MEASUREMENT OF THE CROSS SECTIONS FOR THE REACTIONS $^{52}Cr(n,2n)^{51}Cr$, $^{66}Zn(n,2n)^{65}Zn$, $^{89}Y(n,2n)^{88}Y$ AND $^{96}Zr(n,2n)^{95}Zr$ FROM 13.5 TO 14.8 MeV

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ABSTRACT Cross sections for the reactions $^{52}Cr(n,2n)^{51}Cr$ $^{66}Zn(n,2n)^{65}Zn$, $^{89}Y(n,2n)^{88}Y$ and $^{96}Zr(n,2n)^{95}Zr$ were measured in the energy range 13.47 MeV to 14.79 MeV applying the activation technique. Energy of neutrons produced via the $T(d,n)^{4}He$ reaction was changed by the emission angle. The neutron fluences and energies incident on the samples were determined by the measurements of the ^{92m}Nb and ^{89}Zr specific activities produced in the $^{93}Nb(n,2n)$ and $^{90}Zr(n,2n)$ reactions.
The induced γ-ray activities of the irradiated Cr, Zn, Zr and Y_2O_3 samples and their monitor foils were measured by means of calibrated Ge(Li) and NaI well-type γ-ray detectors.
The results compared to the corresponding data in the literature show that the uncertainties obtained in this work are considerably smaller in most cases than those given by other authors.

1. INTRODUCTION

Measurements of activation cross sections for production of long-lived isotopes at around 14 MeV neutron energy are of interest for testing nuclear reaction models. Furthermore, the data in the case of structural

materials of a fusion reactor are important for the estimation of neutron multiplication, nuclear heating, nuclear transmutation and radiation damage effects. Cross section data available for such reactions are very scarce and contradictory even in the vicinity of 14 MeV especially in the case of ^{52}Cr(n,2n) and ^{96}Zr(n,2n) reactions.
This work describes precise activation cross section measurements for (n,2n) reactions on ^{52}Cr, ^{66}Zn, ^{89}Y and ^{96}Zr in the 13.5 to 14.8 MeV range.

2. EXPERIMENTAL PROCEDURE

Rectangular high-purity metallic samples of natural Cr, Zn and Zr, with the dimensions 16 mm x 8 mm and thicknesses of 0.75 mm, 1.0 mm and 1.0 mm, respectively, as well as Y_2O_3 powder samples were irradiated at the Cockcroft-Walton neutron generator of the Institute of Experimental Physics, Kossuth University (KFI), Debrecen. The Y_2O_3 powder with 2.0 mm effective layer thickness was contained in thin-walled (0.5 mm) cylindrical perspex containers with an inner diameter of 14.0 mm. The neutrons in the 14 MeV range were produced via the reaction T(d,n)^{4}He, using an analyzed d^+-beam with (190±10) keV mean incident energy. The total neutron yield achieved with an air-jet-cooled 0.5 mm thick Al-backed Ti-T target was $\approx 10^{14}$ neutrons in approximately 275 hours. The scattering free arrangement used for the irradiation of the samples has been described elsewhere[1].

For fluence monitoring metallic Nb foils, 0.65 mm thick, with the same shape as the samples were placed back-to-back behind each sample; the Y_2O_3 samples positioned at 0°, 55° and 135° relative to the incident deuteron beam were sandwiched between two fluence monitor foils. Thus all cross sections were measured relative to the well-evaluated cross sections of the reference reaction ^{93}Nb(n,2n)^{92m}Nb in this energy range[2,3]. The distribution of the neutron production in time was monitored by means of a BF_3 long-counter. The neutron-energy scale was verified by measuring the ratio of the ^{89}Zr to ^{92m}Nb specific activities induced in Zr and Nb foils, which were exposed as a sandwich at 12.5°

and 97.5°. The measured activity ratios were compared to expected ones based on accurate cross section data from Palvik et al.[4] for the $^{90}Zr(n,2n)^{89}Zr$ reaction and on the above mentioned $^{93}Nb(n,2n)^{92m}Nb$ cross section data. Another very sensitive check of the energy scale was the $^{52}Cr(n,2n)^{51}Cr$ excitation function measured in the course of this work.

Neutron energy profiles were calculated for each sample using the Monte Carlo simulation code PROFIL[5], and the full width at half maximum (FWHM) and the average energy were determined. Examples of energy profiles are shown in Fig. 1.

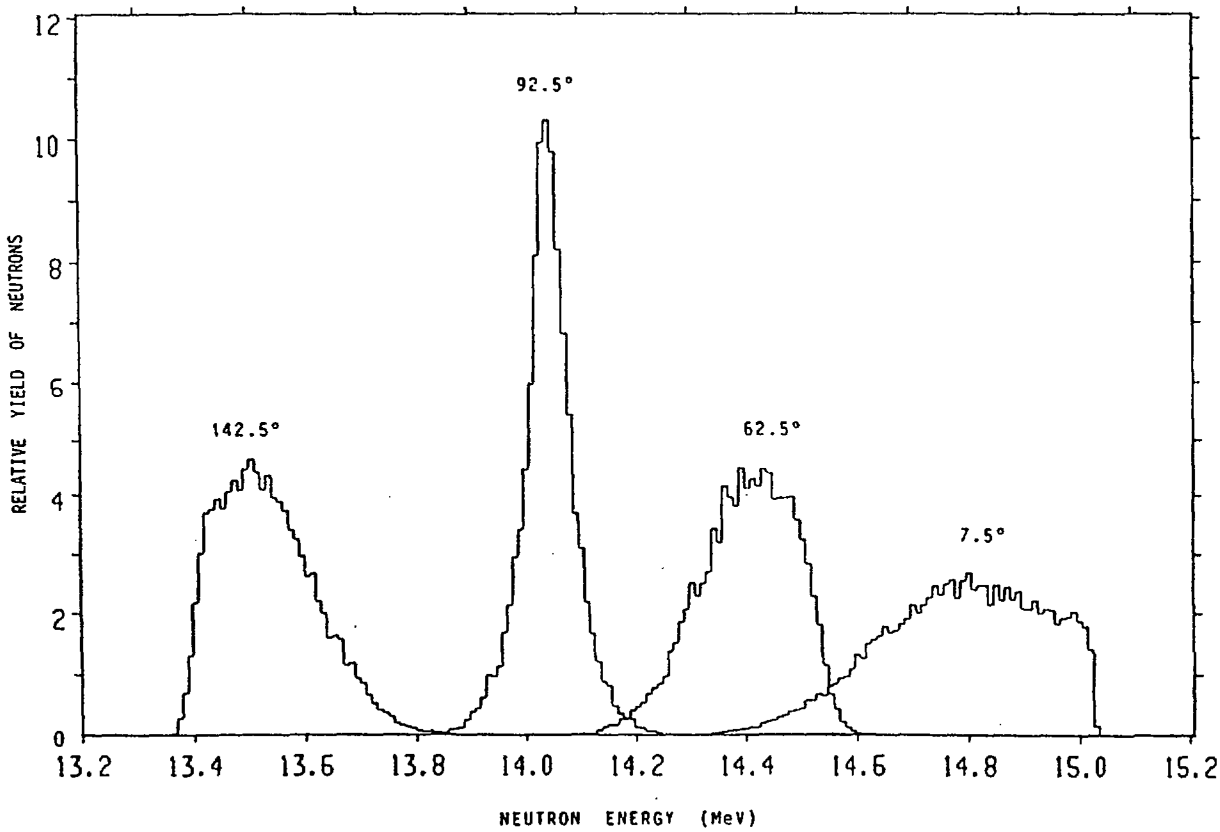

Fig.1. Calculated neutron energy distribution profiles for the different irradiation angles used in this experiment for the chromium samples. All distributions are normalized to equal areas

The activities of the Zn, Zr and Y_2O_3 samples and of the corresponding Nb fluence monitor foils were measured with a Ge(Li)γ-ray detector at the KFI, Debrecen, evaluating the relevant full-energy peak areas and taking into account γ-ray self-attenuation in the samples. The relative efficiency of the Ge(Li)detector has been determined in the

Table 1: Relevant decay data of the product nuclei.

Radio-nuclide	Abundance of the target isotope (%)	Half-life (days)	Ref.	Energies of the principle γ-rays emitted (keV)	Emission probabilities	Ref.
^{51}Cr	83.789±0.012	27.704±0.004	Tuli (1987)	320.08	0.0985±0.0009	Lorenz (1987)
^{65}Zn	27.9 ±0.2	243.9 ±0.1	"	1115.55	0.5065±0.0020	"
^{88}Y	100	106.64±0.08	"	898.04 1836.06 2734.09	0.924 ±0.004 0.9930±0.0005 0.0072±0.0007	"
^{92m}Nb	100	10.15±0.02	"	912.6 934.44 1847.54	0.0178±0.0010 0.9892±0.0010 0.0083±0.0004	Luksch (1980)
^{95}Zr	2.80 ±0.01	64.02±0.04	"	235.69 724.20 756.73	0.0029±0.0005 0.4415±0.0020 0.5450±0.0020	Lorenz (1987)
^{95}Nb		34.97±0.03		765.81	0.9980±0.0002	"

186-2448 KeV energy range by placing a ^{226}Ra source of 19 mm in diameter in different positions to the detector[6]. The absolute efficiency has been determined by ^{203}Hg, ^{137}Cs, ^{60}Co and ^{88}Y standard gamma-ray sources at 60 mm distance from the surface of the Ge(Li) detector. An empirical analytical expression was given for the description of the energy-efficiency curve for three different positions of the sources. The total error of the full-energy-peak efficiency in the 180-1500 keV energy range was found to be 1.0 %.

The relative activities of the Cr samples and their monitor foils as well as those of the Zn and Zr samples were determined with a 15 %-efficiency (relative to a 7.62 cm x 7.62 cm NaI(Tl) crystal) intrinsic Ge γ-ray detector at the IRK, Vienna. For normalization purposes, absolute activity measurements were performed at the IRK on the Cr, Zr and Zn sample with the highest activity, and on some Nb foils, employing a 12.7 cm x 12.7 cm NaI(Tl) well-type detector counting above an energy discrimination level of 22.1 keV[7]. Its efficiency for the radiation of the product nuclei ^{51}Cr, ^{65}Zn, ^{88}Y, ^{92m}Nb and ^{95}Zr-^{95}Nb was determined according to the characteristics of the respective decay schemes, taking into account the self-attenuation and the Compton scattering of the γ-rays in the samples[8]. In the case of ^{92m}Nb the fractional peak area for K-shell X-rays above a discrimination level of 22.1 keV was accounted for[9]. The activities of the Y_2O_3 samples were also measured at the IRK by integral γ-ray counting since higher accuracy and precision of the results could be achieved as compared to the γ-ray measurements in Debrecen using a Ge(Li) detector. The decay characteristics of the product nuclei summarized in Table 1. were taken from the Nuclear Data Sheets and from Tuli[10] and Lorenz[11]. The absolute activity measurements on the mother-daughter pair ^{95}Zr-^{95}Nb required to wait for the decay of ^{89}Zr and were commenced 57 days after the end of the irradiation, approximately at the time of the optimal signal-to-

Table 2: Results of the measurements of (n,2n) cross sections

Reaction	Position of the sample relative to the incident d^+-beam	Average neutron energy (MeV)	Width of the energy distribution (1/2 FWHM) (MeV) 1)	Cross section (mb)	
				IRK	KFI
$^{52}Cr(n,2n)^{51}Cr$	(7.5±0.5)°	14.783±0.013	0.210	400.6±6.8	
	(62.5±0.5)°	14.397±0.011	0.105	339.3±5.2	
	(92.5±0.5)°	14.040±0.010	0.035	270.5±4.8 2)	
	(142.5±0.5)°	13.528±0.010	0.095	172.9±3.6	
$^{66}Zn(n,2n)^{65}Zn$	(17.5±0.5)°	14.754±0.013	0.190	734.5±11.8	738.1±16.8
	(72.5±0.5)°	14.283±0.011	0.080	652.0±11.9	663.4±15.4
	(102.5±0.5)°	13.922±0.010	0.030	590.6±10.3 2)	589.8±16.1
	(152.5±0.5)°	13.466±0.010	0.115	503.9± 9.5	495.5±11.2
$^{89}Y(n,2n)^{88}Y$	(0.0±0.5)°	14.789±0.014	0.210	1009.8±14.3	1015.8±21.8
	(55.0±0.5)°	14.476±0.012	0.120	945.8±14.2	917.9±19.9
	(85.0±0.5)°	14.132±0.010	0.054	872.6±12.0 2)	847.1±25.4
	(135.0±0.5)°	13.586±0.010	0.092	703.6±10.8	686.4±15.1
$^{96}Zr(n,2n)^{95}Zr$ +	(12.5±0.5)°	14.771±0.013	0.185	1506 ±22	1512.2±38.6
^{96}Zr [(n,d)+(n,np)	(67.5±0.5)°	14.341±0.011	0.090	1497 ±26	1480.0±37.7
+(n,pn)] $^{95}Y \rightarrow ^{95}Zr$	(97.5±0.5)°	13.981±0.010	0.030	1489 ±23 2)	1483.3±43.5
+6.207*$^{94}Zr(n,\gamma)^{95}Zr$ 3)	(147.5±0.5)°	13.495±0.010	0.115	1477 ±26	1436.6±39.4

1) FWHM = full width at half maximum

2) Weighted average of the results obtained for the two samples positioned symmetrically to the incident d^+-beam

3) See text.

background ratio. In fact, when measuring the sum of the ^{95}Zr and ^{95}Nb activities produced by 14 MeV neutrons hitting a Zr sample, one measures the sum of the following cross sections:

a) for the $^{96}Zr(n,2n)^{95}Zr$ reaction, which will provide by far the main contribution;

b) for the $^{96}Zr((n,d)+(n,np)+(n,pn))^{95}Y$ reaction, since the radionuclide ^{95}Y decays to ^{95}Zr via β^-emission with a relatively short half-life (≈10.3 min);

c) for the $^{94}Zr(n,\gamma)^{95}Zr$ reaction, weighted by a factor 6.207, which is the ratio of the isotopic abundances of ^{94}Zr to ^{96}Zr in natural Zr.

3. RESULTS, UNCERTAINTIES AND DISCUSSION

The results for the (n,2n) cross sections of the investigated nuclides in the energy range from 13.47 MeV to 14.79 MeV are listed in Table 2, together with the average neutron energies and its uncertainties, and the spread of the energy distributions. As it can be seen in Table 2 cross section data measured in Vienna and Debrecen by two independent methods are in good agreement. The total uncertainty for each cross section value was obtained by adding the uncertainty components in quadrature. Figures 2 through 5 display the results of our work together with those taken from the literature. For the reason of better legibility and demonstration the cross section data obtained for ^{89}Y were split into two parts: the first comprises work performed from 1959 to 1975, the second the more recent results. All data given in the literature were normalised to the latest values of the cross sections for the fluence monitor reactions employed and of the decay data, especially of the intensity of the ^{51}Cr γ-radiation. In general the results agree with those given by a number of other authors, but the uncertainties obtained in this work are considerably smaller in most cases. For $^{66}Zn(n,2n)^{65}Zn$

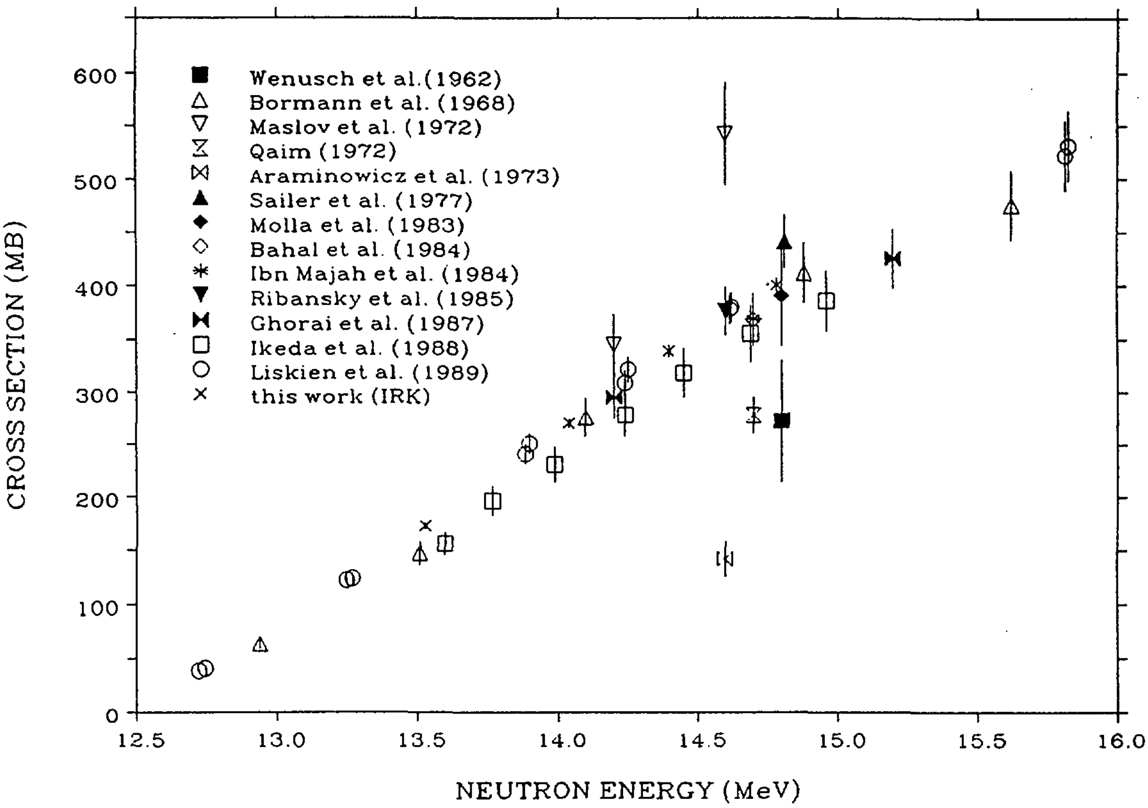

Fig.2. The cross sections for the reaction $^{52}Cr(n,2n)^{51}Cr$ resultant from this work as compared to data from the litereature

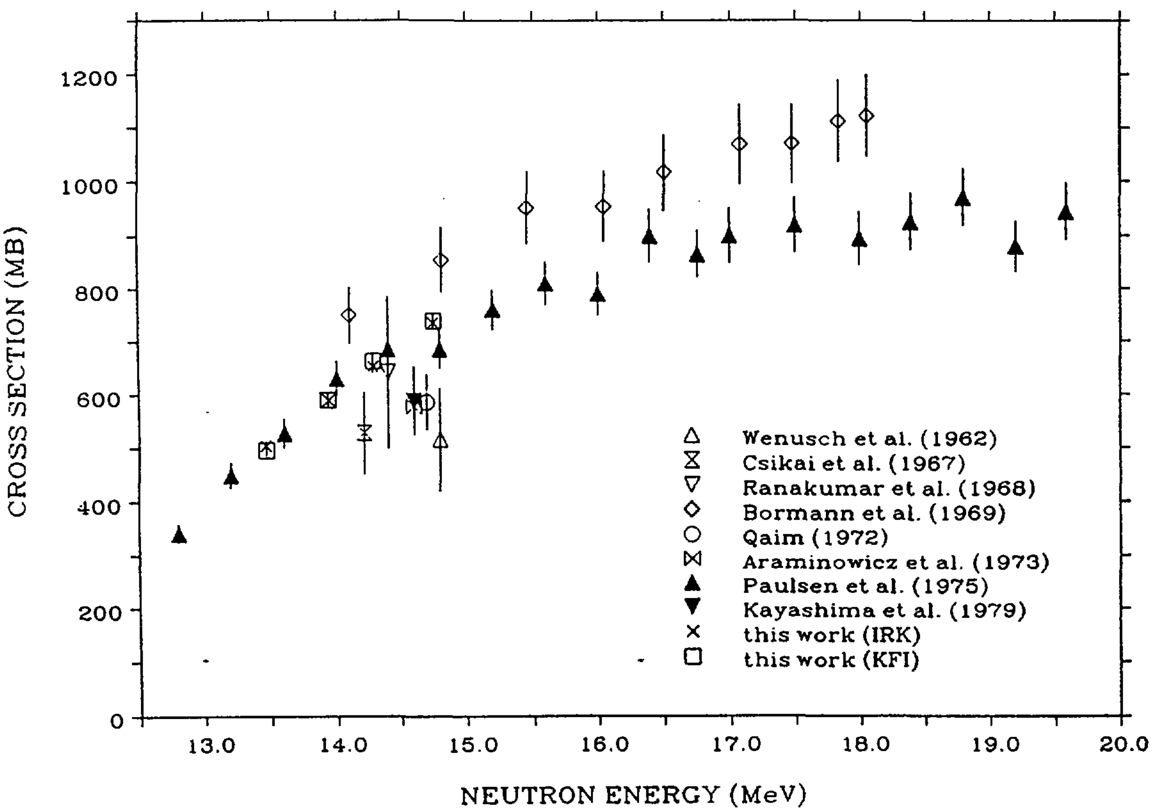

Fig.3. The cross sections for reaction $^{66}Zn(n,2n)^{65}Zn$ resultant from this work as compared to data from the literature

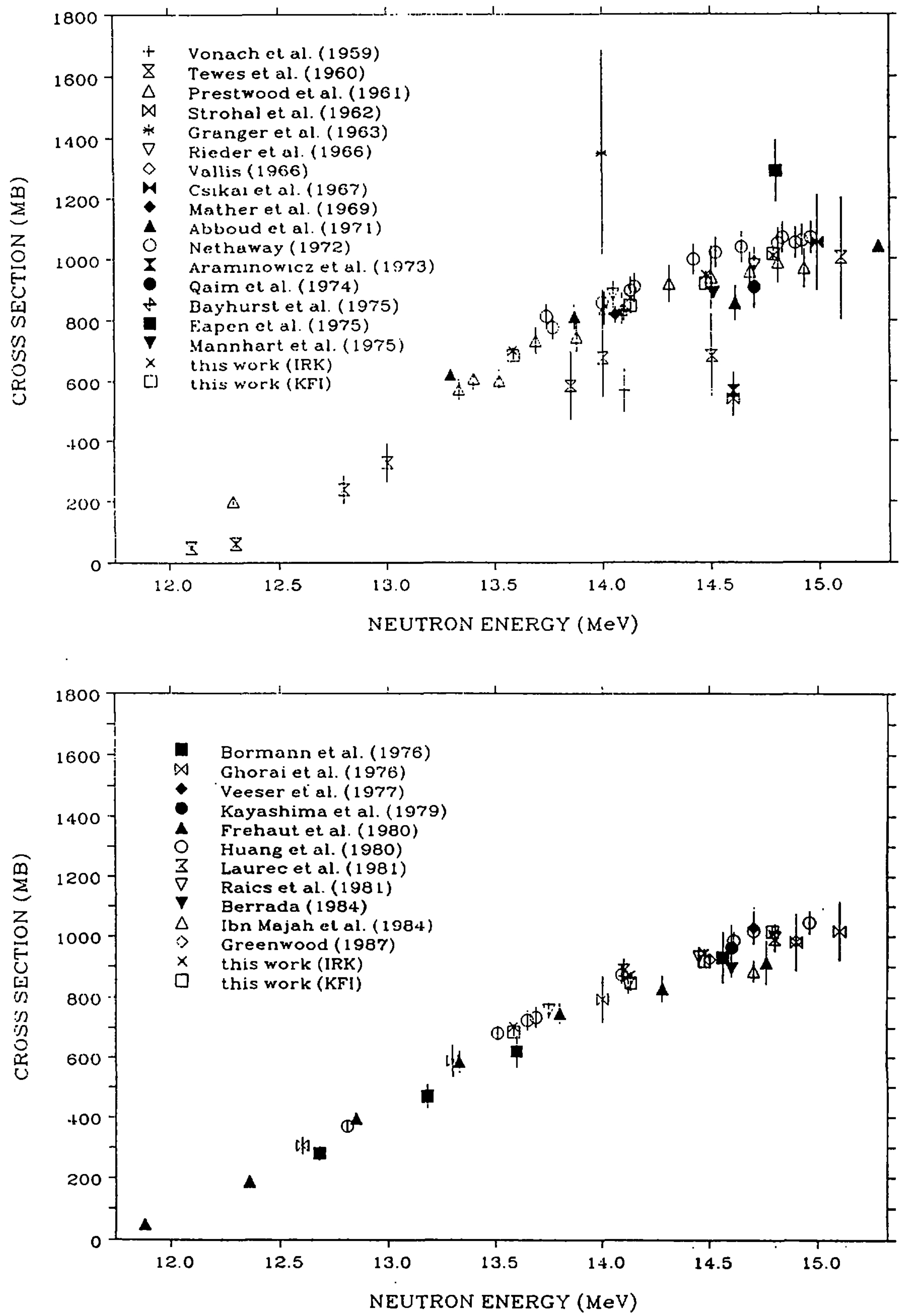

Fig.4. The cross sections for the reaction $^{89}Y(n,2n)^{88}Y$ resultant from this work as compared to data from the literature: published from 1959 to 1975 (upper) and 1976 to 1988 (lower).

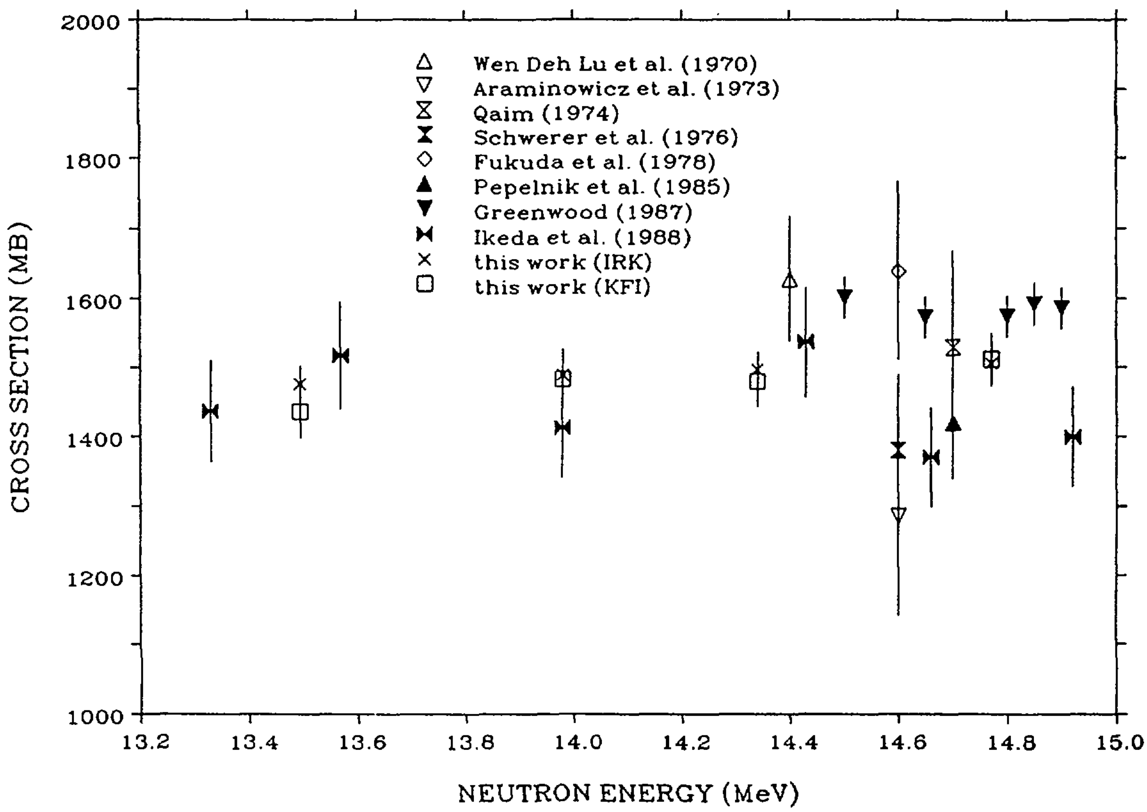

Fig.5. The cross sections for the reaction $^{96}Zr(n,2n)^{95}Zr$ resultant from this work as compared to data from the literature. (Note the suppressed zero!)

our results definitely confirm the measurements of Paulsen[12] and suggests that this work should be used for the whole excitation function rather than the measurements of Bormann and Lammers[13]. For $^{89}Y(n,2n)^{88}Y$ there is now excellent agreement between all recent measurements and a thorough cross section evaluation is now needed more than further measurements. For the $^{96}Zr(n,2n)^{95}Zr$ reaction our cross sections are somewhat lower than the recent results from Greenwood[14], the discrepancy being somewhat larger than the combined uncertainties of both experiments, our results are however in better agreement with the systematic trend of these cross sections with mass number.

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