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SYSTEMATICS OF $(n, 2n)$ REACTIONS AT 14 MeV[1]

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There exist a large number of experimental data for the $(n, 2n)$ cross sections at a neutron energy of 14—15 MeV [1]. Several authors [2—5] have plotted the systematics of $(n, 2n)$ cross sections as a function of $(N-Z)/A$ or $(N-Z)$ parameters. The conclusions drawn from these systematic studies during the last ten years have, however, been rather different. There was a controversy regarding the existence of structural effects in $(n, 2n)$ cross sections.

All previous results confirm two main trends in $(n, 2n)$ cross sections plotted against $(N-Z)$ or $(N-Z)/A$: *a*) a structureless gross trend, and *b*) the so-called Csikai—Petö trend [6] (positive slope of isotonic and isotopic lines).

Bormann [2] and S. Chatterjee and A. Chatterjee [4] found distinct minima in the mass dependence of $(n, 2n)$ cross sections in the region of closed neutron and proton shells. In Ref. [2] the author made a systematic study at an approximately constant value of the incident neutron energy $E_n \approx 14.5$ MeV. On the other hand, S. Chatterjee and A. Chatterjee [4], as well as Csikai and Petö [6], pointed out the importance of Q-value effects and made a systematic study at a constant value of the maximal residual excitation energy. The structural effects which were observed in Refs. [2] and [4] appeared to be due to the fact that partial $(n, 2n)$ cross sections were taken in those cases where the total cross section was not experimentally known. Another reason for the minima was that many experimental results were rather old and inaccurate.

In recent years a number of new results, obtained with the high-resolution γ-ray detection technique, has become available. Thus, it is now possible to reinvestigate the earlier systematics and reexamine their conclusions.

The experimental results of this work were obtained in the region where strong minima were reported in Ref. [4]. These are the data for the nuclei ^{84}Sr, ^{86}Sr, ^{88}Sr, ^{93}Nb, ^{134}Ba and ^{136}Ba. In all these cases, except ^{84}Sr and ^{86}Sr, only the partial cross section could be measured by the activation technique, and therefore the theoretical prediction for isomeric cross section ratios, based on the statistical theory, was used to estimate the total cross sections.

The systematics presented in this work is based on new experimental data in literature [1] and experimental data obtained in this work. B plot of $(n, 2n)$ cross sections versus residual neutron excess $(N\ Z)_R$ at a constant value of the residual excitation energy is in good agreement with the gross trend without pronounced minima, even in the region of closed neutron and proton shells.

Neutrons were obtained from the ^{3}H$(d, n)\,^4$He reaction produced in the 200 kV Cockcroft-Walton accelerator of the "Rudjer Bošković" Institute in Zagreb. The energy of neutrons was 14.6 ± 0.3 MeV.

To determine the $(n, 2n)$ cross sections, the standard activation method was used. Gamma rays were measured with a 20 cm^3 Ge(Li) detector with a resolution of about 4 keV at 1332 keV. The mixed powder and sandwich methods were used to monitor the neutron flux. The choice of the monitor reaction for determining the neutron flux depended on the half-life and gamma-ray energy of the product nucleus in the $(n, 2n)$ reaction. The following monitor reactions were employed to evaluate the neutron flux:

$$^{27}\mathrm{Al}(n, p)\,^{27}\mathrm{Mg} \quad (t_{1/2} = 9.46\ \mathrm{m},\ \sigma = 73 \pm 5\ \mathrm{mb}\ [7]),$$

$$^{27}\mathrm{Al}(n, \alpha)\,^{24}\mathrm{Na} \quad (t_{1/2} = 14.96\ \mathrm{h},\ \sigma = 114 \pm 6\ \mathrm{mb}\ [8])$$

and

$$^{56}\mathrm{Fe}(n, p)\,^{56}\mathrm{Mn} \quad (t_{1/2} = 2.576\ \mathrm{h},\ \sigma = 100 \pm 6\ \mathrm{mb}\ [9]).$$

The calculation of the isomeric cross-section ratio was performed using the statistical model formalism described by Huizenga and Vandenbosch [10]. According to the evaporation theory it was assumed that neutrons in each neutron-emission step were emitted with the same average energy $\varepsilon_n^{(i)} = 2T_i$ ($i = 1, 2$ for the $(n, 2n)$ reaction). The nuclear temperatures T_i were derived from the residual excitation energies, corrected for the pairing δ.

The calculation of the excitation energy U, the level density ϱ and the spin cut-off factor σ was performed using two different models. In most cases the best fits to the experimental isomeric ratios were obtained with the shifted Fermi-gas model for even-mass residual nuclei, and with the superconductor model for odd-mass residual nuclei. The level density in the shifted Fermi-gas model was taken from Ref. [11]. The superconductor level-density formula was proposed by Lang [12] and applied by several authors [13—17].

The programme of Hafner et al. [18] was used for the calculation of isomeric cross-section ratios. Neutron transmission coefficients were taken from Mani et al. [19]. The level density parameter a was taken from Gilbert and Cameron [11], and the pairing energies were taken from Nemirovsky and Adamchuk [20]. The calculations were carried out on the CAE 90-40 computer of the Computing Centre in Zagreb.

The experimental results obtained in this work are shown in Table 1. In some cases the $(n, 2n)$ cross-section was measured for the ground as well as for the metastable states, and the total $(m + g)$ cross-sections were obtained. For ^{88}Sr, ^{93}Nb, ^{134}Ba and ^{136}Ba, only partial cross sections could be measured by the activation method, since one isomeric state was long-lived or stable. The total cross sections were then calculated using the theoretical σ_m/σ_g ratios.

The results of the present work and other recent total cross-section values were classified in three different residual excitation-energy ranges of $U_R = 2 \pm 1$, 4 ± 1 and 6 ± 1 MeV. These results are compared with the data used in Ref. [4] and with the statistical theory results calculated using the Pearlstein semiempirical formula [21] (Table 1).

Fig. 1 shows the present results and the new experimental data for $U_R = 4 \pm 1$ MeV in the region around $(N-Z)_R \sim 10$, where a pronounced minimum was found in Ref. [4] and explained in terms of a shell-clossure effect. One can see from this figure that the new experimental data fit the gross trend rather well, without structure effects.

Fig. 2 shows the results of this work and other new experimental data for $U_R = 6 \pm 1$ MeV in a wide region of $(N-Z)_R$, together with the results used in Ref. [4]. Contrary to the old experimental data, the new results agree with the gross trend rather well.

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Table 1

Results for $(n, 2n)$ cross sections obtained in this work, compared with the statistical theory, results used in ref. [4] and other literature data. $E_n = 14.6 \pm 0.3$ MeV.

Target	Res. Nucl.	$(N-Z)_R$	U_R (MeV)	$T_{1/2}$	I_R	σ_{exp} (mb) present res.	σ_{th} (mb) present res.	$\sigma_{stat, th,}$ (mb)	σ_{exp} (mb) used in ref. [4]	σ_{exp} (mb) other res.
$^{84}_{38}$Sr	^{83}Sr^t	7	2	32 . 4*h*	1/2⁻	594 ± 57		$665^{21)}$	180.6 ± 9	482 ± $80^{9)}$
$^{86}_{38}$Sr	^{85}Sr^m	9	4	70*m*	1/2⁻	270 ± 50				247 ± $25^{8)}$
	^{85}Sr^g	9	4	64*d*	9/2⁺	676 ± 40				
	^{85}Sr^t	9	4			946 ± 90		$790^{21)}$	592 ± 51	
$^{88}_{38}$Sr	^{87}Sr^m	11	4	2.83*h*	1/2⁻	238 ± 23			215 ± 24	235 ± $24^{8)}$
	^{87}Sr^g	11	4	*stab.*	9/2⁺		765 ± 74			
	^{87}Sr^t	11	4				1003 ± 97	$963^{21)}$		
$^{93}_{41}$Nb	^{92}Nb^m	10	6	10.16*d*	2⁺	484 ± 50			480 ± 70	578 ± $30^{23)}$
	^{92}Nb^g	10	6	>350*y*	7⁺		1078 ± 111			
	^{92}Nb^t	10	6				1562 ± 161	$1526^{22)}$		1350 ± $250^{22)}$
$^{134}_{56}$Ba	^{133}Ba^m	21	6	38.9*h*	11/2⁻	728 ± 40			940 ± 80	783 ± $56^{23)}$
	^{133}Ba^g	21	6	7.2*y*	1/2⁺		423 ± 23			
	^{133}Ba^t	21	6				1151 ± 63	$1722^{21)}$		
$^{136}_{56}$Ba	^{135}Ba^m	23	6	28.7*h*	11/2⁻	1053 ± 36			700 ± 80	1149 ± $80^{23)}$
	^{135}Ba^g	23	6	*stab.*	3/2⁺		329 ± 11			
	^{135}Ba^t	23	6				1382 ± 47	$1726^{21)}$		

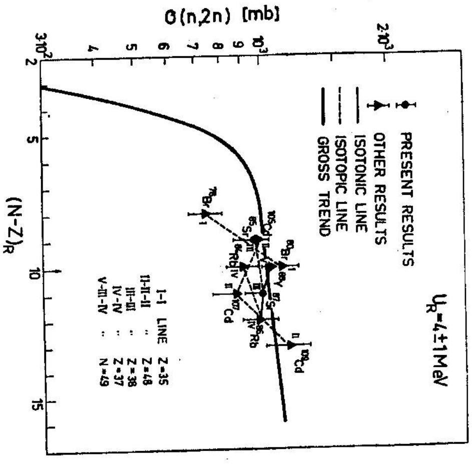

Fig. 1. The experimental $\sigma(n, 2n)$ versus $(N-Z)_R$ at $U_R = 4 \pm 1$ MeV. The heavy solid line represents the gross trend of $\sigma(n, 2n)$, obtained by averaging the existing experimental results [1]. The experimental results are given explicitly only around $(N-Z)_R = 10$.

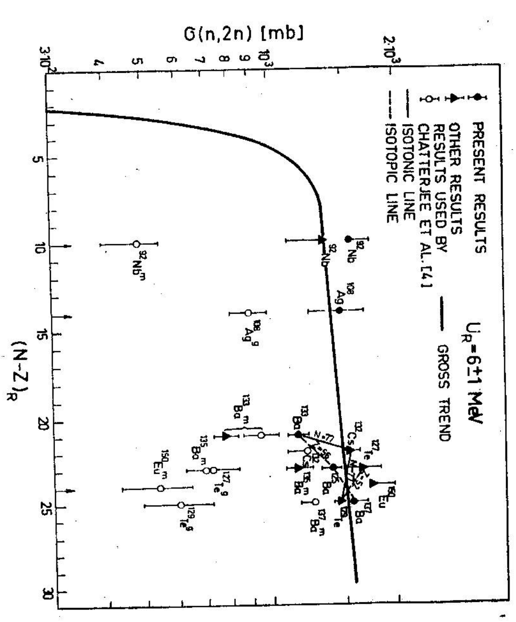

Fig. 2. The experimental results for $\sigma(n, 2n)$ versus $(N-Z)_R$ used in Ref. [4] and the new results for $U_R = 6 \pm 1$ MeV in a wide $(N-Z)_R$ region. The heavy solid line represents the gross trend of $\sigma(n, 2n)$, obtained by averaging the existing experimental results. The experimental results for partial cross sections for ^{109}Ag and ^{138}Ba are taken from Refs. [24] and [25], respectively. The figure shows the total cross sections (^{108}Ag, ^{137}Ba) calculated in this paper.

The agreement with the Csikai – Petö trend was also generally observed. A small deviation, however, appeared in some cases. The isotonic lines $N = 49$ and 77, and the isotopic lines $Z = 48$ and 52 (Figs. 1 and 2) show a slightly negative slope. At present it is not possible to explain these deviations. They can be due to experimental uncertainties, but if this is not the case, they could be treated as a small shell-closure effect and a second-order correction to the cross sections.

As a conclusion we stress the following: (*i*) $(n, 2n)$ cross sections have to be considered and compared at a constant residual excitation energy U_R in order to eliminate the Q-value effects on the cross sections; (*ii*) total $(n, 2n)$ cross sections plotted versus $(N-Z)_R$ or $(N-Z)/A$ at a constant value of U_R follow a smooth, structureless curve, known as the gross trend, and are also in a rather good agreement with the Csikai – Petö trend; (*iii*) structures effects, if any, are not pronounced.

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