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GAMMA RAY PRODUCTION CROSS SECTIONS FOR ^{52}Cr(n,xγ) AT 14.6 MEV

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Total γ ray production spectrum for ^{52}Cr bombarded with 14.6 MeV neutrons was measured. Reported are cross sections in the spectral energy range 0.2 MeV $\leq E_\gamma \leq$ 22.3 MeV. Energy-angle integrated γ ray production cross section is 3540 $\pm$ 230 mb and the average energy per γ ray emitted is 2.49 $\pm$ 0.15 MeV. High energy spectral component referring to (n,γ) process is consistent with predictions of the preequilibrium exciton model including angular momentum coupling.

In addition, previously reported discrete γ ray production cross sections in $^{52}Cr(n,x\gamma)$ at 14.6 MeV were reanalyzed. The new cross sections for the dominant 1434.1 keV transition in $^{52}Cr(n,n'\gamma)$ is 783 $\pm$ 30 mb. This value is consistent with the above total γ production as well as with previously reported coincident data.

1. Introduction

Nuclear reaction data at 14 MeV neutron incident energy are often used as a probe to test nuclear reaction codes that become of key importance in data evaluation procedures. Importance of γ production for the evaluated nuclear data libraries is growingly recognized and one would wish to have a complete set of γ production data for a number of elements/isotopes at 14 MeV. Ideally, such a set for a given isotope should comprise of singles γ ray production cross sections as well as coincident data. The formers include discrete γ ray production cross sections, total γ production spectrum as well as their angular distributions. The latters are due to γ-γ and n-γ coincident techniques and include average γ ray multiplicities, exclusive γ and/or exclusive neutron spectra.

$^{52}Cr(n,x\gamma)$ at 14.6 MeV as studied by us provides an example of an effort to achieve the above complexity in measuring γ

production data. In two previous works we reported coincident data[1] and discrete γ production cross sections[2]. In the present report we deal with total γ production spectrum preliminary results of which were presented at the recent Kiev neutron conference[3]. In addition, we reanalyse our discrete γ production cross sections since inconsistencies were found that implied a systematical bias in these cross sections. The origin of the bias has indeed been identified and the whole set of γ production data now seems to be fairly consistent.

2. Experimental procedure

Measurements were performed using the multidetector system described in detail elsewhere[4]. A part of the system used in the present experiment is shown in fig.1. Neutrons of energy 14.6 MeV are collimated electronically by the associated α particle detector, they pass through the 155 cm long mechanical collimator and reach the sample at 199 cm distance from the TiT target.

Enriched sample (99.8±0.1%, weight 119.8 g) of powder form borrowed from Techsnabexport, Moscow was filled in a thin polyethylene bag (weight 1.5g) of cylindrical shape (Ø 3.5cm x 6.5cm). Its average thickness was 0.0609 at/b.

Gamma rays were observed by a Ø 16cm x 10cm NaI(Tl) spectrometer. The NaI(Tl) was surrounded by a lead shield to suppress background and by a lead collimator with Ø 11cm apperture to suppress Compton continuum in the detector response. The spectrometer was placed at the first minimum of the elastic scattering of 14 MeV neutrons on ^{52}Cr, at 70° towards the incident beam, in order to suppress the fraction of neutrons detected by the NaI(Tl). Neutrons were further discriminated by the time-of-flight technique. The energy threshold of the spectrometer was 0.18 MeV, its time resolution was 7.5 ns and the distance between the front face of the NaI(Tl) and the centre of the sample was 30.4 cm.

Neutron fluence was determined from the associated α particle count corrected for the solid angle and for the figure of merit of neutron collimation as measured by the stilbene monitor.

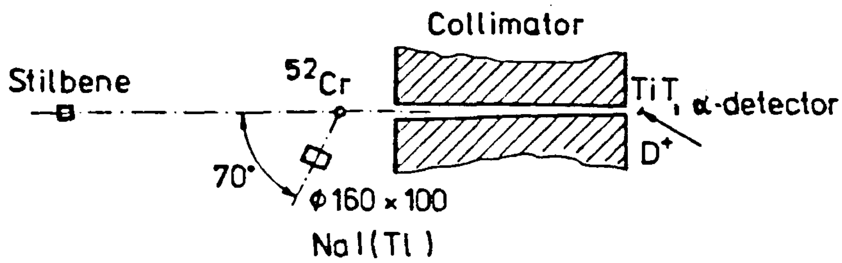

Fig.1. Simplified drawing of the experimental arrangement.

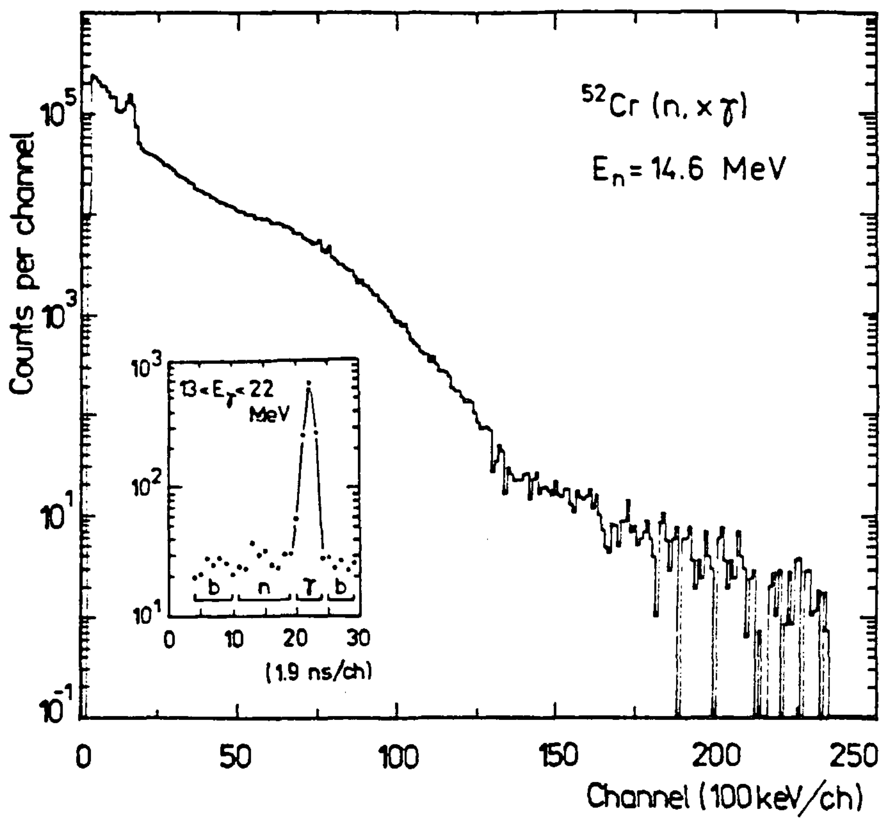

Fig.2. Net energy pulse height γ ray spectrum. Shown in the insert is the high energy part of the two-parametric pulse height spectrum projected on the time axis (b stands for the random background, n is the neutron component).

Recorded was two-parametric pulse height spectrum, 32 time channels x 256 energy channels. The whole matrix was processed so that neutron component and random background component were subtracted to get net γ ray energy pulse height spectrum. This spectrum can be seen in fig.2. Shown in the insert is the high energy part of the spectrum projected on the time axis.

A question may arise to what extent the high energy events are distorted by pile-up effect. Among possible sources of this effect (random γ-γ , random γ-n, coincident γ-γ and coincident γ-n) the most likely is the one caused by detection of a γ ray and a neutron from the very same (n,n'γ) reaction. Since the γ ray reaches the detector first, the time-of-flight discriminator accepts the event, while the neutron is detected somewhat later and deteriorates only slow signal used to fed ADC. An upper estimate of this effect, however, represents only about 4–5% of observed events with pulse height above 14 MeV. Since a more realistic, though much more complicated, estimate is expected to give a value of the order of 1%, no correction of this type was applied.

The net pulse height spectrum was unfolded by means of the code UNFOLD[5]. Response matrix for γ rays incident on the NaI(Tl) was deduced from the experimentally observed lineshapes for a number of discrete γ lines. They were measured using standard radionuclides for $E_\gamma \lesssim 3$ MeV and reactions $^{12}C(n,n'\gamma)$, $^{11}B(p,\gamma)$ and $^{3}H(p,\gamma)$ for higher energies. Absolute effeciency curve was determined by the coincidence technique[4].

The resulting γ ray energy spectrum is still distorted by interactions of primary γ rays in the sample itself. For example, Monte Carlo calculations show that about 13% out of 2 MeV γ rays interact in the sample. Only part of these interactions led to γ ray absorption since major interactions for MeV γ rays are Compton scattering and pair production. The latter process generally leads to creation of a new γ ray via positron annihilation as well as via bremsstrahlung radiation of slowing down electron/positron.

To account for the above effects we applied the second unfolding. The response matrix now refered to distortion of primary γ rays by interactions in the voluminous ^{52}Cr sample. The response was calculated using realistic γ ray absorption coefficients and theoretical prescriptions for the Compton scattering and pair production. Bremsstrahlung radiation was assumed to follow the low frequency approximation that implies $1/E_\gamma$ distribution function, where E_γ is the energy of a created γ ray. Efficiencies were calculated as the number of γ rays emitted from the sample relative to the number of primary γ rays. This procedure changed the spectrum in average by several percent(-7.5% at 2 MeV and +3% at 10 MeV .

3. Total γ ray production

3.1. Spectrum and integral quantities

Differential cross sections of 70-deg γ ray production for $^{52}Cr(n,x\gamma)$ at 14.6 MeV are summarized in tab.1. Quoted uncertainties are composed of contributions from neutron fluence (4%), efficiency of the spectrometer (5%) and statistics (1-10%), no contribution from the unfolding procedure was considered. It should be pointed out, however, that relatively large scatter of the data at high energy end of the spectrum is due to unfolding and not to a possible physics involved.

Total γ ray production spectrum is obtained by neglecting a possible angular anisotropy and by multiplying the observed 70-deg spectrum by a factor of 4π. This is shown in fig.3. Comparison is made with the spectrum as measured for ^{nat}Cr at 14.2 MeV under 90^o in the spectral energy range E_γ= 0.4-8.5 MeV by Drake et al.[6]. Accord of the spectra seems good in view of the differencies in the experimental conditions (sample, neutron energy, detection angle). Peaks in the low energy region of our spectrum are less pronounced because of the modest energy resolution of our spectrometer.

Further comparison is made with the high energy spectrum ($E_\gamma \geq$ 12.5 MeV) for ^{nat}Cr at 14.6 MeV measured by Budnar et al.[7] using pair spectrometer. The accord is reasonable except for the energy range $E_\gamma \approx$ 14 - 18 MeV, where our spectrum exceeds the data of ref.7 by about a factor of 3. A possible explanation might be in contribution from strong $(n,n'\gamma)$ channel via high energy tails in the response functions of about 10 -12 MeV γ rays. While this point deserves further attention, we note that similar thing happened to three spectra(^{28}Si, ^{59}Co and ^{88}Sr) by Rigaud et al.[8] (also measured by NaI(Tl)) when compared with the data of ref.7.

Shown in fig.3 finally is the calculated spectrum of primary capture γ rays. The calculation was performed in the frame of the preequilibrium exciton model for γ ray emission with angular momentum coupling as developed in ref.9. For some more details of this calculation see ref.3.

Two integral quantitites are of special interest, the energy-angle integrated total γ ray production cross section and

Tab. 1. 70-deg production cross sections of continuous γ rays from $^{52}Cr(n,x\gamma)$ at 14.6 MeV. Energy bin width is 0.1 MeV below 13 MeV and 1 MeV above 13 MeV. E_γ given in the table is the starting energy of the bin. Uncertainties given in parentheses refer to last digits quoted.

E_γ (MeV)	$d^2\sigma/dE_\gamma d\omega_\gamma$ (b/MeV.sr)	E_γ (MeV)	$d^2\sigma/dE_\gamma d\omega_\gamma$ (b/MeV.sr)	E_γ (MeV)	$d^2\sigma/dE_\gamma d\omega_\gamma$ (b/MeV.sr)
0.2	1.31(9)-1	4.8	1.18(8)-2	9.4	3.49(28)-3
0.3	1.00(7)-1	4.9	1.16(8)-2	9.5	3.33(27)-3
0.4	1.13(7)-1	5.0	1.49(10)-2	9.6	2.73(20)-3
0.5	8.89(58)-2	5.1	1.16(8)-2	9.7	2.16(18)-3
0.6	1.15(8)-1	5.2	1.22(8)-2	9.8	1.77(15)-3
0.7	9.71(63)-2	5.3	1.54(10)-2	9.9	2.51(19)-3
0.8	6.83(44)-2	5.4	9.07(59)-3	10.0	2.13(25)-3
0.9	1.31(9)-1	5.5	1.15(8)-2	10.1	2.92(35)-3
1.0	8.99(58)-2	5.6	1.15(8)-2	10.2	1.91(23)-3
1.1	4.86(32)-2	5.7	1.59(11)-2	10.3	1.30(16)-3
1.2	7.69(50)-2	5.8	1.32(9)-2	10.4	1.13(14)-3
1.3	1.67(10)-1	5.9	1.00(7)-2	10.5	1.09(13)-3
1.4	3.40(22)-1	6.0	1.15(8)-2	10.6	7.61(91)-4
1.5	2.01(13)-1	6.1	1.34(9)-2	10.7	8.04(96)-4
1.6	4.45(29)-2	6.2	1.39(10)-2	10.8	9.95(99)-4
1.7	1.62(10)-2	6.3	1.27(9)-2	10.9	6.21(74)-4
1.8	1.95(13)-2	6.4	1.40(10)-2	11.0	1.26(15)-3
1.9	1.51(10)-2	6.5	1.33(9)-2	11.1	8.51(99)-4
2.0	1.56(10)-2	6.6	9.07(64)-3	11.2	5.79(69)-4
2.1	2.29(15)-2	6.7	1.11(8)-2	11.3	8.12(97)-4
2.2	1.98(13)-2	6.8	1.31(9)-2	11.4	8.67(99)-4
2.3	2.35(15)-2	6.9	9.47(61)-3	11.5	7.41(89)-4
2.4	2.28(15)-2	7.0	9.71(63)-3	11.6	3.32(40)-4
2.5	1.17(8)-2	7.1	9.95(65)-3	11.7	3.12(37)-4
2.6	2.71(18)-2	7.2	8.99(58)-3	11.8	4.22(51)-4
2.7	1.85(12)-2	7.3	1.38(9)-2	11.9	3.40(41)-4
2.8	2.14(14)-2	7.4	1.00(8)-2	12.0	3.05(36)-4
2.9	1.40(9)-2	7.5	9.63(77)-3	12.1	4.86(58)-4
3.0	1.53(10)-2	7.6	9.39(75)-3	12.2	4.93(59)-4
3.1	1.93(13)-2	7.7	7.78(62)-3	12.3	2.97(36)-4
3.2	2.08(14)-2	7.8	8.59(69)-3	12.4	1.93(23)-4
3.3	1.42(9)-2	7.9	8.04(64)-3	12.5	1.56(19)-4
3.4	2.20(14)-2	8.0	6.56(52)-3	12.6	2.58(31)-4
3.5	8.28(54)-3	8.1	7.75(62)-3	12.7	3.19(38)-4
3.6	1.19(8)-2	8.2	6.95(56)-3	12.8	2.75(33)-4
3.7	1.55(10)-2	8.3	6.77(54)-3	12.9	2.19(26)-4
3.8	1.26(8)-2	8.4	7.52(60)-3	13.0	5.91(71)-5
3.9	1.71(11)-2	8.5	5.15(41)-3	14.0	4.33(52)-5
4.0	1.22(8)-2	8.6	3.18(25)-3	15.0	2.18(26)-5
4.1	1.46(9)-2	8.7	6.00(47)-3	16.0	2.32(28)-5
4.2	1.25(8)-2	8.8	4.56(36)-3	17.0	1.66(20)-5
4.3	1.09(7)-2	8.9	5.15(41)-3	18.0	6.99(84)-6
4.4	1.69(11)-2	9.0	4.50(36)-3	19.0	1.19(14)-5
4.5	1.45(9)-2	9.1	3.53(28)-3	20.0	1.81(21)-6
4.6	1.58(10)-2	9.2	4.48(36)-3	21.0	3.96(47)-6
4.7	1.58(10)-2	9.3	3.29(27)-3	22.0	4.85(58)-7

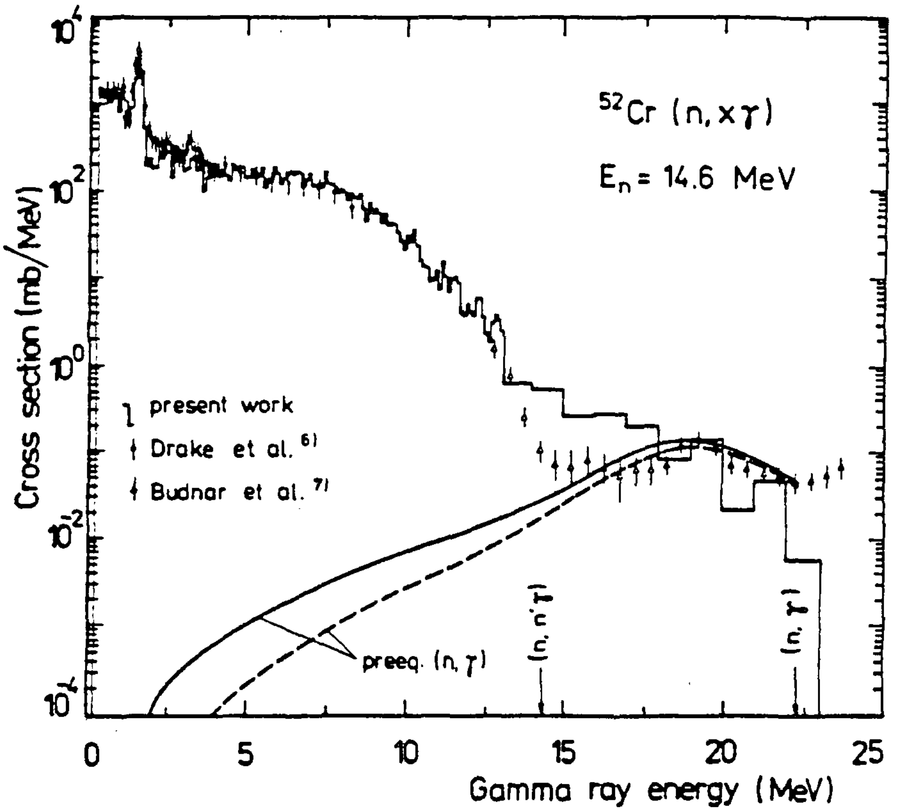

Fig.3. Observed total γ ray energy spectrum for ^{52}Cr(n,xγ) at 14.6 MeV. Shown for comparison is the spectrum by Drake et al.(ref.6) and at the high energy part the spectrum by Budnar et al.(ref.7). The curves refer to primary capture γ rays calculated in the preequilibrium exciton model (full curve is the sum over exciton states, dashed curve is contribution of the initial n_o=1 state).

the average energy per one γ ray emitted. Integration of our spectrum over the entire spectral energy range 0.2 — 22.3 MeV yields σ_γ^{tot} = 3540 ± 230 mb, while the energies 0.2 - 0.5 MeV contribute by 430 ± 30 mb and the energies ≥ 8.5 MeV by 101 ± 11 mb. Our integral is in good accord with two earlier measurements, see tab.2. On the other hand, the systematics of (n,xγ) at 14 MeV by Bezotosnyi et al.[11] suggests the value 4200 mb. Their data, however, seems to be systematically too high[14] and our ^{52}Cr(n,xγ) total cross section indeed supports this suggestion. On the contrary, recent theoretical number by Hetrick et al.[12], 2750 mb, seems to be too small.

The centroid of the spectrum means the average γ ray energy. Our spectrum yields $\overline{E}_\gamma$(n,xγ) = 2.49 ± 0.15 MeV. This value is somewhat higher than the two experimental averages obtained earlier in refs.[10,6] on ^{nat}Cr, see tab.2.

Tab.2. Comparison of total γ ray production cross sections and average γ ray energies for $Cr(n,x\gamma)$ around 14 MeV.

Reference	This work	This work	Drake 6)	Morgan⁺ 10)	Bezotosnyi 11)	Hetrick 12)
Data	exp.	exp.	exp.	exp.	systematics	calc.
Sample	^{52}Cr	^{52}Cr	^{nat}Cr	^{nat}Cr	^{nat}Cr	^{52}Cr
E_n (MeV)	14.6 ±.2	14.6 ±.2	14.2 ±.5	14-17	~14	14.5
ϑ_γ	70°	70°	90°	125°	--	--
E_γ (MeV)	≥0.2	≥0.5	0.4-8.5	0.3-10.5	≳0.5	≥0.5
σ_γ^{tot} (mb)	3540 ±230	3110 ±220	3345 ±300	3550 ±100	4200	2850
$\overline{E}_\gamma$ (MeV)	2.49 ±.15	2.78 ±.15	2.3 ±.2	2.4 ±.1	--	--

(+) Taken from fig.4 given in the paper of Dickens et al.[13].

3.2. Comparison with discrete γ production and coincident data

The total $^{52}Cr(n,x\gamma)$ spectrum allows several comparisons with our Ge(Li) and coincident data reported earlier[1,2]. Each of the three pieces of data, total γ ray production spectrum, discrete γ ray production cross sections and the coincident γ-γ and n-γ data represents a specific part of information related to γ production. Since an overlap between them exists one can check internal consistency of the whole data set. The three pieces of data were obtained by independent, at least to a large extent, methods and in fact in different experimental runs. By cross checking of the data one can identify a possible systematical error in one piece of the data and to achieve higher reliability of the whole set.

The γ ray production cross section integrated over the peak in the spectral energy range 1.2 - 1.6 MeV is 987 ± 70 mb. This can be compared with the γ production cross sections as measured by the Ge(li) spectrometer (see ref.2 and the next section of the present report). Four discrete γ lines were observed in this energy range. Major contribution comes from the dominant 1434.1 keV γ line that amounts to 783 ± 30 mb. By adding the cross sections for the 1246.2, 1333.6 and 1530.7 keV γ lines one gets 1067 ± 41 mb.

The total γ ray production cross section, 3540± 230 mb, can be compared with that deduced from the discrete γ ray production cross sections[2] and the average γ ray multiplicities[1]. It holds

$$\sigma_\gamma^{tot} = \sigma(n,n'\gamma)\overline{M}(n,n'\gamma) + \sigma(n,2n\gamma)\overline{M}(n,2n\gamma) + \sigma(n,ch.p.\gamma)\overline{M}(n,ch.p.\gamma), \qquad (1)$$

where $\sigma(n,n'\gamma)$ is the cross section of neutron inelastic scattering after which γ ray is emitted, $\overline{M}(n,n'\gamma)$ is the average γ ray multiplicity in the $(n,n'\gamma)$ channel and similar notation is used for the $(n,2n\gamma)$ channel and for the sum of channels involving charged particles.

In eq.(1), the first term is basically determined by the dominant $2_1^+ \rightarrow 0^+$ (g.s.), 1434.1 keV γ line with $\overline{M}_{1434} = 3.7 \pm 0.2$. However, $\sigma(n,n'\gamma)$ should be increased by a factor of 1/0.918 compared to σ_{1434} due to γ cascades that do not pass through the 2_1^+ state[15]. The second term is small since out of 360 ± 22 mb of total (n,2n) cross section[16] only a small fraction gives rise to γ rays, the cascades being very short. Indeed, we observed two γ lines, 749.1 and 1164.4 keV, with the sum cross section 78 ± 6 mb. The corresponding average multiplicity can be deduced from the decay schemes as close to 1. As regards the third term we observed only one discrete γ line, 319.3 keV, in the $(n,np\gamma)$ channel with the cross section 19 ± 2.5 mb. The $\sigma(n,ch.p.\gamma)$ can be estimated as $\sigma(n,ch.p.\gamma) \approx \sigma(n,np\gamma) + \sigma(n,p) + \sigma(n,d) + \sigma(n,\alpha) = (19 \pm 2.5) + (71 \pm 3) + (8 \pm 3) + (36 \pm 6) = 134 \pm 8$ mb, where charged particle production cross sections were taken from refs.16, 17. Estimating the average γ ray multiplicities in the partial channels as correspondingly, 1, 3 ± 0.5, 2.5 ± 0.5 and 2.5 ± 0.5 one gets $\overline{M}(n,ch.p.\gamma) \approx 2.5 \pm 0.5$.

Inserting the above values into eq.(1) one gets

$$\sigma_\gamma^{tot} = \frac{1}{0.918}(783 \pm 30)(3.7 \pm 0.2) + (78 \pm 6)1 + (134 \pm 8)(2.5 \pm 0.5) = 3570 \pm 250\,\text{mb}. \qquad (2)$$

This cross section agrees well with the value obtained from the total γ production spectrum.

Our final check concerns the average energy per one γ ray emitted. The total spectrum yields $\overline{E}_\gamma(n,x\gamma) = 2.49 \pm 0.15$ MeV. In the $(n,n'\gamma)$ channel itself one should thus have somewhat higher energy

$$\overline{E}_\gamma(n,n'\gamma) \approx 2.6 \pm 0.2 \text{ MeV}. \qquad (3)$$

These averages can be compared with that deduced from our coincident data[1]. Exclusive neutron spectrum (inelastic neutrons in coincidence with the 1434.1 keV γ line) gives for the average energy of inelastic neutrons $\overline{E}_{n'} = 4.19 \pm 0.17$ MeV. This implies that the energy left for γ cascades in the $(n,n'\gamma)$ channel is

$$\overline{E}_{exc}(n,n'\gamma) \approx \left[(14.6 \pm 0.2) - (4.19 \pm 0.17)\right] \frac{52}{53} \approx 10.20 \pm 0.25\,\mathrm{MeV}. \qquad (4)$$

Using $\overline{M}(n,n'\gamma) \approx \overline{M}_{1434} = 3.7 \pm 0.2$ one gets

$$\overline{E}_{\gamma}(n,n'\gamma) = \frac{\overline{E}_{exc}(n,n'\gamma)}{\overline{M}(n,n'\gamma)} = 2.76 \pm 0.16\,\mathrm{MeV} \qquad (5)$$

in agreement with eq.(3).

4. Reanalysis of discrete γ ray production

Discrete γ ray production cross sections for $^{52}Cr(n,x\gamma)$ at 14.6 MeV were reported by us in ref.2. Partial cross sections were measured for 15 transitions, out of them angular distributions were determined for 10 transitions in the $(n,n'\gamma)$ channel and for 2 transitions in the $(n,2n\gamma)$ channel. The production cross section of the dominant $2_1^+ \rightarrow 0^+$ (^{52}Cr g.s.), 1434.1 keV γ line should be close to full (n,n') cross section. We reported $\sigma_{1434} = 1171 \pm 40$ mb. That number, as we already discussed in ref.2, was by about 30% higher than those measured by Abbondano et al.[18] as well as by Larson[19].

After publishing the report[2], three independent arguments appeared each showing that our cross sections are too high. First, Vonach[20] pointed out that the cross section bilance, $\sigma(n,n') = \sigma(non) - \sigma(n,2n) - \sigma(n,ch.p.)$, leads to $\sigma(n,n') = 780 \pm 60$ mb, consequently, $\sigma_{1434} \lesssim 780 \pm 60$ mb. This argument was further supported by the actually measured cross section in Vienna[21] $\sigma_{1434} = 727 \pm 33$ mb. Secondly, Mengoni et al. calculated $^{52}Cr(n,n'\gamma)$ cross sections and found that while our relative cross sections agree nicely with theoretical predictions[15] the absolute values are too high[22]. The decisive clue, however, came from our own independent data.

The total γ production σ_{γ}^{tot} as measured by the NaI(Tl) spectrometer, see previous chapter, shows that the above σ_{1434}

Tab. 3. Differential cross sections of discrete γ ray transitions observed in $^{52}Cr(n,x\gamma)$ at various angles. Uncertainties are given in parentheses.

ϑ_γ (°)	42(12)	61(10)	90(12)	103(11)	136(9)	158(9)
E_γ (keV)			$d\sigma(\vartheta_\gamma)/d\omega_\gamma$ (mb/sr)			
319.3	-	-	1.1(0.1)	0.9(0.1)	-	-
568.0	1.5(0.3)	-	2.0(0.2)	2.5(0.6)	-	-
647.4	5.7(0.8)	5.7(0.7)	4.5(0.4)	4.8(0.6)	6.3(0.6)	7.2(1.0)
704.6	2.8(0.4)	-	3.5(0.4)	3.5(0.6)	3.5(0.4)	2.7(0.4)
744.2	6.1(0.8)	-	4.7(0.4)	4.6(0.4)	6.6(0.6)	7.4(0.9)
749.1	3.3(0.4)	-	3.6(0.4)	2.6(0.2)	4.0(0.5)	4.6(0.6)
848.2	2.8(0.7)	-	2.8(0.4)	2.4(0.7)	2.8(0.4)	5.1(0.5)
935.5	19.8(1.6)	19.2(1.8)	17.0(1.5)	16.1(1.3)	18.7(1.5)	24.8(2.1)
1164.4	3.6(1.4)	-	3.7(0.6)	3.5(0.9)	2.2(0.3)	1.8(0.4)
1212.7	-	-	2.0(0.9)	-	-	-
1246.2	2.5(0.8)	-	3.8(0.7)	4.4(0.8)	2.4(0.4)	1.8(0.4)
1333.6	17.2(1.5)	15.4(1.5)	14.8(1.3)	13.1(1.5)	18.7(1.9)	20.5(1.9)
1434.1	63.8(5.3)	63.5(5.7)	57.8(4.7)	60.2(4.7)	61.5(5.4)	70.2(6.0)
1530.7	4.1(1.1)	-	3.9(0.5)	4.0(0.8)	2.2(0.3)	4.2(0.4)
1727.5	1.8(0.9)	-	3.1(0.8)	3.4(1.5)	1.2(0.3)	0.9(0.3)

Tab. 4. Angle-integrated production cross sections and Legendre coefficients for angular distributions of discrete γ rays emitted in $^{52}Cr(n,x\gamma)$ at 14.6 MeV.

E_γ (keV)	Reaction	a_2	a_4	σ_{γ}(mb)
647.4	(n,n'γ)	0.33(14)	-0.02(17)	70(4)
704.6	(n,n'γ)	-0.19(11)	-0.11(15)	42(3)
744.2	(n,n'γ)	0.39(13)	-0.01(18)	71(4)
749.1	(n,2nγ)	0.42(13)	0.26(20)	42(2)
848.2	(n,n'γ)	0.60(16)	0.60(20)	38(3)
935.5	(n,n'γ)	0.31(09)	0.12(12)	237(9)
1164.4	(n,2nγ)	-0.52(19)	0.13(20)	36(4)
1246.2	(n,n'γ)	-0.59(17)	0.10(19)	39(4)
1333.6	(n,n'γ)	0.31(09)	0.04(12)	205(8)
1434.1	(n,n'γ)	0.12(08)	0.04(11)	783(30)
1530.7	(n,n'γ)	0.04(15)	0.74(18)	40(3)
1727.5	(n,n'γ)	-0.90(30)	0.32(28)	26(4)

is clearly too high. Furthermore, the exclusive neutron spectrum measured in coincidence with the 1434.1 keV line, see tab.4 of ref.1, suggests that $\sigma_{1434} = 791 \pm 98$ mb. This number was already corrected for the angular anisotropy of inelastic neutrons. The anisotropy at 100° was estimated from neutron spectra, $E_{n'} \geq 2$ MeV, measured on ^{nat}Cr at 14 MeV by Hermsdorf et al.[23], as 0.89 ± 0.05.

The discrete γ ray production data were reprocessed. The source of the systematical error has indeed been identified: the 90-deg run that was used to adjust the absolute scale was internally divided into 3 roughly equal subruns but the α particle count of the third subrun was due to software error never added into the total count. Consequently, there was systematical bias in neutron fluence by a factor of about 2/3 (more precisely 0.71). This means that all previously reported cross sections must be reduced by this factor.

Furthermore, we accounted for multiple processes in the sample not considered in ref.2. The correction has practical meaning only for $(n,n'\gamma)$ cross sections. For example, for the 1434.1 keV γ line it was evaluated as ≈ 48 mb with the estimated uncertainty of ≈ 10 mb. The final cross section for this line is thus

$$\sigma_{1434} = 783 \pm 30 \text{ mb}. \tag{6}$$

This number is in accord with the observed σ_{γ}^{tot} as discussed in the previous chapter. It is supported by the value deduced from our exclusive neutron spectrum[1]. Furthermore, it is close to Vonach's estimate[20] corrected by the Mengoni et al. factor[15], $\sigma_{1434} = 0.918 \times (780 \pm 60)$ mb $= 716 \pm 55$ mb.

The new data are summarized in tab.3 and tab.4. They supersede the earlier data published in the IAEA Report[2] and reported also at the Dubrovnik Neutron Conference[24]. The shapes of the angular distributions remain unchanged.

5. Conclusion

This paper is the last of our three reports on measurements of $^{52}Cr(n,x\gamma)$ data at 14.6 MeV. Each of the three parts of data, coincident, discrete γ production and total γ production provides an independent albeit complementary insight into $^{52}Cr(n,x\gamma)$ reactions. Where an overlap between the data exists they are mutually consistent. To the best of our knowledge these data represent the most comprehensive γ emission data set at 14 MeV neutron incident energy ever measured for one isotope.

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