Resonance Neutron Capture in ^{55}Mn and Levels in ^{56}Mn

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(Z. Naturforsch. **29 a**, 385—388 [1974]; received 24 December 1973)

The γ-spectrum of ^{56}Mn from resonance neutron capture in ^{55}Mn has been measured in the energy range $4.2 \leqq E \leqq 7.3$ MeV. The 215 keV level of ^{56}Mn was found to be populated through about 30% of the primary γ-ray intensity leading to the 212/215 keV doublet.

1. Introduction

Previous studies of the level scheme of ^{56}Mn have revealed [1] states at 26.6, 110.5, 212.0, 215.1, 335.5, 341.0, 454.3, 486.3, 716.2 and 840.4 keV. The spins and parities proposed for these levels are consistent with all available data. It is noteworthy, however, that the 215.1 keV level for which the low-energy data require spin and parity 2^+ has not been disclosed through the observation of a primary γ-ray from any of the low energy resonances with spins and parities 2^- or 3^-. This result, although it does not contradict the statistical theory [2], seems highly improbable. Since the measurement of γ-lines with $E_\gamma \approx 7$ MeV and an energy separation of only 3 keV is rather difficult, we have studied the γ-rays from resonance neutron capture in ^{55}Mn with a high resolution Ge(Li) spectrometer.

2. Experimental Method

The low flux of the FRM reactor at Garching, where the experiment has been carried out, did not allow a measurement in the individual resonances. Therefore, we have used a technique similar to that applied by Bollinger [3]: the measurement of the γ-spectrum resulting from the capture of epithermal reactor neutrons in the low-energy resonances of the sample.

The target, 9 grams of Mn powder with impurities less than 0.7% of iron and carbon was enclosed in a graphite container surrounded by B_4C tubes and discs resting on a graphite support and located in the tangential through-tube close to the reactor core (Figure 1). The γ-radiation from the target passed a narrow and about 2 m long collimator of graphite and lead with its face at a distance of 1.3 m from the sample and was detected by means of a Ge(Li) diode located within a lead shield about 7 m from the target. The geometry of the inner collimator and another collimator in front of the detector was such that the diode could not receive radiation directly from the B_4C tubes. These B_4C tubes contained ^{10}B with its natural isotopic abundance corresponding

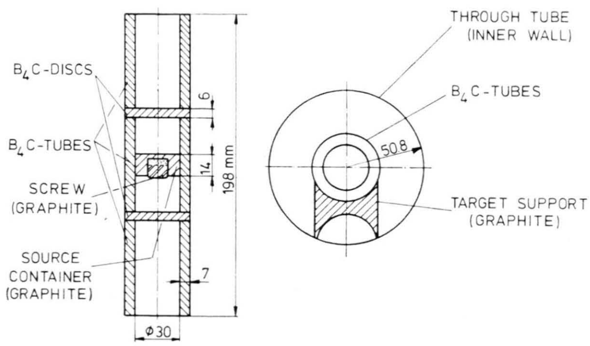

Fig. 1. Source arrangement for the measurement of γ-rays from the capture of resonance neutrons.

to 0.27 g/cm^2 of ^{10}B. This boron filter changes the neutron flux spectrum φ of the reactor into a spectrum φ' which after a sharp increase below $E_n = 10$ eV has a broad maximum until 100 eV and then slowly approaches the spectrum φ until $E_n \approx 10$ keV. On the basis of the resonance neutron spectrum φ' and the parameters [4] of the low lying resonances of ^{56}Mn it was possible to calculate the percentages p_i

Table 1. Comparison between the expected relative γ-intensities I_c and the measured values I_m for the primary resonance neutron capture γ-lines feeding the low-lying levels with excitation energies E_x. The set I_m has been adjusted against the set I_c for minimal variance without the use of the data for the 212/215 keV doublet and the 840 keV state.

E_x/keV	I_c	I_m
0	89 ± 10	80 ± 3
26	118 ± 10	108 ± 5
110	46 ± 7	48 ± 2
212	25 ± 4	63 ± 4 (212 + 215)
215	<4.5	
341	18 ± 5	20 ± 4
454	5.5 ± 2.0	9 ± 4
486	26 ± 5	28 ± 3
716	1.4 ± 1.7	<2
840	0.8 ± 1.6	7 ± 2

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of the capture rates in the individual resonances i with the energies E_i. These numbers: $p = 2.7\%$ in $E < 50$ eV, 69.2% in $E = 335$ eV, 25% in $E = 1098$ eV, 2.5% in $E = 2355$ keV, $< 0.3\%$ in $E = 7.11$ keV and $< 0.3\%$ in $E = 8.74$ keV multiplied with the intensities $I_{\gamma i}$ measured at the fast chopper at the High Flux Beam Reactor of the Brookhaven National Laboratory by Rimawi et al. and listed in Table 2 of Ref. [1] yield the relative intensities

$$I_c = \Sigma\, p_i\, I_{\gamma i}$$

of the primary resonance neutron capture γ-lines expected in the present experiment (see Table 1).

3. Measurements and Results

The γ-measurement was performed with a small (7 cm^3) planar Ge(Li) detector with a ratio of 50:5:1 for the intensities of the double escape peak: single escape peak: full energy peak for $E_\gamma \approx 7$ MeV. This detector was chosen because it effectively suppresses disturbances due to single escape and full energy peaks in the region of the spectrum where the double escape peaks of the transitions with 6.4 MeV $\leqq E_\gamma \leqq$ 7.3 MeV to the low-lying states of ^{56}Mn are recorded. The energy resolution of the

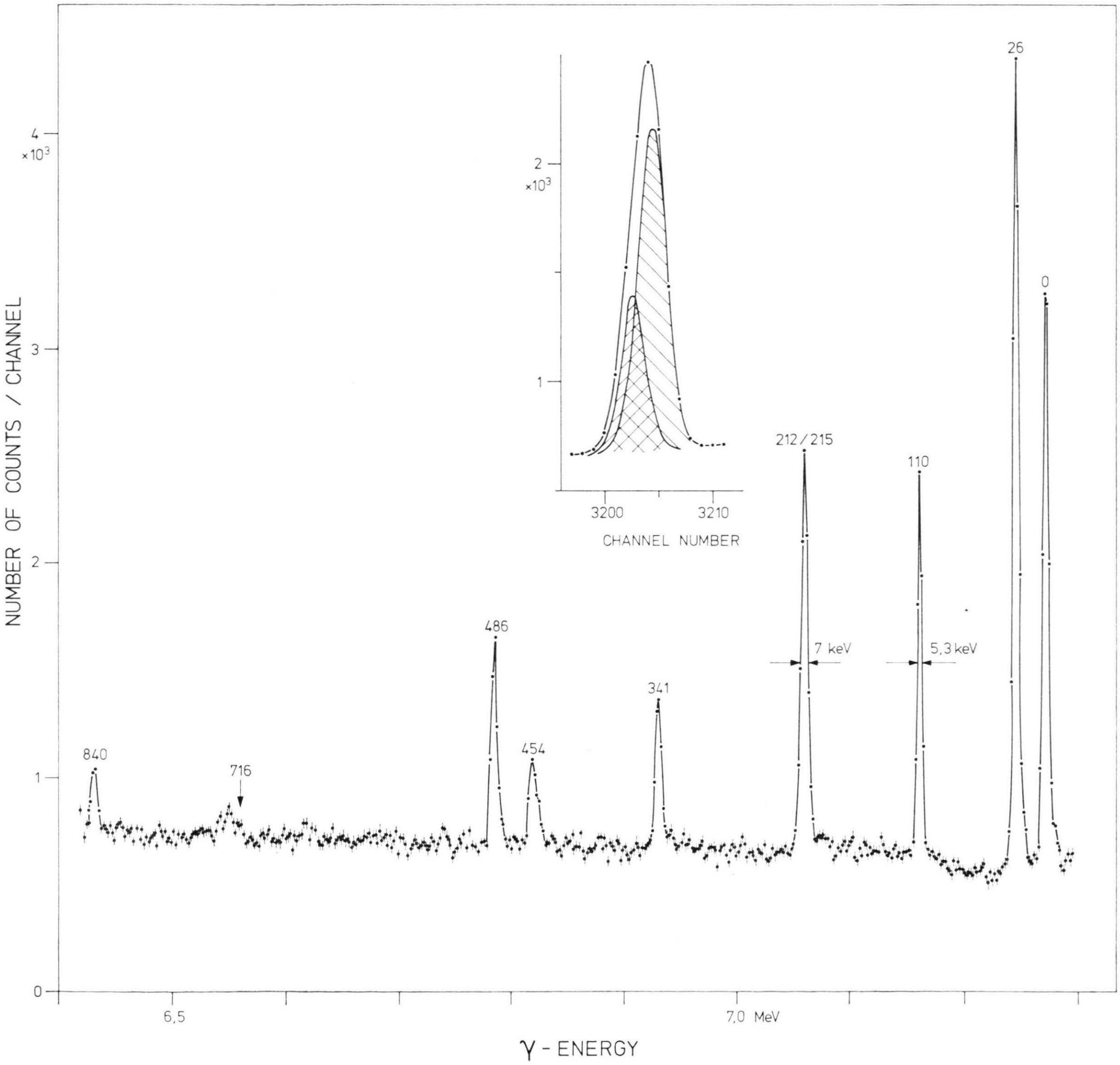

Fig. 2. Spectrum of double escape peaks of primary γ-rays from resonance neutron capture in ^{55}Mn. These data were accumulated during 24 hours. The numbers on top of the peaks are the energies (in keV) of the levels in ^{56}Mn populated through primary transitions.

E_x/keV	E_γ/keV	ΔE_γkeV	E_t/keV	E_c/keV
0	7272.05 ± 0.10	5.5 ± 0.1	7272.55 ± 0.10	7272.55 ± 0.10
26	7245.40 ± 0.10	5.7 ± 0.2	7245.90 ± 0.10	7245.95 ± 0.10
110	7161.31 ± 0.10	5.3 ± 0.1	7161.80 ± 0.10	7161.95 ± 0.10
212 } 215	7060.32 ± 0.15	7.0 ± 0.2	7060.80 ± 0.15	7061.25 ± 0.10
341	6931.33 ± 0.20	5.9 ± 0.3	6931.79 ± 0.20	6931.85 ± 0.20
454	6819.0 ± 0.5	5.7 ± 0.5	6819.4 ± 0.5	6819.2 ± 0.3
486	6785.8 ± 0.3	5.9 ± 0.2	6786.2 ± 0.3	6786.55 ± 0.10
840	6433.0 ± 0.4	5.9 ± 0.2	6433.4 ± 0.4	6433.05 ± 0.20

Table 2. Energies E_γ of the primary complex transitions from the lowest neutron resonances to low-lying levels E_x in ^{56}Mn. The errors of E_γ contain only the fitting error and the uncertainty of the energy slope of the system for $E_\gamma \approx 7$ MeV.

spectrometer was $\Delta E = \text{FWHM} = 5.3$ keV at $E_\gamma \approx 7$ MeV and 3.0 keV at $E_\gamma < 0.9$ MeV. The energy calibration is based on ^{60}Co, ^{88}Y [5], the 2111.7, 1809.3, 845.8, 7646.6 and 7632.2 keV lines [6] of ^{56}Fe and the distance between the single and double escape peaks of the 7245 keV line of ^{56}Mn. A precision pulser was used in the energy region from 2 – 7.5 MeV.

The measured pulse height spectrum of primary γ-rays between 6.4 and 7.3 MeV is plotted in Figure 2. The insert shows the doublet structure of the peak corresponding to the transitions feeding the 212 and 215 keV levels. The observed relative intensities I_m are listed in Table 1. Table 2 contains the measured γ-energies E_γ, the FWHM of the peaks ΔE_γ, the transition energies E_t corrected for recoil and the transition energies E_c expected on the basis of the results of Rimawi et al. if one uses $S_n = 7272.1$ keV for the neutron binding energy and the level energies E_x from the low-energy data. The neutron binding energy $S_n = 7272.1 \pm 2.0$ keV was obtained from our energies E_t, the level energies E_x based on the low energy data of Van Assche et al. [1] and energy contributions ε due to the capture of resonance neutrons and computed with the use of the data of Rimawi et al.:

$$S_n = \overline{E_t + E_x - \varepsilon}, \quad \varepsilon = \Sigma p_i E_i I_{\gamma i}/I_c .$$

For the evaluation of S_n, the transitions feeding the states at 212, 215, 716 and 840 keV have not been used. For the evaluation of the γ-energies E_γ, the energies of the iron lines have been used without correcting them for the energy shift due to the resonance capture. This implies an additional uncertainty of about 1 keV of the γ-energies. This error is included in the uncertainty of S_n. In Table 1 discrepancies are observed between I_c and I_m for the γ-lines feeding the 212/215 keV doublet and the 840 keV level. Table 2 shows a discrepancy between E_t and E_c if E_c is calculated assuming that the γ-transition only feeds the 212 keV level.

The peaks shown in Fig. 2 could be reasonably well fitted by Gaussians (see the FWHM: ΔE_γ in Table 2). This fit clearly resolves the complex peak labeled 212/215 into two components (see the insert of Fig. 2) with an intensity ratio 70:30. From the energy separation of these components we conclude that the 215 keV state is predominantly fed from the 1.1 keV resonance.

This result is in contrast to the upper limits given in Table 2 of Ref. 1 for the 215 keV state. A careful inspection of the spectra (Fig. 2 of Ref. 1) shows, however, that the peak labeled 212 is systematically broader in the 2.4 and 1.1 keV spectra than the other peaks so that we are led to assume that the discrepancy is largely due to a systematic error in the corresponding values $I_{\gamma i}$. An estimate of the intensities of the peaks "212" in these 1.1 and 2.4 keV spectra from a comparison of their areas with those of other peaks lends strong support to the above assumption and suggests that I_c for the 212/215 keV doublet should rather be around 50 which removes the discrepancy. The remaining difference can be due to our insufficient knowledge of the exact neutron spectrum φ around 1 – 3 keV at the target position.

The second discrepancy evident only in Table 1 seems to be due to a trivial error in Table 2 of Ref. 1, since the 1.1 keV spectrum clearly shows an intense peak labeled 840 while the table suggests the absence of the transition. We have again estimated the intensity of the line to the 840 keV state from the figure and obtain a corrected value around 6 instead of 0.8 for I_c.

This then implies that the corrected data of Rimawi et al. are in agreement with the results of the present work.

The peaks labeled 0, 26, 454 and 486 show definite tails at their high-energy wings. These tails are due to the resonance at 8.7 keV (for peak 0) and at 7.1 keV (for the other three peaks), which is clearly born out through the Gaussian fit.

Additional high-energy transitions have been disclosed with energies between 6.1 and 4.2 MeV. They are listed in column 1 of Tab. 3 and have been identified with primary transitions since their energies suggest excited states E_x close to levels E_x' observed in the (d, p)-study[7]. As the mean energy ε of the resonances contributing to E_γ is unknown, we have used $\varepsilon = 0.5$ keV and computed

$$E_x = S_n - E_t + 0.5 \text{ keV} .$$

Therefore, the uncertainty dE_x is about 2.5 keV.

E_γ/keV	E_x/keV	E_x'/keV
6104.4	1167.9	1166
6031.2	1241.1	1238
5921.3	1351.0	1349
5762.3	1510.0	1510
5579.2	1693.1	1695
5527.8	1744.5	1742
5433.4	1838.9	1834
5254.4	2017.9	2015
5197.6	2074.7	2071
5180.3	2092.0	2088
5067.3	2205.0	2205
5033.8	2238.5	2234
5014.0	2258.3	2255
4949.2	2323.1	2321
4840.2	2432.2	2432
4830.3	2442.1	2438
4724.1	2548.3	2546
4642.9	2629.5	2628
4565.8	2706.6	2704
4266.4	3006.0	3001

Table 3. High-energy γ-transitions from resonance neutron capture in ^{55}Mn. The level energies E_x' are from Reference 7.

4. Conclusion

The present study has shown that the technique[3] of the γ-spectroscopy from average resonance neutron capture is useful even in cases where only few resonances contribute. Although statistical information cannot be extracted from the γ-ray intensities, their energies yield approximate excitation energies of low-lying levels. It is obvious that in this way levels can be disclosed which are not populated with measurable intensity in thermal neutron capture. As has been demonstrated, the experiment can be carried out at reactors of fairly low power. If enriched B_4C is used and if fast neutron scattering in the vicinity of the source is minimized, even low-energy data of good quality can be gained.

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