NEUTRON INDUCED REACTION CROSS-SECTIONS ON ^{115}In AT AROUND 14 MeV*

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ABSTRACT

A systematic investigation was carried out on ^{115}In isotope to determine the contribution of different reactions to the total non-elastic cross-section in the 13.43 and 14.84 MeV range. All the major component cross-sections of σ_{NE} were measured with exception of the $\sigma^{g}(n,n')$. In the knowledge of σ_{NE}, the energy dependence of $\sigma^{g}(n,n')$ could be deduced. The isomeric cross section ratios both for (n,2n) and (n,n') processes were also determined in the given energy range. The present experiment proves the dependence of $\sigma^{m}/(\sigma^{g}+\sigma^{m})$ ratio on the spin value (I_m) of the isomeric state in (n,2n) reaction. Excitation functions of (n,2n), (n,n') and (n,ch) reactions were compared with results calculated by STAPRE code.

1. INTRODUCTION

The knowledge of the shape and magnitude of excitation functions for fast neutron induced reactions on ^{115}In is of interest for nuclear reaction theory, and it is in connection with the use of indium as a threshold detector for unfolding the neutron spectra. In the case of $A \leq 100$, the difference between the nonelastic (σ_{NE}) and the (n,2n) cross sections is mainly due to the inelastic scattering

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because of the negligibly small contributions from any other reactions at 14 MeV neutron energy. Therefore, by studying the (n,2n) and (n,n′) cross-sections, one can get information on those properties of nuclei which are dominant in nuclear reactions. The aim of this work is to measure the partial cross-sections of 14 MeV neutron induced reactions on ^{115}In and to deduce the $\sigma^{g}(n,n')$ and $\sigma^{g}(n,n')/\sigma^{m}(n,n')$ values from a comparison of these data with the evaluated σ_{NE} values. The energy dependences and magnitudes of the (n,2n), (n,n′) and (n,p) reactions obtained from the present experiment between 13.43 and 14.84 MeV neutron energy have been compared with results calculated by STAPRE code.

2. EXPERIMENTAL PROCEDURES

High-purity (Goodfellow Metals) metallic samples of natural In with dimensions of 15x10 mm^2 and thickness of 375 mg/cm^2 were irradiated by the home-mode neutron generator of the Institute of Experimental Physics. Neutrons of energy between 13.43 and 14.84 MeV were produced via the $^{3}H(d,n)^{4}He$ reaction, using an analyzed D^{+}-beam of 200 keV. In order to reduce the number of secondary neutrons from the generator an air-jet cooled 0.3 mm thick Al-backed Ti-T target was used in a scattering free arrangement[1]. Samples and Nb fluence monitor foils of 0.5 mm thick placed back-to-back were fastened to an aluminium support ring of a 23 cm inner diameter with the beam spot (diameter ~0.5 cm) at the centre[1]. The energy points in the available energy region were distributed roughly equally by the angular positions of the samples. To estimate the effect of scattered neutrons, the yields of $^{115}In(n,\gamma)$, $^{115}(n,n')$ and $^{27}Al(n,\alpha)$ reactions have been measured as a function of distance up to 16 cm from the target spot. The neutron energy versus emission angle has been determined by measuring the ratio of the ^{89}Zr to ^{92m}Nb specific activities produced both in the Zr and Nb foils by (n,2n) reactions[2,3,4]. Cross-section data for the $^{90}Zr(n,2n)^{89}Zr$ and $^{93}Nb(n,2n)^{92m}Nb$ reactions were taken from Pavlik et al.[5] and Ryves[6], respectively. Neutron energy spreads (1/2 FWHM) at E_n=14.8, 14.4, 14.0 and 13.5 MeV were found to be[7,8] 210, 130, 40 and 130 keV, respectively.

The neutron fluence rate was monitored continuously by a BF_3 long-counter over time intervals much shorter than the half-life of the isotope being measured. Correction for the variation of the neutron output with time was applied both for single isotopes and for a parent-daughter relationship between two isotopes[9,10,11].

The activities of the In samples and of the corresponding Nb fluence monitor foils were measured both by Ge(Li) and NaI gamma-ray detectors. The self-absorption correction factor for the 190 keV gammas has been determined experimentally by measuring the relevant peak areas obtained by indium foils of various thicknesses, having activated the In homogeneously by thermal neutrons.

The absolute full-energy peak efficiency of the Ge(Li)[12] and the NaI[15] γ-ray detectors has been determined by using standard gamma-ray sources and activated samples. Empirical analytical expressions were given for the description of the energy-efficiency curves for different positions and dimensions of both the sources and samples. The total error of the full-energy-peak efficiency in the 180-1500 keV range was found to be 1.0 % for the Ge(Li) detector. The NaI detector has been used only for relative activity measurements.

The parent-daughter ^{115g}Cd-^{115m}In pair required an analysis of the complex decay curve for the determination of the cross-sections for the ^{115}In(n,p)^{115g}Cd and ^{115}In(n,n') ^{115m}In reactions. The contribution of the ^{115g}Cd decay to the ^{115m}In activity-during the irradiation and measurement - was taken into account by using the following expression[9,10,11]:

$$\frac{\sigma_d}{\sigma_p} = \left(\frac{A_d}{A_p}+1\right) \frac{\lambda_d}{\lambda_d-\lambda_p}\cdot\frac{D}{B}+f_p\left(\frac{\lambda_d}{\lambda_d-\lambda_p}\cdot\frac{C}{B} -1\right) \qquad (1)$$

where A_p and A_d are the activity of the parent and daughter nuclei at the end of the irradiation, f_p is the fraction of the parent nuclei decays to the daughter nuclei, while B, C and D describe the time variation of the neutron fluence rate as well as the build up and decay of the radioactive nuclei.

The cross-section of the ^{115}In(n,2n)^{114g}In reaction was determined by measuring the 72s β^--activity of ^{114g}In and referred to the ^{27}Al(n,p)^{27}Mg reaction. Corrections for the G-M counter efficiency and self-absorption in the samples as a function of maximum beta energy were determined by experiment. Cross-section curve between 13.0 and 15.0 MeV for ^{27}Al(n,p)^{27}Mg taken from Manokhin et al.[12] was normalized to the recommended data[6] at 14.7 MeV.

The contribution of the ^{113}In(n,γ) reaction to the ^{114m}In and ^{114g}In activities has been determined experimentally by placing In samples at different distances from the beam spot. The effect of background neutrons was deduced from the distortion of the $1/r^2$ dependence of the ^{114}In activities. The corrections for the low-energy neutrons reduced the measured ^{114m}In and ^{114g}In activities by 1.8 % and 1.0 %, respectively, at the 11.5 cm source-sample distance. The real coincidence correction was below 1 % in all cases.

A significant contribution to the ^{115m}In activity from neutrons produced in D-D reaction was found. This correction has been measured by replacing the TiT target with a Ti plate, assuring the same irradiation conditions as hold for D-T neutrons. The $1/r^2$ dependence of the ^{115m}In activity has shown that the contribution of the target and sample scattered neutrons both for D-T and D-D reactions can be neglected. It was found that neutrons produced by a D^+-beam of 200 keV and 200 μA in a Ti target can contribute to the ^{115m}In activity with about 4 % in average, depending on the position of the sample. The relative angular distribution of D-D background neutrons measured by the ^{232}Th(n,f) process using Makrofol KG track-etch detector foils was found to be in agreement with a thick target yield of a point-like source.

Table 1. Nuclear data and detection methods

Radio nuclide	Half-life [15]	Energies of the measured γ-rays [16]	γ-emission probabilities [16]	Detector	Fluence method
^{114g}In	71.9 s	-	-	GM	^{27}Al(n,p)
^{114m}In	49.51 d	191.6	0.16	NaI, Ge(Li)	^{93}Nb(n,2n)
^{115m}In	4.486 h	336.2	0.458	NaI, Ge(Li)	^{93}Nb(n,2n)
^{115g}Cd	53.38 h	336.2	0.497	NaI, Ge(Li)	^{93}Nb(n,2n)

Table 2. Cross-section results for ^{115}In

Neutron energy (MeV)	σ(mb)					
	^{115}In(n,2n) ^{114g}In	^{115}In(n,2n) ^{114m}In	^{115}In(n,n′) ^{115m}In	^{115}In(n,p) ^{115g}Cd	^{115}In$_{NE}$	^{115}In(n,n′) ^{115g}In
14.84	268±6	1346±42	55.0±1.0	5.3±0.5	1917	229±21
14.66	271±7	1329±37	55.0±1.0	4.9±0.4	1921	248±23
14.35	263±7	1314±58	57.4±1.0	4.4±0.4	1928	277±27
14.10	263±7	1307±30	60.4±1.2	4.9±0.5	1932	285±28
13.85	259±8	1291±45	61.5±1.3	4.2±0.5	1938	312±40
13.74	-	1278±15	62.5±1.2	4.1±0.4	1940	-
13.64	258±8	1271±18	68.2±1.5	4.1±0.5	1940	328±34
13.48	-	-	-	3.5±0.4	1946	-
13.43	249±8	1229±41	73.0±1.5	-	1947	-

The decay data accepted for the determination of the cross-sections[15,16] are given in Table 1.

3. RESULTS AND DISCUSSION

The results obtained for the ^{115}In(n,2n), (n,n') and (n,p) reaction cross-sections between 13.43 and 14.84 MeV incident neutron energies are summarized in Table 2. Uncertainties combined by quadrature have been estimated at 1 σ. The assumed values of the ^{93}Nb(n,2n)^{92m}Nb and ^{27}Al(n,p)^{27}Mg cross-sections[6] at 14.7 MeV were (460±5)mb and (68.8±0.7)mb, respectively. As it can be seen in Figs. 1 and 2, the shapes and magnitudes of the measured and calculated excitation functions for the (n,2n) and (n,n') reactions are in good agreement. Among the charged particle emission cross-sections,

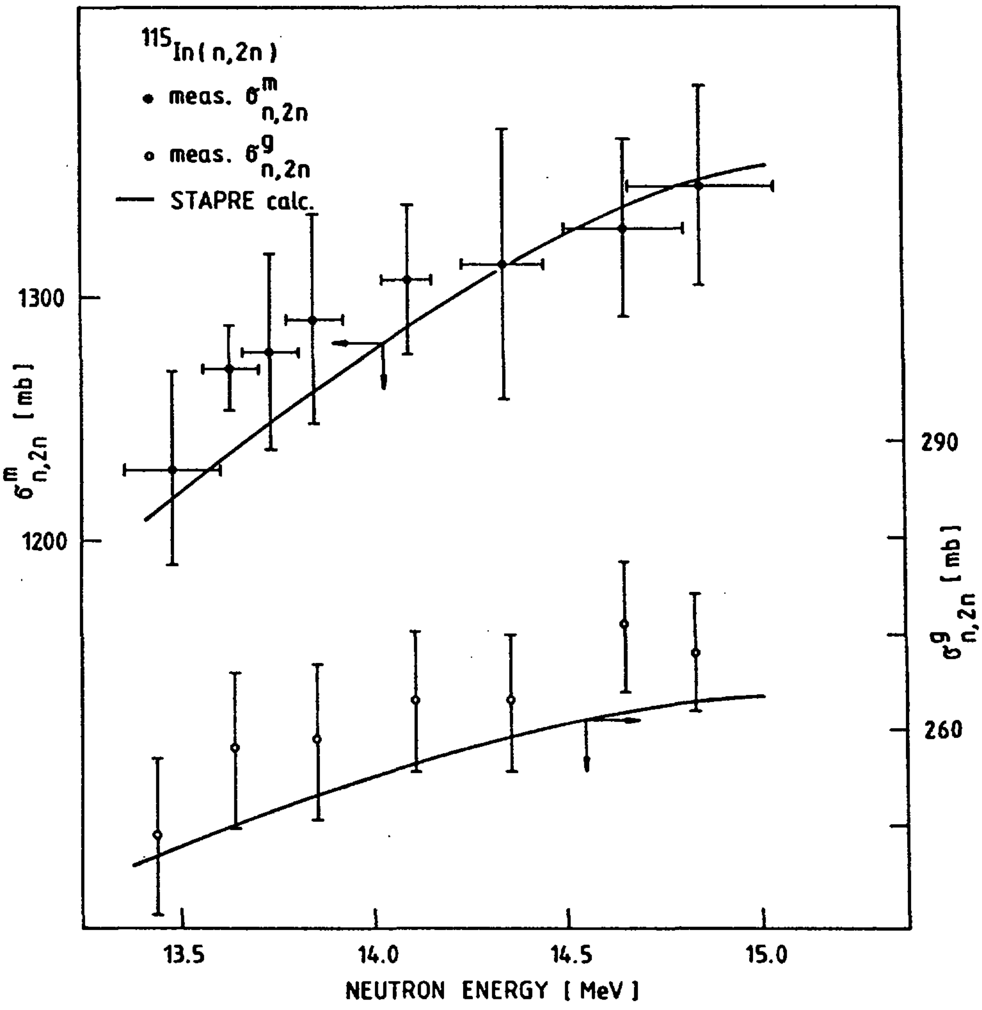

Fig. 1. Measured and calculated excitation functions for ^{115}In(n,2n)^{114m,g}In reactions

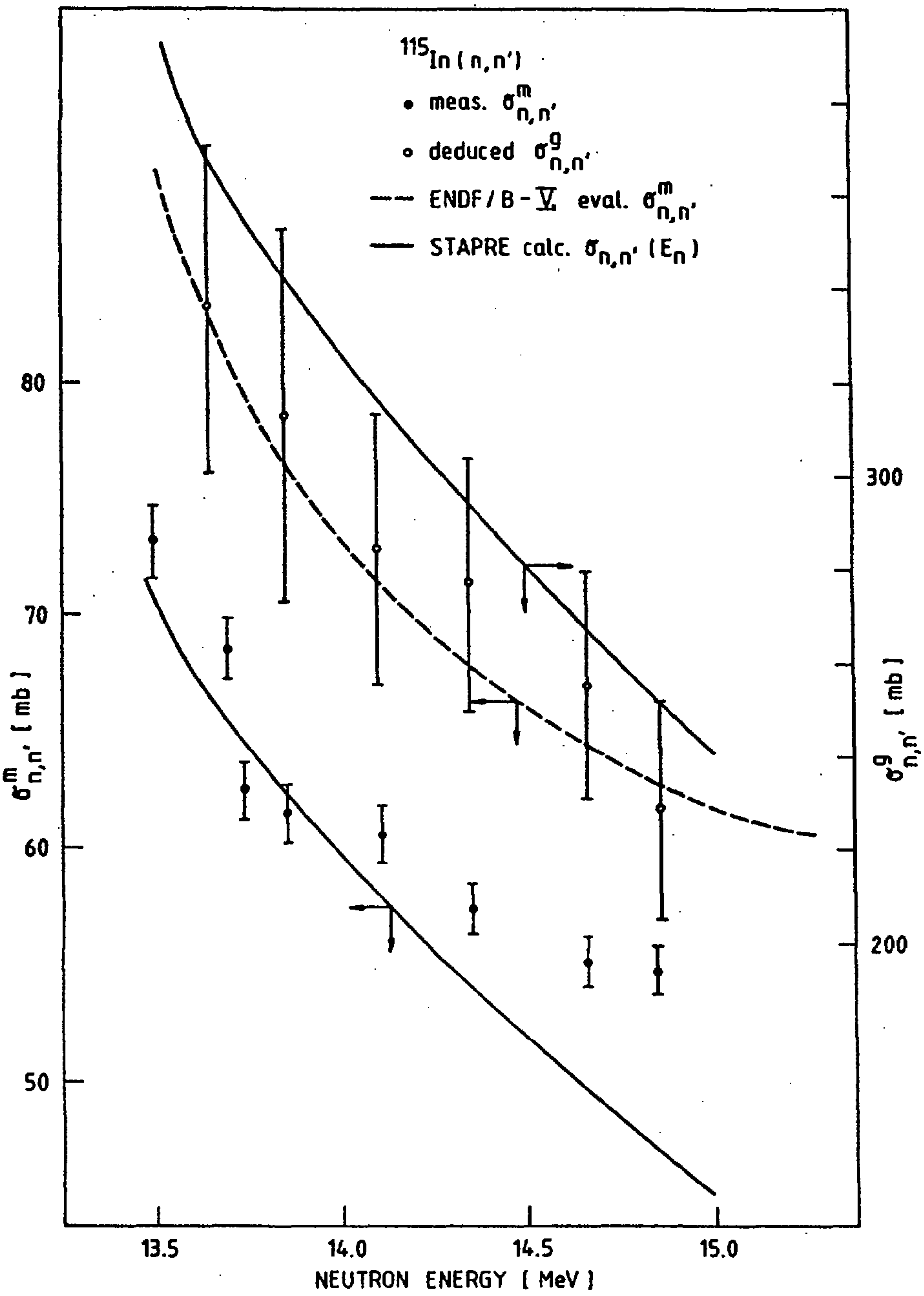

Fig. 2. Measured and calculated excitation functions for ^{115}In(n,n')^{115m,g}In reactions

only the (n,p) was measured. The results are shown in Fig.4 together with σ_{tot}(n,ch), the (calculated) total charged particle emission cross-section.

In a previous work[17] an analytical expression was given for the description of the energy and mass number dependence of the nonelastic cross-sections. The mass number dependence of σ_{NE} at 14 MeV can be well approximated[18] by the following formula (see Fig.5)

$$\lg\sigma_{NE}(b) = a_o + a_1 \lg A \qquad (2)$$

from which σ_{NE}=1932 mb for ^{115}In is obtained at 14.1 MeV. The σ_{NE} has not been measured for indium up till now. All the major component cross-sections of σ_{NE}, with exception of $\sigma^{g}_{n,n'}$, were measured, therefore, from the difference of σ_{NE} and $\Sigma\sigma(n,x)$ the $\sigma^{g}(n,n')$ could be deduced:

$$\sigma_{NE}-[\sigma^{g+m}(n,2n)+\sigma_{tot}(n,ch)+\sigma(n,\gamma)+\sigma^{m}(n,n')]=\sigma^{g}(n,n') \qquad (3)$$

In eq.(3), all the cross-sections obtained in this experiment were accepted. The calculated $\sigma_{tot}(n,ch)$ is consistent both with the measured values[10,19] and the systematics given by Qaim[20]. A value of (1.2±0.3)mb was assumed for the $\sigma(n,\gamma)$[21]. Though the error bars are large, the deduced $\sigma^{g}_{n,n'}$ data are in surprisingly good agreement with the calculated $\sigma^{g}_{n,n'}(E)$ function.

The isomeric cross-section ratios for ^{115}In(n,2n)^{114m,g}In and ^{115}In(n,n')^{115m,g}In are shown in Fig. 3. The measured

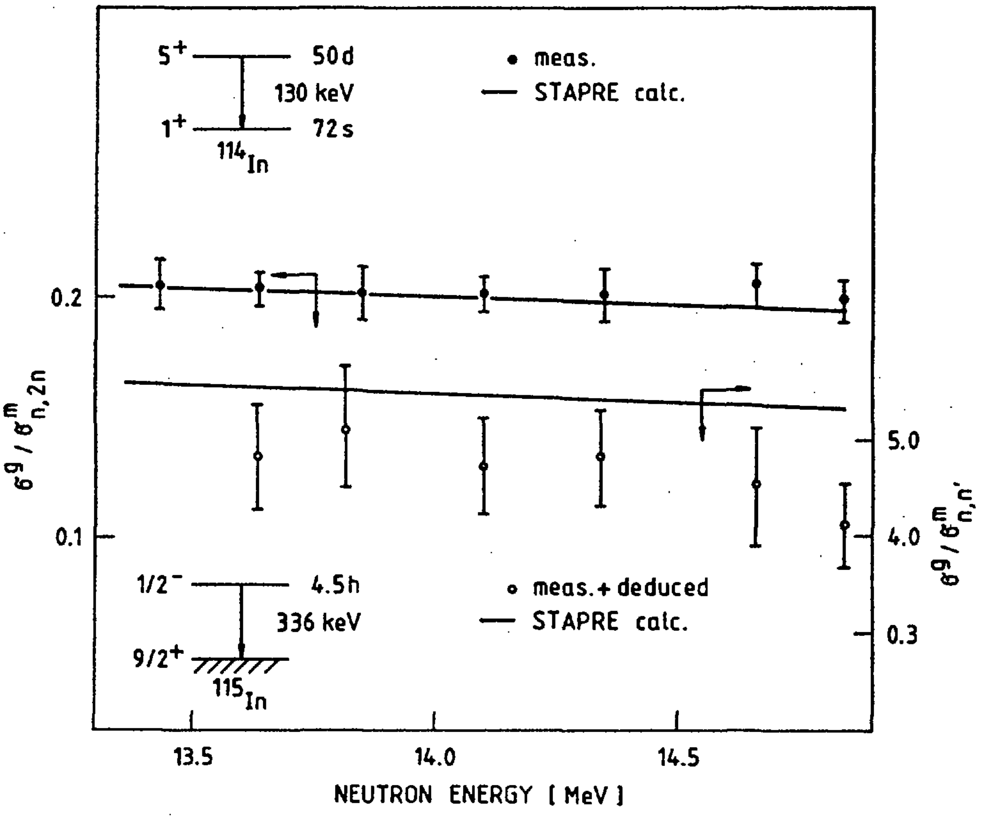

Fig.3. Isomeric cross-section ratios for ^{115}In(n,2n) ^{114m,g}In and ^{115}In(n,n')^{115m,g}In reactions

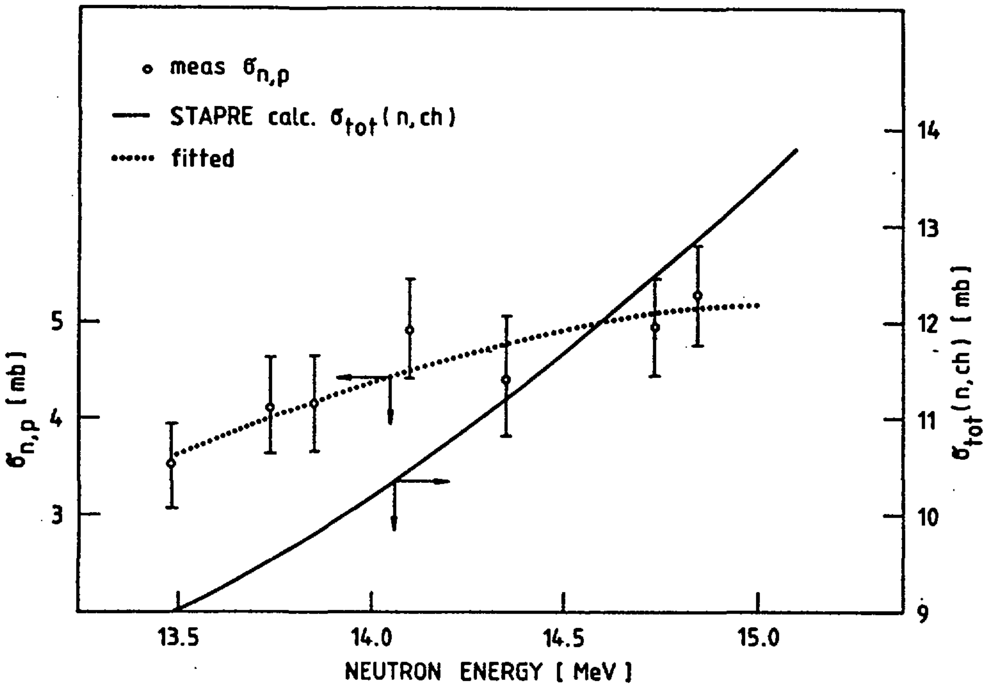

Fig.4. Charged particle emission cross-sections for ^{115}In

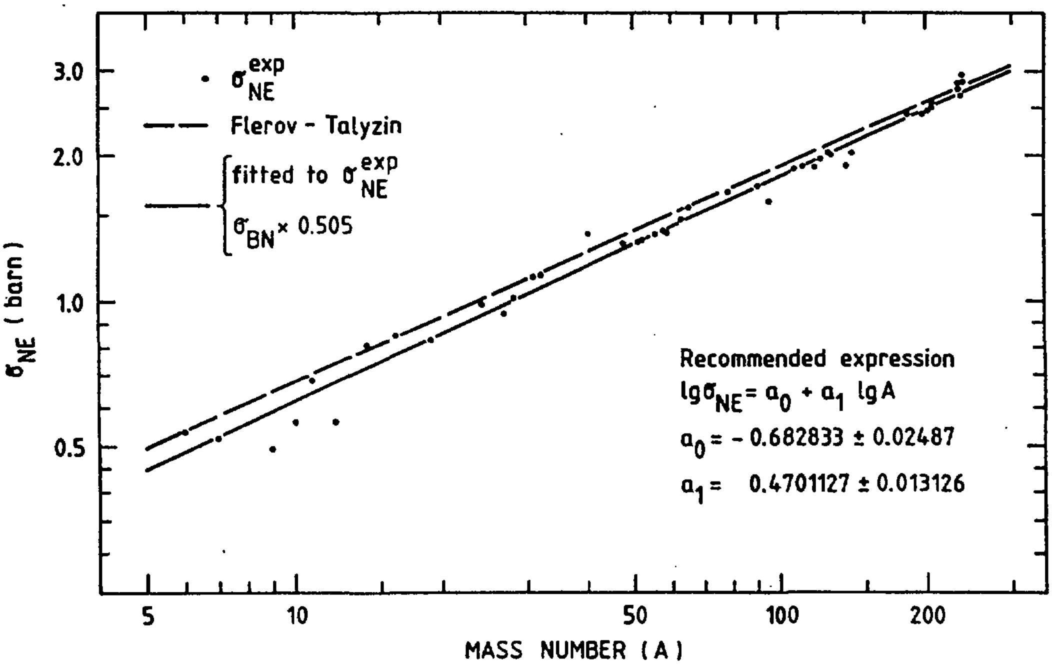

Fig. 5. Mass number dependence of the nonelastic cross-sections at 14 MeV

and calculated σ^g/σ^m values are in good agreement for (n,2n) reaction, while in the case of (n,n′) process a difference of about 10-15 % exists, i.e. σ^g/σ^m (meas.)< σ^g/σ^m(calc.).

Table 3. Input parameters used in the STAPRE code

Nucleus	a $[\mathrm{MeV}^{-1}]$	Δ [MeV]	E_d [MeV]	N_d	E_{sep} [MeV]
^{115}In	16.31	- 0.20	1.496	17	6.779
^{115}Cd	16.31	- 0.20	0.962	16	7.447
^{112}Ag	9.90	- 0.90	0.019	2	4.100
^{114}In	15.23	- 0.26	0.969	20	9.029
^{114}Cd	15.74	1.46	2.219	18	6.816
^{111}Ag	9.84	0.04	0.809	15	3.743
^{113}In	14.81	- 0.38	1.471	20	7.313
^{113}Cd	14.81	- 0.38	0.708	10	6.828
^{110}Ag	15.79	- 0.92	0.192	6	3.553

The cross sections for the ^{115}In(n,2n), (n,n′) and (n,ch) reactions were calculated by the preequlibrium model using the STAPRE[22] code. Neutron, proton, alpha and gamma emissions were taken into account. The transmission coefficients for these particles have been calculated on the bases of the optical model, using the parameters for neutrons, protons and for alphas as given in[23] and [24], respectively. For the energy and mass dependence of the effective matrix element the $|M|^2 = FM\ A^{-3}E^{-1}$ formula was used with a value of FM=250. The separation energies of the emitted particles were taken from the table of Wapstra[25]. The energies, spins, parities and branching ratios of the discrete levels were taken from Nuclear Data Sheets[26]. In the continium region, the level density was calculated by the back-shifted formula[27] using $\sigma = \sigma_{rigid}$. The parameter values accepted in these calculations are summarized in the Table 3.

The experimental results obtained in the present measurements are compatible in general with those published by Ryves et al.[10]. The best agreements with the literature

Table 4. Published ^{115}In cross-sections

Reaction	Energy (MeV)	Cross-section results (mb)	Reference
$\sigma^{m}_{n,2n}$	14.67	1250±30	Ryves et al.[10]
	14.6	1337±120	Barrall et al.[28]
	14.68	1399±81	Santry et al.[29]
	14.96	1393±137	Menlove et al.[30]
	14.6	1331±110	Kayashima et al.[31]
	14.66	1329±37	Present value
$\sigma^{g}_{n,2n}$	14.3	269±7	Ryves et al.[10]
	14.7	269±20	Minetti et al.[32]
	14.35	263±7	Present value
$\sigma^{m}_{n,n'}$	14.3	54.3±2.0	Ryves et al.[10]
	14.5	57.7±2.3	Santry et al.[29]
	14.6	50±7.8	Nagel [35]
	14.3	55±2	Tang Hongqing[33]
	14.35	57.4±1.0	Present value
$\sigma^{g}_{n,p}$	4.3	4.37±0.26	Ryves et al.[10]
	14.6	4.46±0.27	Leschenko et al.[19]
	14.35	4.4±0.4	Present value
$\sigma^{m}_{n,2n}/\sigma^{g}_{n,2n}$	14.3	4.59±0.03	Ryves et al.[10]
	14.7	5.88±0.70	Minetti et al.[32]
	13.86	5.78±0.10	Grochulski et al.[37]
	14.52	5.23±0.08	- " -
	14.35	5.0±0.25	Present value

data are summarized in Table 4. The $\sigma^{g+m}_{n,2n}$ is lower by about 6 % than the BOSPOR evaluation[12] and agrees with the recommended value of Pearlstein[34]. The shape of the $\sigma^{m}_{n,n'}(E)$ function follows the ENDF/B-V. and IRDF evaluations, however, its magnitude lies below the recommended values by 20 %. The present experiment confirms the observed[36] dependence of $\sigma^{m}/(\sigma^{g}+\sigma^{m})$ ratio on the isomeric state spin value in (n,2n) reaction. Further accurate measurements are needed for other isotopes to confirm the procedure by which the $\sigma^{g}_{n,n'}$ data are deduced.

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