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Neutron activation cross sections for Cr isotopes at 14.8 MeV neutron energy [+]

Ribanský I.
Institute of Physics, EPRC, Slovak Academy of Sciences, 84228 Bratislava, Czechoslovakia

and

Panteleev Ts. and Stoeva L.
Institute of Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia 1181, Bulgaria

Abstract. Neutron activation cross sections for Cr isotopes were measured using Ge(Li) γ-spectroscopy of the reaction products. The linear least-squares method was used to resolve the interfering reactions. The results are compared with other data measured at 14.6 - 14.8 MeV.

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1. Introduction

Activation technique have been used to measure the cross sections for neutron induced reactions on Cr isotopes with the emphasize to (n,p) and (n,np) [+] processes. Though many such data have been measured in the past it is generally difficult to find out what value is to be preferred in different kind of applications or comparisons with theoretical calculations. The point is that the measured data often exhibit mutual disagreement substantially exceeding the quoted uncertainties. This is probably the reason why the new data are still requested in WRENDA 83/84 (1983). Moreover the chromium is one of the potential component of the fusion reactor construction material and obviously precise and reliable activation data are needed for that purpose. Recently the Coordinate Research Programme was launched by the International Atomic Energy Agency, Vienna to encourage this kind of measurements. We believe that one of the efficient way to improve the existing situation in activation data for Cr is their careful remeasurements using modern experimental procedures, data processing techniques and error handling methods.

The activation cross sections measured in this work will be compared with all other results contained in CINDA (The index to the literature and computer files on Microscopic Neutron Data, published by IAEA, Vienna). However only those data measured between 14.6 and 14.8 MeV incident neutron energy will

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[+] The (n,np) symbol stands for the sum of (n,n'p), (n,pn) and (n,d) contributions.

be considered in order to minimize the influence of the excitation functions behaviour around 14 MeV. These data will be referenced by the year during which they were included in CINDA. The original references are omitted as many of them were not available to present authors. They can be found in CINDA however.

2. Experimental procedure

The details of the experimental technique and data aquisition system are described in our previous papers (Gmuca and Ribanský, 1983a and Ribanský and Gmuca, 1983). Here we report only details pertinent to the present experiment.

The samples used were prepared by pressing Cr_2O_3 powder into plexiglass containers (ø 16 mm). The enriched samples were supplied by TECHNABEXPORT, Moscow. All samples were of spectral purity and at least two targets were prepared from each isotopic mixture. The isotopic abundances are listed in Table 1. The sample thickness varied from 200 to 400 mg/cm^2.

The required neutrons were produced via the $T(d,n)^4He$ reaction using small electrostatic accelerator (120 kV) and thick water-cooled Ti-T target. The time variation of the neutron flux was monitored by two neutron detectors and was taken into account in the cross section calculations. These detectors were calibrated several times before each run using $^{56}Fe(n,p)$ reaction assuming σ_{np}=105.4 ± 1.1 mb, Ryves et al. (1978a). To check the experimental procedure the Al samples were also irradiated and the cross section for $^{27}Al(n,p)$ reaction was determined. Its value-relative to $\sigma_{np}(^{56}Fe)$ - turned out to be 71.8 ± 2.3 mb. It is not in as good agreement with 66 ± 2 mb reported by Ryves et

al. (1978b) as one would expect. It is however in perfect agreement with the ENDF/B-5 (1979) evaluation (71.6 mb).

When possible the irradiation of Cr samples were repeated in order to lower the statistical uncertainties. The activities of the reaction products were measured with Ge(Li) detector (2.5 keV at 1332 keV) and at least two γ-ray spectra were taken after each irradiation and recorded on a disc for off-line processing. The full energy peak areas were evaluated using the code GWENN (Gmuca and Ribanský, 1983b). They were corrected for the selfabsorbtion and the coincidence summing effects using the code KORSUM (Debertin and Schötzig, 1979). To determine the contributions of (n,p) and (n,np) processes on neighbouring isotopes leading to the same reaction product, measurements were made on samples with several different isotopic abundances. The corresponding cross sections were evaluated using a linear least - square method.

3. Uncertainties

A great care was devoted to the correct treatment of both correlated (systematic) and uncorrelated (statistical) errors connected with the present experiment. The covariance matrix method (Mannhart, 1981 and Smith, 1981) was employed for the estimation of our total data uncertainties. The sources of uncertainties which were taken into account are listed in Table 2. All uncertainties quoted in our papar represent one standard deviation.

4. Results and discussion

The results of our measurements are presented in Table 3. Those data which are correlated with each other are grouped and the corresponding covariance matrix is given in the last column. The number of independent irradiations is shown in the 4th column.

The decay data of the reaction products are presented in Table 4. The coincidence summing corrections (factors by which the measured full energy peak areas were multiplied) are given in the last column. Note that for $^{54}Cr(n,p)$ reaction these corrections amount to 20 %. The numbers in brackets (column 2 and 4) represent the uncertainties of the half-lives and γ-transition intensities in the same format as used by Lederer and Shirley (1978).

Our results are compared with the previous measurements performed at 14.6 - 14.8 MeV in Tables 5 and 6. In general the detailed comparison with other data is difficult because many important experimental details are often not presented by the authors, different reference reactions were frequently used and different experimental technique (e.g. β counting) was sometimes employed. Therefore only very general observations based on Tables 5 and 6 will be presented. The data are ordered according to the year they were included into the CINDA.

Table 5. Our cross section for $^{52}Cr(n,2n)$ reaction is in very good agreement with the majority of other results. This statement includes also those data which do not overlap with our value within the quoted uncertainties by less than ± 2 mb.

The reason is that the measured excitation function (Chatterjee et al., 1969 and Borman, 1965) exhibits gradient ~ 2 mb/0.1 MeV between 14 and 15 MeV. The remaining three values are compatible with our results only at 3σ confidence level.

For $^{52}Cr(n,2n)$ reaction the gradient of the excitation function is ~ 18 mb/0.1 MeV. Having this in mind one can see that our result is in very good agreement with just the half of other data. The result of Araminovicz and Dresler (1972) is clearly too low. The value reported by Maslov et al. (1972) is very probably too high and this is probably true also for Sailer et al. (1977) value. The last observation is based on the non-activation measurement of $^{Nat}Cr(n,2n)$ cross section (406 $\pm$ 32 mb) measured by Frehaut et al. (1980) at 14.76 MeV. The contributions of (n,2n) reactions on ^{54}Cr and ^{53}Cr isotopes to the Frehaut et al. (1980) value can be estimated from the semiempirical calculations of Pearlstein (1973). They represent 23 mb and 87 mb respectively. The contribution of $^{50}Cr(n,2n)$ reaction is only ~ 1 mb and we are left with 353 $\pm$ 28 mb for the cross section of $^{52}Cr(n,2n)$ reaction. This value is in agreement with our result and support our above mentioned assertion.

Table 6. Our cross section for $^{52}Cr(n,p)$ reaction is in agreement with only 4 out of 10 other measurements presented in Table 6. Disturbing fact is that the rest of the data are substantially larger than our result. The contribution of $^{53}Cr(n,np)$ reaction (admitting it was not taken into account) can not explain the observed discrepancy. For natural samples

assuming $\sigma_{n,np}(^{53}Cr) \approx 7$ mb, this contribution represents ~ 1 % because the product $\eta(^{53}Cr)\,\sigma_{n,np}(^{53}Cr)$ - η is the isotopic abundance - is $\sim \frac{1}{100}\,\eta(^{52}Cr)\,\sigma_{n,p}(^{52}Cr)$. For samples enriched in ^{52}Cr the situation is still more favourable. The incident neutron energy spread is also irrelevant because the excitation function of $^{52}Cr(n,p)$ reaction is practically constant around 14 MeV (Clator, 1969 and Kern et al., 1959). It appears that our cross section is probably too low though no obvious reasons can be identified. The measured proton spectra of ^{52}Cr (n,xp) reaction (Grimes et al., 1979) can also be used to deduce the (n,p) activation cross section. Assuming that the second particle (in this case the neutron) is certainly emitted from ^{52}V nucleus once its excitation energy reaches the neutron binding energy the (n,p) activation cross section can be approximated by the integral of the experimental proton spectrum from pn-threshold to the maximum proton energy. From Grimes et al. (1979) data we obtained $\sim 80 \pm 15$ mb a value which is in agreement with our measurement.

For other two (n,p) reactions the situation is much better. Our $\sigma_{np}(^{53}Cr)$ is in very good agreement with other results. Only the Qaim and Molla (1977) value is noticable higher than ours. For $^{54}Cr(n,p)$ reaction no comment is needed as all results are in perfect mutual agreement.

The (n,np) data are characterized by a large discrepances between our measurements and those of Qaim and Molla (1977) which are substantially higher. While for $^{53}Cr(n,np)$ reaction their value can very probably be in error (other two results

are practically identical with our result) new measurements are needed for $^{54}Cr(n,np)$ reaction in order to resolve the observed discrepancy.

The present value for $^{54}Cr(n,\alpha)$ cross section is in very good agreement with Valkonen (1976) and Husain and Kuroda (1967) measurements. We differ slightly with Sailor et al. (1977) and significantly with Qaim (1974).

References

1 Araminowicz J. and Dresler J. (1972) CINDA 76/77

2 Borman M. (1965) CINDA 76/77

3 Borman M. (1968) CINDA 76/77

4 Clator I.G. (1969) CINDA 76/77

5 Dobertin K. and Schötzig U. (1979) Nucl. Instr. Meth. 158, 471

6 Dresler J., Araminowicz J. and Garuska U. (1972) CINDA 76/77

7 ENDF/B-5 (1979) Dosimetry file

8 Frehaut J., Bertin A., Bois R. and Jary J. (1980) CINDA 83

9 Gmuca Š. and Ribanský I. (1983a) Acta Phys. Slov. 33, 9

10 Gmuca Š. and Ribanský I. (1983b) Jaderná Energie 29, 56

11 Grimes S.M., Haight R.C., Alvar K.R., Barshall H.H. and Borchers R.R. (1979) Phys. Rev. C19, 2127

12 Husain L. and Kuroda P.K. (1967) CINDA 76/77

13 Chatterjee A., Nath A. and Ghose M. (1969) CINDA 76/77

14 Chittendon D.M. and Gardner D.G. (1961) CINDA 76/77

15 IAEA (1983) Nuclear Data Standards for Nuclear Measurements, IAEA Technical Reports Series No. 227, Vienna

16 Kern B.D., Thompson W.E. and Ferguson J.M. (1959) CINDA 76/77

17 Khurana C.S. and Hans H.S. (1961) CINDA 76/77

18 Lederer C.M. and Shirley V.S. (1978) Tables of Isotopes, 7th edn.

19 Mannhart W. (1981) A Small Guide to Generating Covariances of Experimental Data, PTB-FMRB-84, Braunschweig, June 1981

20 Maslov G.N., Nasyrov F. and Pashkin N.F. (1972) CINDA 76/77

21 Mitra B. and Ghose A.M. (1965) CINDA 76/77

22 Mola N.I., Mizanul I.M., Mizanur R.M. and Khatun S. (1983) CINDA 83

23 Mukherjee S.K., Ganguly A.K. and Majumder N.K. (1961) CINDA 76/77

24 Pearlstein S. (1973) J. Nucl. Energy 27, 81

25 Prasad R. and Sarkar D.C. (1969) CINDA 76/77

26 Qaim S.M. (1972) CINDA 76/77

27 Qaim S.M. (1974) CINDA 76/77

28 Qaim S.M. and Molla N.I. (1977) CINDA 76/77

29 Reus U., Westmeier W. and Warnecke I. (1979) Gamma-Ray Catalog, GSI Report 79-2, Darmstadt

30 Ribanský I. and Gmuca Š. (1983) J. Phys. G: Nucl. Phys. 9, 1537

31 Ryves T.B., Kolkowski P. and Zieba K.J. (1978a) Metrologia 14, 127

32 Ryves T.B., Kolkowski P. and Zieba K.J. (1978b) J. Phys. G: Nucl. Phys. 4, 1703

33 Smith D.L. (1981) Covariance Matrices and Applications to the Field of Nuclear Data, ANL/NDM-62, Argonne, November 1981

34 Sigg R.A. (1976) CINDA 76/77

35 Valkonen M. (1976) CINDA 76/77

36 Webber L.D. and Duggan J.L. (1968) CINDA 76/77

37 WRENDA 83/84 (1983) World request list for nuclear data measurements, Report IAEA INCD(SEC) - 88/URSF

Table 1. Isotopic abundances (%) of Cr samples

Sample	Isotope 50	52	53	54
Natural Cr	4.35	83.79	9.50	2.36
^{50}Cr	90.5	8.5	0.8	0.2
^{52}Cr	0.01	99.8	0.19	0.01
^{53}Cr	0.03	2.19	97.7	0.08
^{54}Cr	0.13	4.06	2.01	93.8

Table 2. The principal sources of uncertainties

Source	Resulting uncertainty (%)
Counting statistics	0.5 - 6
Sample mass	0.1
Isotopic abundances	0.2
γ-ray intensities	0.0 - 7.8
Detector efficiency (FEP)	1.5
Reaction product half-life	0.3 - 3.0
Irradiation and counting geometry	0.2
Coincidence summing corrections	0.7
γ-ray selfabsorbtion	0.5
Monitor calibration (including $^{56}Fe(n,p)$ reference reaction)	2.8

Table 3. Neutron activation cross sections for Cr isotopes at 14.8 MeV

Reaction	σ (mb)	Uncertainty (mb)	No. of irradiations	Correlation matrix	
$^{50}Cr(n,2n)^{49}Cr$	20.4	1.1	2	-	
$^{52}Cr(n,2n)^{51}Cr$	361	22	1	-	
$^{52}Cr(n,p)^{52}V$	70.7	3.1	33	100	
$^{53}Cr(n,np)^{52}V$	7.3	0.6		-14	100
$^{53}Cr(n,p)^{53}V$	35.60	1.50	27	100	
$^{54}Cr(n,np)^{53}V$	1.53	0.14		-25	100
$^{54}Cr(n,p)^{54}V$	14.70	0.61	27	-	
$^{54}Cr(n,\alpha)^{51}Ti$	10.63	0.46	7	-	

Table 4. Decay data of reaction products

Reaction product	$T_{1/2}$	E_γ (keV)	I_γ (%)	Coincidence summing corr.	Ref.
^{49}Cr	42.09(15)m	90.6	54.2(9)	1.113	a)
		152.9	30.9(5)	1.108	
^{51}Cr	27.703(4)d	320.1	9.85(9)	1.0	b)
^{52}V	3.760(8)m	1434.1	100.0	1.007	c)
^{53}V	1.61(5) m	1006.0	90.0(2.0)	1.001	c)
^{54}V	49.8(1.0)s[d]	834.8	100.0	1.215	c)
		986.0	81.8(6.4)	1.224	
^{51}Ti	5.76(3) m	319.7	93.4(9)	1.001	c)

a) ENDF/B-5 (1979)

b) IAEA (1983)

c) Lederer and Shirley (1978)

d) Rous et al. (1979)

Table 5. Comparison of our (n,2n) cross sections with other measurements at 14.6 - 14.8 MeV

σ (mb)	Reference	σ (mb)	Reference
$^{50}Cr(n,2n)^{49}Cr$		$^{52}Cr(n,2n)^{51}Cr$	
20.4±1.1	This work	361±22	This work
21.9±0.5	a)	377±45	k)
24 ±5	b)	439±12	a)
26.9±2.0	c)	304±20	d)
26 ±3	d)	143±17	e)
31.4±2.5	e)	543±50	l)
25.0±2.5	f), EF	412±29	m), EF
25.0±2.5	g), EF		
32.0±3.2	h)		
27.0±6.7	i)		
18.8±1.9	j)		

EF = Deduced from the measured excitation function

a) Sailer et al. (1977)
b) Valkonen (1976)
c) Sigg (1976)
d) Qaim (1972)
e) Araminowicz and Dresler (1972)
f) Chatterjee et al. (1969)
g) Borman (1965)
h) Mukherjee et al. (1961)
i) Khurana and Hans (1961)
j) Chittenden (1961)
k) Molla et al. (1983)
l) Maslov et al. (1972)
m) Borman (1968)

Table 6. Comparison of our (n,p), (n,np) and (n,α) cross sections with other measurements at 14.6 - 14.8 MeV

σ (mb)	Reference	σ (mb)	Reference	σ (mb)	Reference
$^{52}Cr(n,p)^{52}$		$^{53}Cr(n,p)^{53}V$		$^{54}Cr(n,p)^{54}V$	
70.7± 3.1	This work	35.6±1.1	This work	14.70±0.61	This work
80 ± 6	n)	48 ±7	n)	18 ±3	n)
94 ±10	b)	40 ±7	b)	15 ±4	b)
96.1± 3.0	o)	36 ±6	p)	13.5 ±1.5	s)
73 ± 3	p)	44 ±5	s)		
110 ±24	r), EF	37.3±3.7	j)		
115 ±15	s)				
82.8±5.8	t)				
105.0±10.5	h)				
82.7± 9.0	j)				
113 ±24	u), EF				
$^{53}Cr(n,np)^{52}V$		$^{54}Cr(n,np)^{53}V$		$^{54}Cr(n,\alpha)^{51}V$	
7.3±0.6	This work	1.53±0.14	This work	10.63±0.46	This work
12 ±3	n)	3.0 ±0.8	n)	13.4 ±1.2	a)
7.3±0.4	v)			7 ±4	b)
7.1±1.5	s)			15.0 ±1.6	x)
				12.5 ±1.3	s)

EF = Deduced from the measured excitation function

n) Qaim and Molla (1977)
o) Dresler et al. (1972)
p) Prasad and Sarkar (1969)
r) Clator (1969)
s) Husain and Kuroda (1967)
t) Mitra and Ghose (1965)
u) Kern et al. (1959)
v) Webber and Duggan (1968)
x) Qaim (1974)

Coincident in-beam measurements on ^{52}Cr bombarded with 14.6 MeV neutrons

P. Obložinský and S. Hlaváč
Institute of Physics, Electro-Physical Research Centre of the Slovak Academy of Sciences, 842 28 Bratislava, Czechoslovakia

Reported are experimental data for ^{52}Cr sample obtained by coincident γ-γ and n-γ in-beam techniques. The data include average γ multiplicities related to 8 discrete transitions, average γ multiplicities following emission of 1.3 - 11.6 MeV neutrons, average energies of these γ rays and exclusive neutron spectrum containing solely inelastic component.

Work performed under IAEA Coordinated Research Programme, Research Agreement No 3436/CF

1. Introduction

Chromium is among basic elements of constructional materials and its interactions with neutrons are of interest for both fusion and fission reactor technology.

Probably most important chromium isotope is ^{52}Cr with 83.8% natural abbundance. It has closed $1f_{7/2}$ neutron shell, N=28, and the Q-value for (n,2n) reaction is 12.04 MeV. Inelastically scattered 14.6 MeV neutrons can effectively populate unbound states of target nucleus and can be exploited in studies of their decay modes, specifically by γ emission, via $(n,n'\gamma)$ reactions. In order to probe such states more directly we used coincident in-beam techniques.

In a natural target, however, one has 9.5% of ^{53}Cr with loosely bound neutron above the closed shell, B_n= 7.94 MeV. This means that γ rays from $^{53}Cr(n,2n\gamma)$, which cannot be separated from $^{52}Cr(n,n'\gamma)$ γ rays even if high resolution spectroscopy is used, should be rather strong. For this reason we irradiated highly enriched ^{52}Cr.

In this report we present complete set of our experimental data for ^{52}Cr sample obtained by γ-γ and n-γ coincident in-beam techniques. Except of average γ ray multiplicities we for the first time report exclusive neutron spectrum which unlike total spectrum contains pure inelastic component only.

2. Experimental procedures

Measurements were carried out with the multidetector setup developed for combined in-beam neutron and γ spectroscopy experiments using the associated particle technique[1]. Geometrical arrangement of the present run is shown in fig.1. All spectrometers are in the reaction plane. Since the NaI(Tl) is sensitive to neutrons it was located under 70^{o} towards the incident beam in order to suppress events due to elastically scattered neutrons. Further suppression was achieved by the time-of-flight discrimination.

Enriched sample (99.8 ± 0.1%, weight 119.8g) of powder form was filled in a thin polyethylene bag (1.5g) of cylindrical

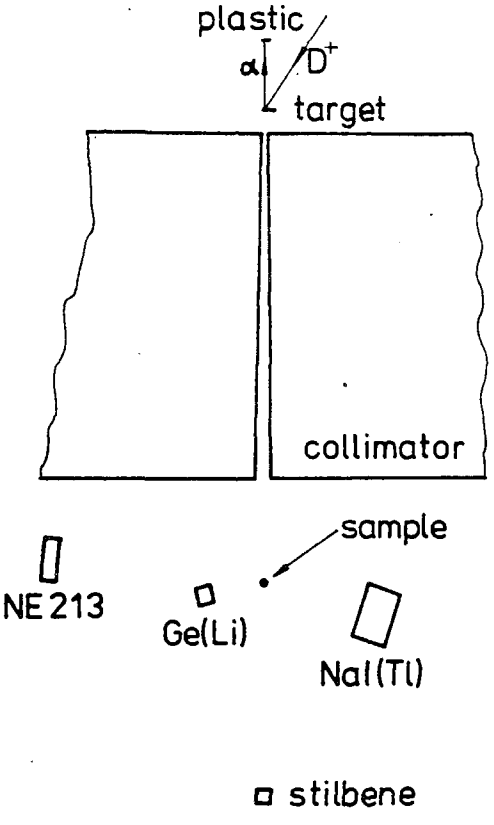

Fig.1. Experimental arrangement. Size of spectrometers, their orientation towards incident beam and sample-to-detector front face distances were, respectively, Ø16cm x 10cm, 70°, 30cm for the NaI(Tl), Ø12cm x 4cm, 100°, 60cm for NE 213 and 70cm^3,70°, 15cm for Ge(Li). The NaI(Tl) was shielded by additional lead collimator with apperture Ø11cm.

shape (Ø3.5cm x 6.5cm). Its average thickness was 0.0609 at/b.

We measured essentially 2 coincident spectra. First, spectrum of discrete γ rays observed by the Ge(Li) spectrometer in coincidence with another γ ray detected by the NaI(Tl) detector. Second, two-parametric spectrum comprising of neutron tof events as observed by the NE 213 in coincidence with energy of γ ray events from the NaI(Tl). In addition, we recorded singles spectra from all the spectrometers. Data were collected by means of standard analyzers and low rate CAMAC oriented two-parametric system based on the TPA-70 minicomputer.

Spectra were processed and analyzed by standard procedures[1]. Particularly, the Ge(Li) spectra were fitted by the non-linear least squares method embodied in the program GWENN (ref.[2]). Average γ ray multiplicities were obtained by comparing coincident to singles Ge(Li) yields and by comparing coincident to singles neutron tof spectra. Absolute scale was retained by using measured total efficiency of the NaI(Tl).

Energy-angle differential cross sections for exclusive neutron spectrum were obtained under the assumption that angular correlation between emitted neutron and discrete γ ray transition (mostly 1434.1keV, $2^+ \rightarrow 0^+$ gs) is weak. We used relation

$$\frac{d^2\sigma}{dE_n\, d\omega_n} = 4\pi \frac{d^3\sigma}{dE_n\, d\omega_n d\omega_\gamma} = \frac{N_{n\gamma}}{4\pi \phi A \Omega_n \Omega_\gamma^{phot}}$$

where N_n is the observed intensity per 1 MeV in the neutron spectrum as measured in coincidence with discrete γ transitions detected by the NaI(Tl), ϕ stands for the neutron fluence, A is the number of target nuclei, Ω_n is the absolute NE 213 efficiency including the solid angle in sr and Ω_γ^{phot} is the absolute photopeak efficiency of the NaI(Tl). Neutron fluence was determined from the count of the associated α particle detector corrected for the solid angle and for the figure of merit observed by the stilbene monitor.

Corrections for sample-to-detector geometry and selfabsorption were calculated by the Monte Carlo procedure. No correction for multiple scattering was applied.

3. Results

Average γ ray multiplicities of cascades passing through specific low lying transition were observed in 8 instances in $(n,n'\gamma)$ channel. The results are summarized in tab.1. Included in uncertainties are statistical error in determining peak area of coincident as well as singles Ge(Li) spectra, 5% uncertainty of the NaI(Tl) efficiency and 3% estimated uncertainty of applied corrections.

Tab.1. Observed average γ ray multiplicities including specific discrete transition in ^{52}Cr. Given in brackets are uncertainties.

Transition(keV)	Multiplicity
647.4, $4^+ \rightarrow 4^+$	5.6 (.6)
704.6,$(3^+) \rightarrow 4^+$	6.8 (.7)
744.2, $6^+ \rightarrow 4^+$	5.8 (.6)
848.2, $5^+ \rightarrow 4^+$	4.8(1.5)
935.5, $4^+ \rightarrow 2^+$	3.7 (.3)
1246.2, $5^+ \rightarrow 4^+$	4.4(1.4)
1333.6, $4^+ \rightarrow 2^+$	3.7 (.4)
1434.1, $2^+ \rightarrow 0^+$	3.7 (.2)

Average γ ray multiplicities of cascades following emission of a neutron with specified energy are summarized in tab. 2 and fig.2. Multiplicities were extracted from ratios of given bins of coincident and singles neutron tof spectra. Background was subtracted from the raw spectra by the procedure devised by H. Klein et al.[3]. The uncertainties qouted for multiplicities are basically due to statistical error in coincident neutron spectrum. Uncertainties in neutron energies run from about 20% at 1.5 MeV up to about 35% at 10 MeV. In the energy region where (n,2n) channel is open long (n,n'γ) cascades are mixed with much shorter ones from (n,2nγ). Most of the secondary neutrons observed in the present experiment, however, refer to (n,2n) process leading directly to the ground state of ^{51}Cr.

Tab.2. Average γ ray multiplicities as a function of observed energy of emitted neutrons. Given in brackets are uncertainties.

E_n (MeV)	Multiplicity
1.3 - 1.5	0.7 (2.0)
1.6 - 1.8	2.26 (.47)
1.9 - 2.2	2.82 (.48)
2.3 - 2.6	4.48 (.48)
2.7 - 3.0	4.59 (.47)
3.1 - 3.6	4.05 (.43)
3.7 - 4.3	4.15 (.45)
4.4 - 5.3	3.70 (.45)
5.4 - 6.7	3.43 (.46)
6.8 - 8.6	3.08 (.45)
8.7 -11.6	2.32 (.53)

Two-parametric spectrum n tof x γ energy contains information about γ ray spectrum as a function of energy of emitted

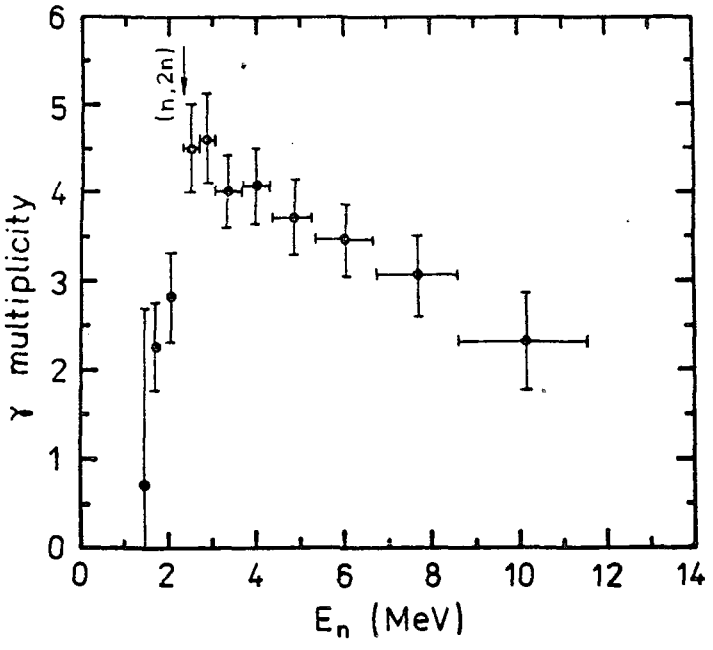

Fig.2. Average γ ray multiplicity as a function of observed energy of emitted neutron in the laboratory frame. Shown by arrow is the (n,2n) threshold.

neutron. Due to low statistics these partial γ ray spectra provide limited, though still useful, insight as concerns their shape. First moment of the spectrum has the meaning of the average energy of cascading γ rays. It can be extracted from the spectrum by means of the calibration curve for centroids without unfolding of the raw spectrum. This procedure is meaningful in our case thanks to fairly constant efficiency of our NaI(Tl) spectrometer in a broad energy region. The results are given in tab.3.

The two-parametric spectrum was further used to extract neutron spectrum in coincidence with 1434 keV γ rays. The latters refer to strong $2^+ \rightarrow 0^+$ gs transition in ^{52}Cr which cumulates almost all (n,n'γ) cross section. This feature, supported by our singles Ge(Li) data, is demonstrated in fig.3 displaying total coincident γ ray spectrum observed by the NaI(Tl) spectrometer. Pertinent neutrons, therefore, represent praccally complete (n,n') component with no admixture from (n,2n) channel. In our case the 1434 keV peak should contain contribution from nerby 1333.6 keV and perhaps also from 1246.2 keV

γ lines. This admixture was taken into account using our singles Ge(Li) data and thus double counting of coincident neutrons was eliminated. The resulting exclusive neutron spectrum is summarized in tab.4 and fig.4.

Tab.3. Average γ ray energy as a function of observed energy of emitted neutrons. Given in brackets are uncertainties.

E_n (MeV)	$\overline{E_\gamma}$ (MeV)
1.0 - 1.2	1.71 (.25)
1.2 - 1.6	2.50 (.36)
1.6 - 1.9	2.33 (.22)
1.9 - 2.2	2.30 (.16)
2.2 - 2.6	2.39 (.12)
2.6 - 3.1	2.43 (.11)
3.1 - 3.5	2.40 (.15)
3.5 - 3.9	2.60 (.16)
3.9 - 4 4	2.50 (.17)
4.4 - 5.0	2.29 (.17)
5.0 - 5.7	2.36 (.19)
5.7 - 6.6	2.45 (.22)
6.6 - 7.7	2.53 (.25)
7.7 - 9.0	2.02 (.22)
9.0 -10.8	1.72 (.22)
10.8 -13.2	1.72 (.29)

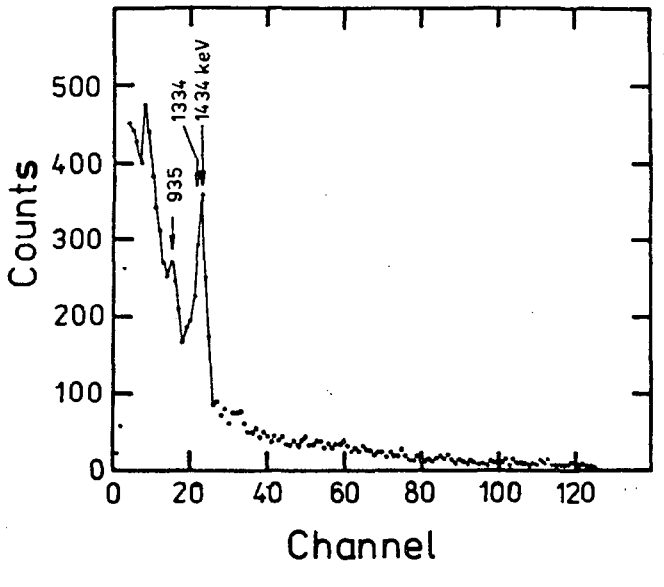

Fig.3. γ ray spectrum observed by the NaI(Tl) in coincidence with $\sim$ 0.8 - 13 MeV neutrons. Indicated lines refer to (n,n'γ) channel.

Tab.4. Exclusive neutron spectrum referring to (n,n' 1434 keV) process (laboratory frame, 100°). Given in brackets are uncertainties.

E_n (MeV)	$\frac{d^2\sigma}{dE_n d\omega_n}$ $\left(\frac{mb}{MeV\ sr}\right)$
1.5 - 1.9	5 (6)
1.9 - 2.2	9 (5)
2.2 - 2.4	14 (7)
2.4 - 2.6	28 (6)
2.6 - 2.8	25 (6)
2.8 - 3.1	17 (5)
3.1 - 3.5	13 (5)
3.5 - 3.9	10 (5)
3.9 - 4.4	11 (4)
4.4 - 5.0	8.4(2.8)
5.0 - 5.7	4.8(2.0)
5.7 - 6.6	1.6(1.1)
6.6 - 7.7	2.5(1.2)
7.7 - 9.0	1.5(1.0)
9.0 -10.8	.9(.6)
10.8 -13.2	.8(.5)

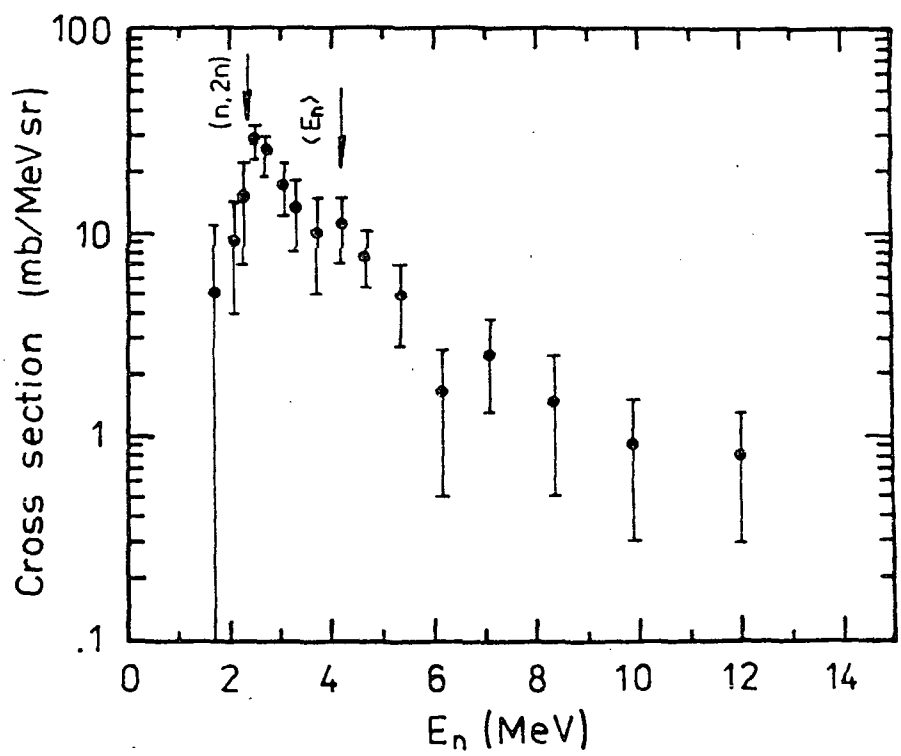

Fig.4. Exclusive neutron spectrum (see tab.4). Average neutron energy indicated by arrow is 4.19(.17) MeV.

4. Discussion

To our best knowledge all data included in this report have been measured for the first time. Still, however, certain comparison with earlier data is possible in two instances.

J.K. Dickens et al.[4] have reported average γ ray energy observed on Cr(n,xγ) reactions as a function of energy of incident neutrons. Their value, $\bar{E}_\gamma \approx 2.3 - 2.4$ MeV taken from figure at 14.6 MeV, seems to be in very good accord with our results. One of course should keep in mind that we report practically ^{52}Cr(n,n'γ) component only.

Our exclusive neutron spectrum at spectral energies above about 2.5 MeV can be compared with full neutron spectra as measured by Hermsdorf et al.[5] at 14.6 MeV, 90° and by Takahashi et al.[6] at about 14.0 MeV, 103° on natural Cr. Accord with these data seems to be fairly good, too.

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References

1) S.Hlaváč and P.Obložinský, Nucl. Instr. Meth. 206(1983)127
2) Š.Gmuca and I.Ribanský, Jad. energie 29(1983)56
3) H.Klein et al., in Proc. of the IAEA Consultants' Meeting held in Smolenice, Czechoslovakia, 1983, see Report INDC(NDS)-146, Vienna 1983, p.191
4) J.K. Dickens et al., Nucl. Sci. Eng. 62(1977)515
5) D.Hermsdorf et al., Report ZfK-277(U), TU Dresden 1975
6) A.Takahashi et al., OKTAVIAN Report A-83-01, University Osaka 1983