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ACTIVATION CROSS SECTION OF Na²³ AROUND 3 Kev

W. K. Ergen

February 4, 1957

A B S T R A C T

The activation cross section of sodium in the range from thermal energy through the 3 kev resonance is generally assumed to be given by the one-level Breit-Wigner formula, the Γ being selected to describe correctly the known thermal absorption cross section. The contribution of this resonance to the resonance activation integral then turns out to be 0.12 barns. This somewhat indirectly inferred value is considerably larger than the value given by Dancoff et al., in an old paper, the latter value being based on experimental work.

It is shown in the present memo that Dancoff's actual measurements are quite consistent with the Breit-Wigner formula and the above mentioned Γ . The discrepancy is a result of Dancoff's transition from the actual measurements to the resonance integral, this transition being based on data that is now obsolete.

The activation cross section of sodium around the 3 kev resonance is usually assumed to be given by the Breit-Wigner one-level formula, with the following parameters: $E_0 = 2.9$ kev, $\sigma_0 \Gamma = 12 \times 10^4$ ev-barns, $\Gamma = 220$ ev, $\Gamma_\gamma = 0.41$ ev.¹ The contribution of this resonance to the resonance activation integral $\int \sigma_\gamma dE/E$ is approximately

$$\frac{\sigma_0 \Gamma \Gamma_\gamma}{4 E_0} \int \frac{dE}{(E-E_0)^2 + (\frac{1}{2} \Gamma)^2} = \frac{12 \times 10^4 \times 0.4}{2 \times 2900 \times 220} \frac{\Gamma}{2} \int_{-\infty}^{\infty} \frac{dx}{x^2 + (\frac{1}{2} \Gamma)^2} = 0.0378\pi$$

$$= 0.12b.$$

The value of Γ_γ and hence the value of the contribution to the integral are not directly measured values. The Γ_γ is inferred from the assumed shape

1. J. S. Levin and D. J. Hughes, Phys. Rev. 101, 1334-1335 (1956).

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of Breit-Wigner σ_γ -curve and the known thermal σ_γ . On the other hand, there exists an experimental measurement of the contribution of the resonance to $\int \sigma_\gamma dE/E$,² and this measurement seemed to yield 0.051 barns, less than half the theoretical value.

The measurement is about 10 years old, and it will be shown in the following, that the actual observations, counts per minute of the activated sodium sample, are quite consistent with the now commonly assumed Γ_γ -values described in the first paragraph of this memo. The interpretation of these actual observations was based on data which are now known to be obsolete, and this is the reason why the old paper finds a low contribution of the resonance to $\int \sigma_\gamma dE/E$.

The experiment consisted essentially in letting a thin, collimated beam of thermal and 1/E neutrons impinge on various thicknesses of " B^{10} " discs, and then on the sodium sample. The B^{10} discs deplete the beam mostly by absorption; the thicker the discs, the more the low energy neutrons get depleted, absolutely and relatively to the high energy neutrons. However, there is also a certain depletion of the beam due to the scattering which also causes the neutrons to leave the beam. The thicker the discs, the more neutrons of all energies get depleted by scattering. Hence, a scattering correction is applied, that is, the actual counts per minute of the sample are divided by $e^{-B\sigma_s}$, where B is the number of B^{10} atoms/cm² of the disc, and σ_s is the scattering cross section per B^{10} atom.

The discs were 28.7% by weight boron, and 71.3% by weight lead. The boron contained 82% B^{10} . The atomic weight of the boron must then have been 10.2, compared to the atomic weight of lead of 207.2. Thus, the ratio of the number of B atoms to the number of lead atoms was $(28.7/10.2)/(71.3/207.2) = 8.18$. For every B^{10} atom, there were $18/82 = 0.219$ B^{11} atoms and $1/(8.18 \times 0.82) = 0.149$ lead atoms. Taking, from BNL 325, the scattering cross sections of B^{10} , B^{11} and lead to be 4, 4.4 and 11.4, respectively, we obtain

$$\sigma_s = 4 + 4.4 \times 0.219 + 11.4 \times 0.149 = 6.66 \text{ barns.}$$

2. S. N. Dancoff et al., CR-3781 (May 6, 1947).

Dancoff et al. assumed $\sigma_g = 4.9$ barns and, hence, underestimated the scattering correction, in particular for larger disc thicknesses. The corrected activation was thus underestimated, especially for the thicker discs, corresponding to higher energy neutrons. This seems to be main reason why the 1947 paper arrives at too low an activation at high energies.

Table 1 lists the scattering correction for the various discs. The "equivalent g/cm² B¹⁰" is taken from Column 5, Table 1, p 5, of Ref. 2, and the scattering correction (Dancoff) is taken from Column 6 of the same table. The scattering correction, computed in this memo, is listed in Column 3 of our Table 1. Included in this table are values corresponding to the actual discs, as well as values corresponding to the use of several discs "in series" since the latter arrangement was also used in the experiments. Where several discs are used, the correction is the product of the corrections belonging to individual discs. Columns 4 and 5 of our Table 1 are derived from saturated activities, as given by Dancoff et al., in Table 3, Column 3 of their paper. These saturated activities were divided by scattering correction; the correction listed in Column 2 of our Table 1 being used to obtain our Column 4, and the corrections listed in Column 3 being used to give Column 5.

The activation of the sodium sample would be proportional to

$$A = \int \sigma_{\gamma} e^{-Bk/\sqrt{E}} dE/E,$$

if the thermal neutrons are filtered from the beam, and the depletion of the beam by scattering is corrected for, as discussed above.

B is the g/cm² B¹⁰, interposed between neutron source and sodium sample, and $k/\sqrt{E}$ is the microscopic absorption cross section of B¹⁰, multiplied by the number of B¹⁰ atoms/g. ($k = \sqrt{0.0253} \times 4010 \times 10^{-24} \times 0.6 \times 10^{24}/10 = 38.3$; this value is slightly different from the value 36.3, assumed by Dancoff et al. on the basis of old data.)

Now

$$\sigma_{\gamma} = \frac{1}{4} \sigma_0 \left(\frac{E_0}{E} \right)^{1/2} \frac{\Gamma_n \Gamma_{\gamma}}{(E-E_0)^2 + \left(\frac{1}{2} \Gamma \right)^2},$$

TABLE I

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8
Equivalent $\text{g/cm}^2 \text{ B}^{10}$	Scattering Correction		Saturated Activities $\times 10^{-3}$ Corrected		Activation $\times 10^{-3}$ according to Hughes and Levin		
	(Dancoff)	(This Memo)	(Dancoff)	(This Memo)	1/V Contribution	Contribution 3 Kev Resonance	Total
0.1479	0.957	0.942	8.93	9.08	1.501	5.896	7.397
0.3149	0.912	0.882	6.01	6.21	0.705	5.236	5.941
0.4628	0.873	0.831	5.06	5.32	0.480	4.713	5.193
0.6280	0.832	0.778	4.35	4.65	0.354	4.191	4.545
0.7832	0.789	0.731	3.87	4.17	0.283	3.753	4.036
0.9484	0.751	0.684	3.25	3.57	0.234	3.337	3.571
1.267	0.689	0.603	2.66	3.03	0.175	2.661	2.836
1.586	0.628	0.532	1.75	2.07	0.140	2.121	2.261
2.050	0.544	0.441	1.35	1.67	0.108	1.525	1.633
2.530	0.472	0.364	1.35	1.74	0.088	1.084	1.172

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and this is, as usual, broken up into a component $\sigma_{\gamma 1}$ which accounts for almost all of the cross section for $E \ll E_0$, and a component $\sigma_{\gamma 2}$ which is responsible for the cross section near the resonance $E_0/E \sim 1$. With the parameter given at the beginning of this memo:

$$\sigma_{\gamma 1} = \frac{1}{4} \frac{\sigma_0 \Gamma_n}{E_0^{3/2}} \Gamma_\gamma \frac{1}{\sqrt{E}} = \frac{12 \times 10^4 \times 0.41}{4 \times 2900^{3/2}} \frac{1}{\sqrt{E}} = \frac{0.0787}{\sqrt{E}}$$

$$\sigma_{\gamma 2} = \frac{1}{4} \sigma_0 \Gamma_n \Gamma_\gamma \frac{1}{x^2 + (\frac{1}{2} \Gamma)^2} = \frac{12 \times 10^4 \times 0.41}{2 \times 220} \times 110 \frac{1}{x^2 + 110^2} = 112 \frac{110}{x^2 + 110^2}$$

Hence

$$A = 0.0787 \int_{E_2}^{\infty} \frac{dE}{E^{3/2}} e^{-38.3 B/\sqrt{E}} + \frac{112}{2900} e^{-38.3 B/\sqrt{2900}} \int_{-\infty}^{\infty} dx \frac{110}{x^2 + 110^2}$$

Here, E_2 is the lowest energy of neutron, which still appreciably penetrates to the disc. As will be seen shortly, the exact value of this energy is irrelevant. In the second integrand, the lower limit should be $-E_0$, but no appreciable error is introduced by integrating from $-\infty$. The first term is evaluated by setting

$$y = \frac{1}{\sqrt{E}}, \quad -2dy = \frac{dE}{E^{3/2}}$$

In the second, the integral is equal to π

$$A = \frac{0.0787 \cdot \pi}{38.3 B} (1 - e^{-38.3 B/\sqrt{E_2}}) + 0.121 e^{-0.711 B}$$

Even for the lowest values of B , given in the table, the exponential in the bracket is practically zero, if E_0 is anywhere near thermal energy. Hence, this exponential can be neglected, and the first term reduces to $0.00410/B$. Since the activation is not determined absolutely we may normalize A so that it coincides with the measured value at one point, say at $0.9484 \text{ g/cm}^2 \text{ B}^{10}$.

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SATURATED ACTIVITY

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$g/cm^2 B^{10}$

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Thus, we write

$$A = \frac{222}{B} + 6550 e^{-0.711B}.$$

Columns 6, 7 and 8 of Table 1 give the activation to be expected from the above equation. Column 6 lists the first term, which represents the $1/V$ contribution and Column 7 lists the second term, which is due to the 3 Kev resonance. The sum of these two terms is listed in Column 8.

The values of the Column 8 that is activation to be expected on the basis of the Hughes and Levin data, is plotted in Fig. 1. The dots in Fig. 1 are values of Column 5, that is the activation derived from the data of Dancoff et al., by proper application of the scattering correction. It can be seen that the dots and the curve coincide fairly well, except at the thermal and the high energy end. Neither of these deviations could be explained by a different value of the contribution of the resonance to the activation. The low energy deviation is probably due to incomplete filtering out of the thermal neutrons and the high energy deviation is probably caused by such processes as multiple neutron scattering, which are not considered in the analysis but become increasingly important as the B^{10} becomes thicker and the neutron attenuation increases. In the middle of the graph, where the agreement is good there is a slight hint that the activation based on Dancoff's experimental data drops off faster with increasing " $\text{g/cm}^2 B^{10}$ " than the computed curve. This would indicate that the contribution from the resonance was not observed quite in full, which could be explained on the basis of self protection of the resonance.