

# Neutron Total Cross-Sections at 18.8 eV

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(Z. Naturforsch. **29 a**, 1750–1753 [1974]; received September 27, 1974)

Neutron transmission measurements were performed at 18.8 eV neutron energy on F, Al, Sc, V, Fe, Co, Cu, Zn and Nb, in order to accurately determine the “free” scattering cross-sections of these elements. Coherent neutron scattering amplitudes are derived for F, Al, Sc, Fe, Cu, Zn and Nb, using available experimental data of the isotopic and spin-incoherent cross-sections. Spin-dependent scattering amplitudes  $a(I+\frac{1}{2})$  and  $a(I-\frac{1}{2})$  are evaluated for the monoisotopes F, Al, Sc, V, Co and Nb.

Neutron transmission experiments at eV energies provide a rather direct and accurate measure of the “free” scattering cross-section for most light and medium mass nuclei, as the contribution of neutron capture to the epithermal cross-section is generally small and binding effects become negligible. Accurate knowledge of the total scattering cross-section may be useful

- (1) in the determination of coherent neutron scattering amplitudes, provided that experimental data of the incoherent cross-sections are available;
- (2) in the determination of spin-dependent scattering amplitudes  $a(I+\frac{1}{2})$ ,  $a(I-\frac{1}{2})$ , for  $I \neq 0$  monoisotopes, which requires the independent measurement of two of the quantities  $\sigma_s$ ,  $\sigma_{coh}$  or  $\sigma_{inc}$ ;
- (3) in the absolute determination of reference standards for the coherent and incoherent scattering of slow neutrons, such as the cross-section of carbon and vanadium, resp.

In some previous experiments<sup>1–3</sup> we have accurately determined the cross-sections of H, D, C, O, Si, Pb and Bi in transmission with 132 eV (cobalt-resonance) neutrons. The present measurements on medium-mass nuclei, in which the s-wave level spacings are typically  $\sim$  keV, were made with 18.8 eV (tungsten-resonance) neutrons<sup>4</sup>. This energy is still well below the first s-wave resonances in the elements under study, and the transmission measurement, reduced by a small correction for capture, yields therefore rather direct estimates of the “free” scattering cross-sections at ‘zero’ energy. The specific materials chosen were mostly those for which the incoherent cross-sections are sufficiently small

and well known<sup>5–7</sup>, in order to derive precise values of the coherent scattering lengths. Besides, measurements were made on Co and V, since for both significant discrepancies exist in available cross-section data<sup>8–10</sup> at eV energies.

The transmission experiment at 18.8 eV was performed at the Munich Research Reactor FRM, using a previously described apparatus<sup>4</sup>, in which the energy selection is made by double resonance scattering in tungsten foils. For a detailed description of the method, experimental conditions and evaluation procedure we refer to<sup>4,1</sup>.

Metallic samples were used throughout, except for Fluorine in which case we used a sample of Teflon,  $(CF_2)_n$ . The nominal purity of the metals, as quoted by the manufacturers, is given in the first column of Table 1. The less pure materials (V, Fe, Nb) were checked for tungsten impurities using neutron activation analysis, as these may very sensitively affect<sup>10</sup> our data obtained with the tungsten-resonance spectrum. Small corrections<sup>10</sup> for tungsten impurities were required for V and Nb ( $< 3\%$  in cross-section for both).

The measured total cross-sections are listed in column 2 of Table 1. The quoted errors include the counting statistical uncertainty, errors in the determination of the sample dimensions, and estimates of the uncertainty due to sample impurities. In the next column we list calculated values of the capture cross-sections at 18.8 eV, derived from the thermal cross-sections<sup>11,12</sup> under the assumption that the absorption varies as  $1/v$ . The value given for Co includes also the effect due to the wings of the level at 132 eV, evaluated from the single-level Breit-Wigner formula using resonance parameters from<sup>11</sup>. The fourth column gives estimates of the variation  $\Delta\sigma_s$  in the scattering cross-section between ‘zero’ energy and 18.8 eV due to the effects of nearby

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Tab. 1. Experimental results, derived values of  $\sigma_{s,\text{free}}$ , and comparison with previous data.

sample/ nominal purity	measured $\sigma_{\text{tot}}(18.8 \text{ eV})$ (b)	corrections $\sigma_c(18.8 \text{ eV})$ (b)	$\Delta\sigma_s^b$ (b)	derived $\sigma_{s,\text{free}}^c$ (b)	Ref. 11 $\sigma_{s,\text{free}}$ (b)	further references (b)
F (CF <sub>2</sub> ) <sub>n</sub> <sup>a</sup>	3.575 (14)	0.000	0.000	3.575 (14)	4.0 (1)	3.30 (15) <sup>d</sup>
Al 99.999	1.425 (3)	0.008	0.000	1.417 (3)	1.49 (3)	1.42 (2) <sup>e</sup> 1.4083 (11) <sup>h</sup>
Sc 99.9	22.03 (25)	1.01 (1)	1.1 (2)	22.1 (4)	24 (2)	
V 99.7	4.98 (2)	0.19	<0.01	4.79 (3)	4.93 (3)	4.74 (7) <sup>e</sup> i
Fe 99.5	11.38 (4)	0.09	0.04	11.33 (4)	10.9 (2)	11.38 (5) <sup>e</sup> 11.39 (4) <sup>j</sup>
Co spec pure	8.35 (4)	1.75 (4)	-0.49 (8)	6.11 (10)	6.7 (3) <sup>f</sup>	5.0 (5) <sup>g</sup> 5.95 (5) <sup>k</sup>
Cu 99.999	7.78 (4)	0.14	0.06	7.70 (4)	7.9 (2)	7.74 (3) <sup>e</sup> 6.9 (3) <sup>l</sup>
Zn 99.985	4.09 (3)	0.04	0.05	4.10 (3)	4.2 (2)	3.79 (12) <sup>m</sup>
Nb 99.9	6.41 (4)	0.04	0.00	6.37 (4)		

<sup>a</sup> Teflon sample. Fluorine value is derived using 4.746 (7) b Ref. 1) for carbon. <sup>b</sup>  $\Delta\sigma_s = \sigma_s(0) - \sigma_s(18.8 \text{ eV})$ , see text.  
<sup>c</sup>  $\sigma_{\text{tot}} - \sigma_c + \Delta\sigma_s$ . <sup>d</sup> Ref. 14. <sup>e</sup> Ref. 15. <sup>f</sup> Ref. 8. <sup>g</sup> Ref. 9. <sup>h</sup> Ref. 16. <sup>i</sup> for further references of V, see Ref. 10. <sup>j</sup> Ref. 17.  
<sup>k</sup> Ref. 18. <sup>l</sup> Ref. 19. <sup>m</sup> Ref. 20.

resonances. These are less than 1% in cross-section, except for Sc and Co. The estimates given for F, Al, V, Co, Zn and Nb are calculated from the known parameters<sup>11</sup> of their resonances at 'positive' energy. In case of Sc, Fe, and Cu, the variation in the low energy cross-section is known to be mainly due to bound levels<sup>11</sup>. Therefore, we have estimated  $\Delta\sigma_s$  in these cases from the nearly linear decrease of the experimental cross-sections<sup>13</sup> in the eV range.

In column 5 we list the slow-neutron "free" scattering cross-sections derived from the present data. Our results are in bad agreement with the BNL 325 recommended values<sup>11</sup> (column 6), except for Sc, Cu and Zn. We find excellent agreement, however, with the data of Rayburn and Wollan<sup>15</sup> derived from transmission measurements at 1.44 eV. Our value of Co disagrees with the former results of 8,<sup>9</sup> but is compatible with the recent measurement by Koester et al.<sup>18</sup> within the errors of both experiments.

The evaluation of coherent scattering lengths for F, Al, Sc, Fe, Cu, Zn and Nb is outlined in Table 2. The first and second column gives, resp., the "bound" scattering cross-sections obtained from the present data and values of the "bound" incoherent cross-sections from the literature. Direct measurements of  $\sigma_{\text{inc}}$  are available for Al and Cu from scattering experiments<sup>5</sup> using cold neutrons. Further data are available for the monoisotopes F, Al, Sc and Nb from recent experiments<sup>6,7</sup> involving the scattering of polarized neutrons on polarized targets. These determine the spin-dependent part ( $b_+ - b_-$ ) of the scattering amplitude, and hence the spin-incoherent cross-section<sup>11</sup>

$$\sigma_{\text{inc,spin}} = 4\pi g_+ g_- (b_+ - b_-)^2. \quad (1)$$

Tab. 2. Evaluation of bound-atom coherent scattering amplitudes; comparison with BNL 325 (Ref. 11) recommended values.

	present $\sigma_{s,\text{bound}}^a$ (b)	adopted $\sigma_{\text{inc,bound}}$ (b)	derived <sup>c</sup> $b_{\text{coh}}$ (fm)	Ref. 11 $b_{\text{coh}}$ (fm)
F	3.964 (16)	0.0004 <sup>b</sup>	5.603 (11)	5.64 (4)
Al	1.525 (3)	0.009 (2) <sup>b,c</sup>	3.455 (5)	3.449 (9) <sup>f</sup>
Sc	23.1 (4)	4.45 (22) <sup>b</sup>	12.15 (13)	11.8 (5)
Fe	11.74 (4)	0.42 (3) <sup>d</sup>	9.45 (2)	9.51 (5)
Cu	7.95 (4)	0.59 (4) <sup>e</sup>	7.61 (3)	7.63 (4)
Zn	4.23 (3)	<0.08 <sup>d</sup>	5.73 (4)	5.8 (1)
Nb	6.51 (4)	0.0024 (3) <sup>b</sup>	7.14 (3)	7.11 (4) <sup>f</sup>

<sup>a</sup>  $(1+\alpha)^2 \cdot \sigma_{s,\text{free}}$ ,  $\mu = M_n/M_A$ , <sup>b</sup> Refs. 6, 7. <sup>c</sup> Ref. 5.  
<sup>d</sup> Estimate using Eq. (2) and isotopic scattering lengths from Ref. 11. <sup>e</sup> Bound atom scattering amplitude, Eq. (3).  
<sup>f</sup> Ref. 21.

Here,  $b_+$  and  $b_-$  are the (bound) amplitudes in the  $I + \frac{1}{2}$  and  $I - \frac{1}{2}$  compound state, resp., and  $g_+ = (I+1)/(2I+1)$  and  $g_- = I/(2I+1)$  are the corresponding statistical weight factors.

Values of  $\sigma_{\text{inc}}$  for Fe and Zn may be estimated from available scattering data<sup>11</sup> of their isotopes. Since both elements include only one odd-mass isotope of low abundance in addition to several even isotopes, their  $\sigma_{\text{inc}}$  may be written as

$$\sigma_{\text{inc}} = f_{\text{odd}} \cdot \sigma_{\text{inc,spin}}^{\text{odd}} + 4\pi \sum f_i f_k (b_i - b_k)^2, \quad (2)$$

where  $f_i$  and  $b_i$  is the abundance and coherent amplitude of isotope  $i$ , resp., and the summation is carried out over all combinations of even and odd isotopes. In case of Fe, Eq. (2) is evaluated using the values  $b_i$  for <sup>54,56,57</sup>Fe from<sup>11</sup> and  $\sigma_{\text{inc}}(57) = \sigma_s(57) - \sigma_{\text{coh}}(57)$  from<sup>13</sup>. For Zn, the calculated isotopic incoherence due to the major abundant even isotopes (see<sup>11</sup>) <sup>64,66,68</sup>Zn is only 2 mb, but

no data are available for  $^{67}\text{Zn}$ . The upper bound given in Table 2, therefore, rests on an assumption  $\sigma_{\text{inc, spin}}(67) < 2$  barn (this means, according to Eq. (1),  $|b_+ - b_-|_{67} < 8$  fm).

It should be pointed out, that the derived coherent scattering lengths given in column 3 of Table 2 pertain to bound *atoms*,

$$b_{\text{coh}}(\text{bound atom}) = \left[ \frac{(\sigma_s - \sigma_{\text{inc}})_{\text{bound}}}{4\pi} \right]^{1/2} + Z a_{\text{nc}},$$

$$a_{\text{nc}} \cong -1.4 \cdot 10^{-3} \text{ fm}. \quad (3)$$

The small correction for neutron-electron scattering is subtracted to allow direct comparison with scattering lengths determined by neutron-optical and diffraction methods, given in the last column <sup>11, 21</sup>. There is excellent agreement within the errors of the BNL 325 recommended values, in any case.

Table 3 gives the spin-dependent scattering lengths for the monoisotopes F, Al, Sc, V, Co and Nb. Here, these amplitudes pertain to *free nuclei*. They are derived combining the present data of  $\sigma_{s, \text{free}}$

$$\sigma_{s, \text{free}} = 4\pi(g_+ a_+^2 + g_- a_-^2), \quad (4)$$

Tab. 3. Spin-dependent scattering amplitudes (free nuclei)  $a_+$  and  $a_-$  in the  $I + \frac{1}{2}$  and  $I - \frac{1}{2}$  state of F, Al, Sc, V, Co and Nb. The values are derived by combining the present results of  $\sigma_{s, \text{free}}$  (Tab. 1) with the listed data of  $(b_+ - b_-)$  and  $b_{\text{coh}}$ , resp.

$I$	adopted		derived		literature	
	$(b_+ - b_-)^a$ (fm)	$b_{\text{coh}}$ (fm)	$a_+$ (fm)	$a_-$ (fm)	$a_+$ (fm)	$a_-$ (fm)
F	1/2	-0.135 (2)	5.301 (11)	5.429 (11)		
Al	5/2	+0.55 (6) <sup>b</sup>	3.57 (3)	3.04 (4)		
Sc	7/2	+12.0 (3)	17.0 (2)	5.3 (3)		
V	7/2		4.96 (12)	-7.45 (12)		
Co	7/2	-0.48 (10) <sup>c</sup> +2.78 (4) <sup>d</sup>	-2.92 (6)	10.01 (7)	-2.78 (4) -3.80 (54)	9.91 (6) <sup>d</sup> 10.60 (70) <sup>c</sup>
Nb	9/2	-0.28 (2)	6.99 (4)	7.27 (4)		

<sup>a</sup> Refs. 6, 7; <sup>b</sup> mean of Ref. 5 and Ref. 7; <sup>c</sup> Ref. 11; <sup>d</sup> Ref. 18.

with data of the bound coherent scattering lengths ( $\text{V}^{11}$ ,  $\text{Co}^{18}$ )

$$b_{\text{coh}} = (1 + \mu)(g_+ a_+ + g_- a_-), \quad \mu = M_n/M_A, \quad (5)$$

or data from the polarized-neutron experiments <sup>6, 7</sup>

$$(b_+ - b_-) = (1 + \mu)(a_+ - a_-). \quad (6)$$

The former procedure leads to an ambiguity in the solution  $(a_+, a_-)$ . The choice of the sets given in Table 3 rests on spin assignments of low energy neutron resonances <sup>22</sup> for V, and on data from polarized neutron diffraction <sup>23</sup> for Co, resp.

### Summary

"Free" scattering cross-sections of some medium mass elements have been accurately determined by neutron transmission measurements at 18.8 eV. The data are generally in bad agreement with BNL 325 recommendations of  $\sigma_s$ . Coherent scattering lengths derived from the present data, however, are well consistent with the recommended values.

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