the SCOP value, derived from the HVM, and the centre of spins of the isomeric pair (COS) we performed a systematic study of all known cross section ratios. In the past, quite different SCOP values were derived from the measured cross section ratios by different authors, even for the same nucleus and the same experimental isomeric ratio.

2. Experimental Methods and Results

Our experiments were carried out at the pulsed bremsstrahlung beam of the Giessen 65 MeV-electron-linac. The isomeric ratios were investigated by γ-spectroscopy using a Ge(Li)- and a high resolution intrinsic Ge-detector. The deexcitation γ-quanta were recorded by a data reduction system

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Table 1. Experimental and theoretical results

Process	Targetspin ($\hbar$)	E_γ(keV)	$t_{1/2}$	Spin high ($\hbar$)	Spin low ($\hbar$)	R_{exp}	SCOP($\hbar$)
^{100}Mo(γ, n)	0^+	449.2	760 ns	$11/2^-$	$5/2^+$	0.11 ± 0.02	4.3 ± 0.4
		137.7		$11/2^-$	$1/2^+$	0.10 ± 0.02	4.3 ± 0.4
		97.8	15.5 μs	$5/2^+$	$1/2^+$	0.94 ± 0.25	1.8 ± 0.3
^{102}Ru(γ, p)	0^+	191.9	636 μs	$9/2^+$	$1/2^-$	1.33 ± 0.30	1.65 ± 0.35
		306.6					

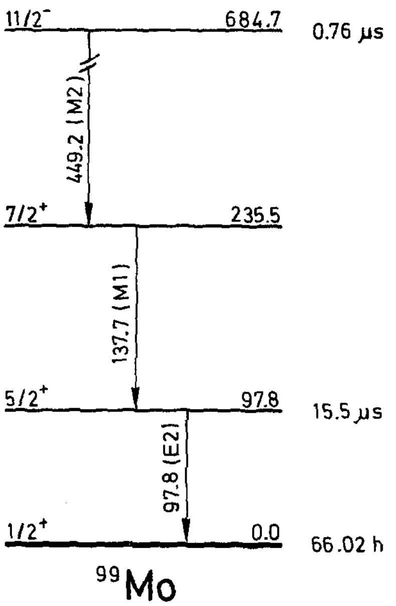

Fig. 1. Level scheme of ^{99}Mo [6]

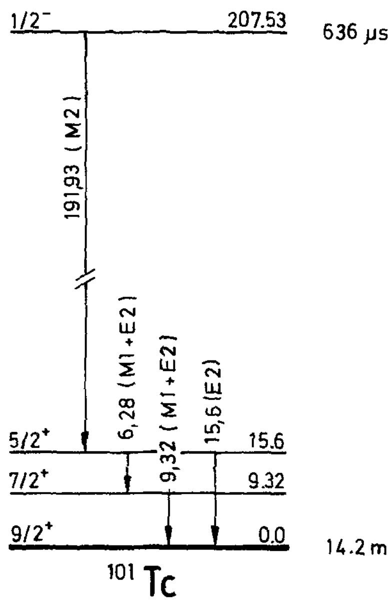

Fig. 2. Level scheme of ^{101}Tc [6, 32]

specially developed for the investigation of isomers [5].

Table 1 shows the experimental and theoretical results for ^{99}Mo and ^{101}Tc, including the new $11/2^-$ isomer in ^{99}Mo (449,2 keV) transition, $t_{1/2} = 760$ ns [6] (see Fig. 1).

3. Discussion

In this section we want to discuss the results of our measurements on the ^{100}Mo(γ, n)- and the ^{102}Ru(γ, p)-reactions with respect to the Huizenga-Vandenbosch decision model. Moreover we represent the results of a systematic recalculation of all known (γ, xn)-isomeric ratios in order to test the applicability of the HVM.

3.1. *Discussion of the ^{100}Mo(γ, n) and ^{102}Ru(γ, p)-Reactions*

The ^{100}Mo(γ, n)-reaction was reinvestigated. A new $11/2^-$-isomer at 684.7 keV ($t_{1/2} \approx 760$ ns) was found (Fig. 1). Together with the known isomer at 97.8 keV ($t_{1/2} = 15.5$ μs) this enables a new test of the decision model of the HVM as we have done recently in the ^{110}Pd(γ, n)-case [4]. The results of the statistical model analysis of the possible isomeric ratios in ^{99}Mo are listed in Table 1. For the ($11/2^-$, $5/2^+$)- and the ($11/2^-$, $1/2^+$)-isomeric ratios the $7/2^+$-level at 235.5 keV must be considered as a decay channel competing with the energetically lower lying states ($5/2^+$ and $1/2^+$). Consequently a COS of 4.5 $\hbar$ must be used within the calculations. SCOP values of (4.3 ± 0.4) $\hbar$ were derived for both isomeric ratios. For the low spin isomeric pair ($5/2^+$, $1/2^+$) with a COS of 1.5 $\hbar$ the obtained SCOP is (1.8 ± 0.3) $\hbar$. The good agreement of the SCOP-values and the COS in both cases as well as the fact that two different SCOP-values for the same residual nucleus were derived show that in this case the SCOP deduced from isomeric photonuclear cross section ratios must be regarded only as a fitting parameter.

Figure 2 shows the decay scheme of ^{101}Tc. The COS for the ($9/2^+$, $1/2^-$)-isomeric ratio is 1.5 $\hbar$ and fits well again the deduced SCOP ((1.65 ± 0.35) $\hbar$). Thus the investigation of the isomeric ratios in ^{101}Tc as well as in ^{99}Mo confirms the supposition that the SCOP

Table 2. The (γ, xn) data

Reaction	Targetspin ($\hbar$)	Spin high ($\hbar$)	Spin low ($\hbar$)	Competing Spin ($\hbar$)	R_{exp}	SCOP ($\hbar$)	Ref.
^{35}Cl (γ, n)	$3/2^+$	3^+	0^+		0.89	1.64	15
^{39}K (γ, n)	$3/2^+$	3^+	0^+		0.82 ± 0.27	1.62 ± 0.18	16
^{45}Sc (γ, n)	$7/2^-$	6^+	2^+		0.23 ± 0.03	2.78 ± 0.10	17
					0.22 ± 0.01	2.75 ± 0.03	18
					0.18 ± 0.01	2.62 ± 0.03	19
					0.28 ± 0.08	2.93 ± 0.24	20
^{59}Co (γ, n)	$7/2^-$	5^+	2^+		0.83 ± 0.03	3.47 ± 0.05	21
					0.79 ± 0.04	3.41 ± 0.06	22
					0.8 ± 0.1	3.42 ± 0.15	23
^{76}Ge (γ, n)	0^+	$7/2^+$	$1/2^-$		0.92 ± 0.13	2.64 ± 0.18	22
^{81}Br (γ, n)	$3/2^-$	5^-	1^+	2^-	0.40 ± 0.02	3.75 ± 0.08	24
					0.47 ± 0.03	4.01 ± 0.12	22
					0.49 ± 0.01	4.09 ± 0.04	25
^{82}Se (γ, n)	0^+	$7/2^+$	$1/2^-$		1.0 ± 0.5	2.6 ± 0.6	26, 22
^{86}Sr (γ, n)	0^+	$9/2^+$	$1/2^-$	$7/2^+$	0.56 ± 0.08	2.17 ± 0.12	22
					0.5 ± 0.1	2.08 ± 0.15	23
^{85}Rb (γ, n)	$5/2^-$	6^+	2^-		0.37 ± 0.01	3.70 ± 0.03	17
^{89}Y (γ, n)	$1/2^-$	8^+	1^+	$5^-, 4^-$	0.056 ± 0.008	[a]	4
^{90}Zr (γ, n)	0^+	$9/2^+$	$1/2^-$		0.49 ± 0.15	2.91 ± 0.54	22
					0.79 ± 0.11	4.07 ± 0.54	27
					0.67	3.56	16
^{92}Mo (γ, n)	0^+	$9/2^+$	$1/2^-$		0.85 ± 0.07	4.18 ± 0.31	22
					1.92 ± 0.15	[a]	28
					1.03 ± 0.21	$5.04^{+1.35}_{-0.99}$	4
^{100}Mo (γ, n)	0^+	$5/2^+$	$1/2^+$		0.85 ± 0.24	1.72 ± 0.22	4
					0.94 ± 0.25	1.80 ± 0.21	this work
^{100}Mo (γ, n)	0^+	$11/2^-$	$1/2^+$	$7/2^+$	0.10 ± 0.02	4.17 ± 0.31	this work
^{100}Mo (γ, n)	0^+	$11/2^-$	$5/2^+$	$7/2^+$	0.11 ± 0.02	4.32 ± 0.31	this work
^{107}Ag (γ, n)	$1/2^-$	6^+	1^+		0.04 ± 0.02	2.22 ± 0.22	22
					0.07 ± 0.02	2.45 ± 0.16	29
^{108}Pd (γ, n)	0^+	$11/2^-$	$1/2^+$	$5/2^+$	0.5 ± 0.2	3.4 ± 0.5	4
^{110}Pd (γ, n)	0^+	$11/2^-$	$5/2^+$		0.11 ± 0.02	3.14 ± 0.15	4
		$11/2^-$	$1/2^+$	$5/2^+$	0.41 ± 0.09	3.00 ± 0.25	4
		$5/2^+$	$1/2^+$		3.2 ± 0.7	3.3 ± 0.4	4
^{113}In (γ, n)	$9/2^+$	4^+	1^+		4.0 ± 0.5	3.21 ± 0.13	22
^{115}In (γ, n)	$9/2^+$	5^+	1^+		5.67 ± 0.33	4.81 ± 0.12	30, 22
^{116}Cd (γ, n)	0^+	$11/2^-$	$1/2^+$		≤ 0.25	≤ 2.67	22
^{140}Ce (γ, n)	0^+	$11/2^-$	$3/2^+$		0.19 ± 0.01	3.05 ± 0.06	29
					0.09 ± 0.01	2.45 ± 0.07	22
^{142}Nd (γ, n)	0^+	$11/2^-$	$3/2^+$		0.055 ± 0.006	2.20 ± 0.06	4
					0.19 ± 0.01	3.10 ± 0.06	28
^{198}Hg (γ, n)	0^+	$13/2^+$	$1/2^-$	$3/2^-, 5/2^-$	0.05 ± 0.01	3.29 ± 0.02	22
^{89}Y $(\gamma, 2n)$	$1/2^-$	$9/2^+$	$1/2^-$		0.42 ± 0.03	2.33 ± 0.05	18
^{55}Mn $(\gamma, 3n)$	$5/2^-$	6^+	2^+		0.41 ± 0.02	3.56 ± 0.03	17
					0.47 ± 0.04	3.7 ± 0.1	18
^{94}Mo $(\gamma, 3n)$	0^+	$9/2^+$	$1/2^-$		1.59 ± 0.16	3.58 ± 0.15	28
^{140}Ce $(\gamma, 3n)$	0^+	$11/2^-$	$3/2^+$		1.10 ± 0.12	4.56 ± 0.21	28
^{144}Nd $(\gamma, 3n)$	0^+	$11/2^-$	$3/2^+$		1.80 ± 0.25	5.68 ± 0.39	28
^{181}Ta $(\gamma, 3n)$	$7/2^+$	7^-	1^+		0.51 ± 0.09	3.6 ± 0.2	4

[a] no SCOP could be deduced

value obtained by the HVM is only related to the COS.

3.2. Systematics

All isomeric ratios for (γ, xn)-reactions known from literature were summarized and were analysed by a uniform computer program in order to get the SCOP values. A level density parameter $a = A/8\ \mathrm{MeV}^{-1}$ (A = mass number) was used within the calculations. The neutron penetrabilities were taken from Auerbach and Perey [7], threshold energies from Mattauch et al. [8]. Since all measurements were carried out with bremsstrahlung the reported isomeric ratios

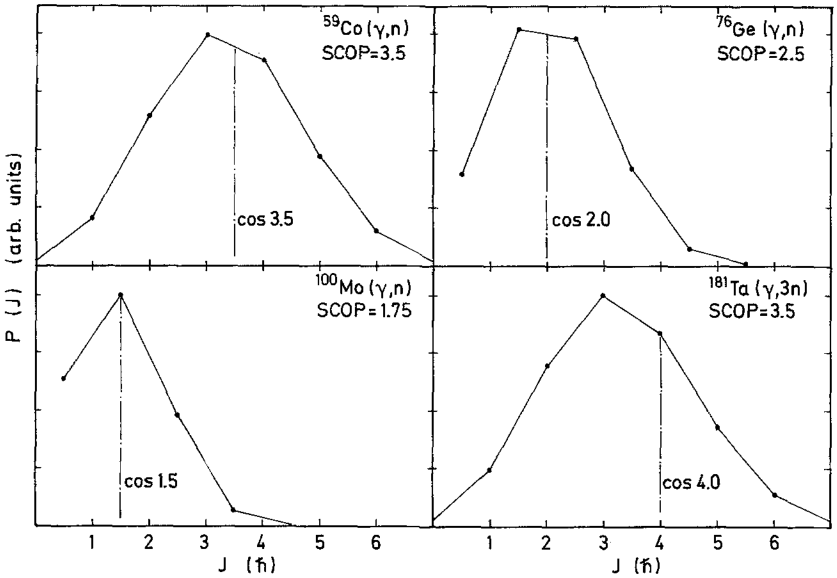

Fig. 3. Examples for theoretical final spin distributions

are yield ratios of the form [9]

$$\frac{\text{Yield (high spin)}}{\text{Yield (low spin)}}=\frac{\int^{E_0} R(E_\gamma)\cdot S(E_\gamma,E_0)\cdot\sigma_{\gamma,xn}(E_\gamma)\,dE_\gamma}{\int^{E_0} S(E_\gamma,E_0)\,\sigma_{\gamma,xn}(E_\gamma)\,dE_\gamma}$$

where $R(E_\gamma)$ = isomeric ratio for the photon-energy E_γ and $S(E_\gamma, E_0)$ = Schiff-Bremsstrahlung-spectrum [10] with endpoint energy E_0. The photoneutron cross sections were approximated by Lorentz curves. The Lorentz parameters were taken from the compilation of [11, 12]. In cases where no Lorentz-parameters were available, the numerical cross section data from [13] were used. Due to the lack of experimental data the $(\gamma, 3n)$ cross sections for ^{94}Mo, ^{140}Ce and ^{144}Nd were calculated using a modified evaporation model of Vandenbosch [14].

The results of our calculations are shown in Table 2, including the experimental isomeric ratios ($R_{exp} = Y_{high\,spin}/Y_{low\,spin}$), the spin values of the isomeric pair and the spins of "competing" spin states.

As we already stated in our previous paper [4] there seems to exist a linear correlation between the deduced spin cut-off parameter (SCOP) and the centre of spins (COS) of the isomeric pair. This relation can be explained by a more detailed consideration of the simple Huizenga-Vandenbosch decision model for the population of the isomeric- and the groundstate (isomeric pair). The calculated spin distributions for different SCOP values after neutron evaporation and $E1$-γ-deexcitation are nearly symmetric with the maximum value at about (SCOP$-1/2\,\hbar$). Figure 3 shows four examples of such distributions. The population probability for the isomeric pair then is calculated by

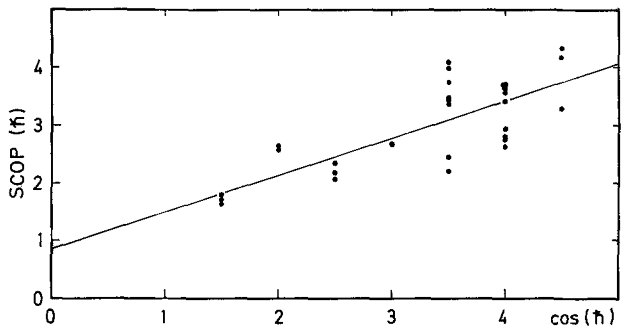

Fig. 4. SCOP as a function of COS for (γ, xn)-isomeric ratios

splitting up these distributions at the COS of the isomeric pair. The experimental isomeric ratios often have a value the order of unity. Therefore, it seems evident that the COS and the deduced SCOP are correlated.

We performed a correlation analysis of all known (γ, xn) data (Table 2). The (γ, n)-data of Haustein et al. [28] are in systematic contradiction to other authors [22, 4], possibly caused by their technique of using the 511 keV annihilation quanta for the detection of the groundstate decay. Their data as well as the results of reactions on neutron magic targets and of reactions with doubly odd residual nuclei were excluded from the analysis. For magic nuclei the application of a statistical model seems not to be reasonable, whilst the γ-deexcitation in a doubly odd nucleus is quite different from the HVM assumptions [4].

Figure 4 shows a plot of the deduced SCOP values versus the COS. A linear correlation seems to be evident, a correlation coefficient of $r = 0.76$ was calculated from the data. From our results we conclude that the HVM and especially the simple decision model proposed for the population of the isomeric pair are too crude to really describe the isomeric cross section ratios from photonuclear reactions. Therefore, no information about spin-distributions or the nuclear moment of inertia should be extracted from the HVM-analysis for this kind of reactions. However, the observed correlation between COS and SCOP is useful for spin assignments to isomeric states from measured population ratios. This method is of particular interest with regard to shape isomers of fissioning nuclei [31].

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