On the Variation in Scattering and Absorption Cross Sections with Resonance Neutron Energy, II.

By Motoharu Kimura.

(Read Dec. 19, 1942.)

Abstracts.*

The scattering and absorption cross sections of Mn, Br, I, Ag, Cu, As, W etc. were measured for various resonance neutrons by the same method as described in the previous paper (K1). Unexpectedly large changes in the scattering c.s. with neutron energies were found for all scatterers examined and the following general rules were found. (A) The scattering c.s. shows a maximum for the neutron energies corresponding to resonance absorption levels. (B) It does not increase, however, corresponding to the 1 - e increase of absorption near the thermal energies. (C) It has larger values in the high energy side of a resonance level than in the low energy side. That is, it jumps up to higher values when the neutron energy increases beyond the resonance level of the scattering nucleus. (D) The scattering c.s. for the nuclei which have no resonance level remains constant or decreases gradually with increasing neutron energies.

The minimum of the scattering cross sections as predicted by the dispersion formula based on the Bohr's theory of compound nucleus was not found.

It was confirmed that W has two resonance levels at the energies near “A” and “I” levels, Co near “D” and “I” levels, As near “I”, and Cu between “Br” and “Mn” levels respectively.

1. Introduction and Experimental Procedure.

In continuation to the previous experiment (K1), the scattering and absorption c.s. measurements for various resonance neutrons were extended to other substances. The measurements were performed for the two sorts of scattering nuclei. (A) The nuclei which were used as the resonance detectors. Various circumstances limited the measurements only to four nuclei, viz. to Mn, Br(NaBr), Ag, and I. (B) The nuclei which seem to have resonance absorption levels. Cu, As, Se, W, Mg, V(V₂O₅) were sorted out for this purposes. Determinations of the previous measurements were performed for Hg and Co scatterers.

When the absorption of neutrons in the scatterer is large, the ratio of the scattering c.s. of the substance to that of standard scatterer (carbon)
will be affected by the degree of absorption of the neutrons in the detectors. It is desirable, therefore, that the detectors are as thin as possible. Consequently, all the detectors except for that of "C" neutrons (In 0.0616 g/cm²) were reprepared in the present series of measurements. The thickness of the detectors was controlled to have 80%-90% transmission at exact resonance. Although the absorption in the detectors is still not negligible, the weakness of the neutron intensity prohibits the use of thinner detectors.

Table 1. Various resonance detectors used.

<table>
<thead>
<tr>
<th>Neutron group</th>
<th>Detectors used</th>
<th>Filters</th>
<th>Transmission at exact resonance</th>
<th>Resonance energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;C&quot;</td>
<td>0.0616 g/cm² In</td>
<td>54°</td>
<td>with and without Cd</td>
<td>95%</td>
</tr>
<tr>
<td>&quot;D₃&quot;</td>
<td>0.0135 g/cm² Rh</td>
<td>44°</td>
<td>Cd</td>
<td>85%</td>
</tr>
<tr>
<td>&quot;D₂&quot;</td>
<td>0.0048 g/cm² In</td>
<td>54°</td>
<td>Cd</td>
<td>75%</td>
</tr>
<tr>
<td>&quot;A&quot;</td>
<td>0.0118 g/cm² Ag</td>
<td>25°</td>
<td>Cd</td>
<td>65%</td>
</tr>
<tr>
<td>&quot;B&quot;</td>
<td>0.199 g/cm² Ag</td>
<td>23°</td>
<td>Cd + 0.424 g/cm² Ag</td>
<td>85%</td>
</tr>
<tr>
<td>&quot;B&quot; (&quot;B&quot;₄)</td>
<td>0.105 g/cm² Ag</td>
<td>23°</td>
<td>Cd + 0.2 g/cm² Ag</td>
<td>85%</td>
</tr>
<tr>
<td>&quot;Mn&quot;</td>
<td>0.13 g/cm² Mn</td>
<td>150°</td>
<td>Cd</td>
<td>83%</td>
</tr>
<tr>
<td>&quot;Br&quot;</td>
<td>0.22 g/cm² PbBr</td>
<td>18°</td>
<td>Cd</td>
<td>90%</td>
</tr>
<tr>
<td>&quot;I₃&quot;</td>
<td>0.12 g/cm² PbI₂</td>
<td>25°</td>
<td>Cd</td>
<td>90%</td>
</tr>
<tr>
<td>&quot;I₄&quot;</td>
<td>0.12 g/cm² PbI₄</td>
<td>23°</td>
<td>Cd + 0.32 g/cm² I</td>
<td>95%</td>
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</table>

† In the latter part of experiment, a thinner filter and detectors were used, and they were indicated by "B"₄ to avoid confusion.

All the detectors, 65×100 mm in area, were cut into four pieces of 65×25 mm and placed in a rectangular plate made of 0.5 mm Al sheet for the purpose of quick exposure and removal against the neutron source. The effect of the Al plate was negligible. After irradiation, they were fastened to the rectangular frame surrounding a Geiger-Müller counter.

All the other geometrical conditions and the measuring arrangements were the same as in (I) (K₁). Generally, those scattering substances in powdered form were contained in cases made of brass foils of 0.1 mm thick. The effect of the container was negligible. Iodine scatterers were made of powdered iodine element contained in glass cases of 0.4 mm wall thickness, which was the least thickness attainable. Very thin scatterers of the powdered from were also contained in the same glass cases. The effect of glass wall was corrected experimentally.

2. Experimental Results.

The increases of the back scattered neutrons as a function of the scatterer thickness are shown in Table 2 and plotted in Fig. 1 for several cases as an example.

For "B" neutrons, the apparent scattering c.s. depends upon the thickness of Ag filter used. The increase of apparent c.s. with the thickness of
Ag filter used can be understood if we consider the change in the angular distribution of the emerging neutrons with the filter thickness. The absorption of laterally emerging “B” neutrons in the filter will increase with the increasing thickness of the latter, and consequently the neutrons that perpendicularly shot into the scatterer will predominate. These considerations and the following calculations of Mr. Miyazima account for the increase of apparent scattering. Mr. Miyazima calculated the back scattering of shooting neutrons for various angular distribution and also for various ratios of scattering to absorption with the assumption that the absorption in the detectors is negligible. According to his result, the apparent scattering increases with the predominance of forward distribution of emerging neutrons as shown in Fig. 2. The similar circumstances exists for the cases of “I₁” and “I₂” neutrons.

Table 2. % increase of the back scattered neutrons.

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<th>Scatt. groups</th>
<th>“C”</th>
<th>“D₁”</th>
<th>“D₂”</th>
<th>“A”</th>
<th>“B”</th>
<th>“B₁”</th>
<th>“Mn”</th>
<th>“Br”</th>
<th>“I₁”</th>
<th>“I₂”</th>
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<tr>
<td>“C” “D₁” “D₂” “A” “B” “Mn” “Br” “I₁” “I₂”</td>
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</table>

Remarks. † see previous paper (I), (K1).
§ The upper glass plates of the reference (empty) scatterers were removed. This gives true values when the absorption of “I₁” neutrons in the scatterer is perfect, that is to the sufficiently thick scatterers.
The apparent scattering c.s.'s were obtained from the initial tangent of the scattering curves, and the true ones were deduced with reference to carbon as was performed in (I). The results were summarized in Table 3 and plotted in Fig. 3A, 3B, and 3C.
Fig. 1. Increase in the back scattered neutrons as a function of the scatterer thickness

Fig. 2. Theoretical back scattering Curves.
Fig. 3 A.

Fig. 3 B.

Fig. 3 C.
### Table 3. Scattering and absorption c.s.'s of various resonance neutrons for different substances in the unit of $10^{-24}$ cm$^2$

<table>
<thead>
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<th>Neutrons</th>
<th>( \sigma_t )</th>
<th>( \sigma_r )</th>
<th>( \sigma_i )</th>
<th>( \sigma_a )</th>
<th>( \sigma_s )</th>
<th>( \sigma_v )</th>
<th>( \sigma_m )</th>
<th>( \sigma_b )</th>
<th>( \sigma_{11} )</th>
<th>( \sigma_{12} )</th>
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<td>4.8 *10^{-24}</td>
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<tr>
<td>V(\delta) (V,(\delta))</td>
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</table>

**Remarks.**

* The figures in parenthesis are the apparent scattering c.s.'s, under which are listed the true c.s.'s computed with reference to carbon. The figures in italics are the absorption c.s.'s deduced from the curvature of the scattering curves by the same process as in (I).

* ) The saturation values of the reflected intensity were used for the calculation of scattering and absorption c.s.'s. See Table 4.

† ) Values for NaBr or \(\frac{1}{2}(\text{V}_2\text{O}_3)\) respectively. The effect of Na or O is subtracted assuming \(\sigma_{\text{Na}}=4.0 \times 10^{-24}\text{cm}^2\) \(\sigma_{\text{O}}=3.0 \times 10^{-24}\text{cm}^2\) for all resonance neutrons. It is very plausible that the scattering c.s.'s of Na and O are constant in the slow neutron region as they emit no \(\gamma\)-ray by slow neutron bombardment and seem to have no resonance level in this region.\[18\]

§ ) Data on \(\text{V}_2\text{O}_3\) are not accurate.
According to the calculation of Mr. Miyazima\(^{(M1)}\), the initial tangent is a little affected by the absorption c.s. of the scatterer. The effect, however, is very small and is within the limit of experimental errors both for $\cos \theta$ and $\cos^2 \theta$ distribution of emerging neutrons as shown in Fig. 2. The dependence of scattering c.s. on absorption was, therefore, neglected entirely.

It becomes difficult to draw the initial tangent of the scattering curve when a strong absorption exists in the scatterer. In these cases, (indicated by * in Table 3) the saturation values of the reflected intensity are more accurately measured than the inclination of the initial tangents.

Fortunately, we have rather accurate knowledge on the absorption c.s.'s in these cases. Thus, we can calculate the scattering c.s.'s with the help of the relationship computed by Miyazima\(^{(M1)}\) between the saturation values and the scattering to absorption ratio. The relationships are reproduced in Fig. 4 for two cases of $\cos \theta$ and $\cos^2 \theta$ distribution of the emerging neutrons. The figures in Table 3 for these cases (indicated by *) were calculated on the assumption of $\cos \theta + \sqrt{3} \cos^2 \theta$ distributions. The results of calculations are summarized in Table 4. The absorption c.s.'s, $\sigma_a'$ measured by previous workers\(^{(D1)(A1)(H1)}\) contain some effect of scattering. The contribution of the scattering to absorption in those measurements ($\sigma_a'$, column IV in Table 4) depends on their geometrical conditions, but was here assumed to be 60\% of $\sigma_s$, that is,

$$\sigma_a' = \sigma_a + 0.6 \sigma_s.$$
The scattering c.s.'s deduced from the initial tangent are listed also in table. The agreement of these values with those deduced from the saturation is generally satisfactory except for the case of Ag for "B" neutrons.1) The scattering c.s.'s of Mn for "Mn" neutrons, and of W for "I1" neutrons have the largest values ever known. The only comparable case is that of proton for "C" neutrons. The large c.s. of proton, however, is due to the equality in the mass of neutron and proton and to the effect of chemical binding of the latter. The nuclear scattering c.s. of proton is, however, less than 20×10⁻²⁴cm² (H2, Cl, S1, A3).

The sharp peak in the scattering c.s. of Co near the "D1" neutrons found in the previous measurements was verified in the present series of measurements. Redeterminations of the Hg scattering c.s. led to a smooth

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Table 4. Absorption and scattering c.s.'s calculated from the saturation values and from Fig. 4, utilizing the relation: \( \sigma_a = \sigma_s + 0.6 \sigma_s \) (in the unit of 10⁻²⁴cm²)

<table>
<thead>
<tr>
<th>Scatterers</th>
<th>Neutron groups</th>
<th>Sat. value of refl. int.</th>
<th>( \sigma_a' )</th>
<th>( N \left( \frac{\cos \theta}{\cos^2 \theta} \right) )</th>
<th>( \sigma_a \left( \frac{\cos \theta}{\cos^2 \theta} \right) )</th>
<th>( \sigma_s \left( \frac{\cos \theta}{\cos^2 \theta} \right) )</th>
<th>( \sigma_s \left( \cos \theta \right) )</th>
<th>( \sqrt{3} \cos^2 \theta )</th>
<th>( \sigma_s ) from init. tag.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl</td>
<td>&quot;C&quot;</td>
<td>12.5% 39(D1)</td>
<td>1.65 1.52</td>
<td>28 30</td>
<td>18 15.5 16.5</td>
<td>12.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Co</td>
<td>&quot;C&quot;</td>
<td>6% 35(D1)</td>
<td>1.27 1.22</td>
<td>30.9 30.8</td>
<td>8.2 7.0 7.5</td>
<td>8.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mn</td>
<td>&quot;C&quot;</td>
<td>5% 14.3(D1)</td>
<td>1.22 1.17</td>
<td>12.6 13.0</td>
<td>2.8 2.2 2.4</td>
<td>2.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ag</td>
<td>&quot;C&quot;</td>
<td>2.8% 55(D1)</td>
<td>1.12 1.08</td>
<td>51 53</td>
<td>6.1 4.2 4.9</td>
<td>4.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hg</td>
<td>&quot;C&quot;</td>
<td>3.3% 300(A1) (D1)</td>
<td>1.14 1.10</td>
<td>27.7 283</td>
<td>39 28 32</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>&quot;T&quot;</td>
<td>3.4% 80(A2)</td>
<td>1.15 1.12</td>
<td>74.4 74</td>
<td>11 9 10</td>
<td>11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ag</td>
<td>&quot;B&quot; ~16%</td>
<td>54(A1)</td>
<td>1.9 1.7</td>
<td>35 38</td>
<td>32 27 ~30</td>
<td>~5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mn</td>
<td>&quot;Mn&quot;</td>
<td>16% 72(H1)</td>
<td>1.9 1.7</td>
<td>47 50</td>
<td>42 36 38</td>
<td>43</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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1) As the Ag filter and Ag detectors used in "B" neutron measurement seemed to be too thick, redetermination was performed with thinner filter and detectors (listed as "B*" neutrons in Table 2 and 3). The back scattering curve obtained was similar as before. Both curves have rather small initial increase and very gradual approach to saturation. The scattering curves must reach the saturation at about 3g/cm² of the scatterer thickness, because the "B" neutrons have a mass absorption coefficient of 0.3cm²/g in Ag. It is strange that the back scattering curves obtained does not show perfect saturation even at the thickness of 6g/cm² Ag. The reliable value of scattering c.s. of Ag for "B" neutrons may only be determined in connection with the research on the structure of the "B" absorption level.
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3. Discussion of the Results.

Variations in scattering c.s.'s of Mn, Br, Ag, and I with the neutron energy (Fig. 3A) seem to point us the following facts: the scattering c.s. shows a maximum value for the neutrons of the energy at the exact resonance of absorption, and decreases towards both sides. It has larger values, however, for the neutron energies higher than the resonance levels than for those of lower energies; that is, it jumps up to higher values when the neutron energy increases beyond a resonance level of the scattering nucleus. Generally it seems that the c.s. decreases very slowly with increasing neutron energy when it is far from the resonance level.

Summarizing the previous and the present results, we may propose a schematic diagram on the general feature of the scattering c.s. as shown in Fig. 5. A nucleus whose c.s. has a large value and shows increase towards the zero neutron energy, such as Hg, must have a resonance level at a negative energy not far from zero. On the contrary, the nuclei which have small scattering c.s.'s such as Al may have resonance levels rather in the region of higher energies, and the c.s.'s may jump up to moderate values beyond such levels. The very irregular change from element to element of the scattering c.s. for thermal neutrons can naturally be understood if we consider the irregular distribution of the resonance levels possessed by various nuclei.

There is, however, no increase of the scattering c.s. corresponding to the 1/v increase of the absorption c.s.'s as already pointed out in (I).

An attempt to explain the above behaviour of the scattering c.s. based on Bethe's dispersion formula of compound nucleus(B1) has utterly failed

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Small scattering c.s.'s for "D_2" neutrons obtained in the previous measurement (I) are accounted for by the fact that the In detectors used were too thick (0.0359 g/cm² In) that it absorbed larger part of the neutrons at exact resonance. Moreover, the low energy part of the transmitted neutrons was strongly absorbed in Hg scatterers than the high energy part because of the rapid change of the absorption c.s. (proportional to 1/v^5) of Hg for slow neutrons. Thus the average energy of the scattered neutrons is higher than "D_2" resonance energy, and this accounts for the apparent small scattering c.s. as compared to that of "D_1" neutrons which was measured by thin Rh detectors.
excepting the case of Hg as shown in (I). An example of the results of the
calculation is shown in Fig. 3A for the case of Mn, whose $\Gamma$ and $\Gamma_n$ are
obtained using the data of Horvath and Salant\textsuperscript{(1)} on the absorption
coefficient. (see Appendix). The variation of scattering c.s. by neutron
energy is very small as already pointed out by Bethe\textsuperscript{(1)}, and is only of the
order of 1 50 of the experimentally found variation as seen in the figure.

The theory predicts a minimum of scattering for the neutron of the
energy lower than that of exact resonance by $\Gamma_n \approx 2R$. This is the natural
results of the dispersion-theoretical treatment of the nucleus. The absence
of this predicted minimum in the experiment is most clearly seen in the
case of iodine scatterer. It has as large a scattering c.s. for the "Br"
neutrons as for the "I", whereas the theory predicts a minimum for the
energy near the "Br" level.

Utilizing these rules, we can estimate the position of the resonance
absorption levels of any other substances by measuring the scattering c.s.
as a function of neutron energy. The measurements were performed for
many nuclei and the results are shown in Fig. 3B and 3C, which included
also the redeterminations on Co and Hg scatterers.

We can conclude from the figure that Cu must have a maximum
scattering c.s. at some point between the "Mn" and the "Br" levels and
at some point higher than the "I" level. Tungsten clearly shows two
jumps at about the "A" and the "I" neutrons. The curve of Co also
seems to point out the existence of two levels at near the "I" neutrons and
at some point lower than the "D" neutrons. It can be said that the above
behaviour of the scattering hold also for these cases. As Cu, As, and W
have weak induced activities, whose half value periods are 5, 25, and 23
respectively, it is very natural to attribute the above scattering maxima to
their resonance levels corresponding to these activities.

The resonance energies of Cu and As have been measured by Goldsmith
and Rasetti\textsuperscript{(1)} from the boron absorption coefficient with the results as
shown in Table 5. The relative position of levels for these nuclei is not
inconsistent with our results deduced from the scattering c.s. measurements.

Jaeckel\textsuperscript{(1)} measured the resonance energy of W with the results shown
in Table 6.

Jaeckel's results may probably be the mean value of the two levels
pointed out by our measurements, though he concluded in the non-existence

| Table 5. Resonance energies\textsuperscript{(1)} of various scatterers. |
|---------------|-----------------|-----------------|
| Rh 44$^\circ$  | (thermal)       | Cu 5             |
| Rh 44$^\circ$  | ($D_1$)         | Br 18$^m$        |
| Ag 23$^n$     | ($A_1$)         | I 25$^n$         |
| Mn 150$^n$    | ($Mn_1$)        | As 26$^n$        |
|               | 0.028eV         | 100eV            |
|               | 1.3 eV          | 180eV            |
|               | 3 eV            | 140eV            |
|               | 60 eV           | 150eV            |
of more than one level from the agreement of the absorption coefficient obtained by the two different thickness of boron absorber. The accuracy of his measurements, however, is not good enough for reaching such conclusions. The resultant boron absorption coefficients calculated by assuming two levels of appropriate intensity at the “A” and the “I₁”, show very small difference for the above two thickness of boron absorber, the difference being far less than the limit of Jaeckel’s experimental errors. The measurements of Horvath and Salant(H1) on the dependence of the boron absorption coefficient of iodine resonance neutrons upon the B absorber thickness also support our point of view. It is generally accepted that iodine has more than one level, and yet the variation of boron absorption coefficient is only of the order of several per cent corresponding to a variation in the thickness of boron absorbers of factor two, and of the order of 25% corresponding to a thickness variation of factor ten.

It is of no doubt that Co has absorption levels at near “D₁” and “I₁” neutron energies as pointed out in (I). Se and Mg have no level in the slow neutron region.

In conclusion, the author expresses his sincere thanks to Professor S. Nishikawa for his kind guidance and encouragement throughout this work. The author is much indebted to the Japanese Foundation for Cancer Research for supplying the radon necessary for this work through helpful interests of the late Dr. H. Yamakawa and Professor M. Miwa. The cooperation and assistance of Mr. Z. Morisima and K. Tukikawa in this work are highly appreciated. The author expresses his heartily thanks also to Professor H. Tominaga for supplying various materials necessary for this experiments and to Mr. I. Nonaka of the Tokyo Shibaura Electric Company, Matsuda Division for lending tungsten which was used as the scatterers.
Appendix. The calculation of Scattering c.s. for Mn from the absorption data.

The total natural width $\Gamma$ can be calculated from the following expression (B1, equation (538)):

$$\Gamma = 2E_r^{3/4}(kT)^{1/4}(K_n/K_r)^{1/2}$$  \hspace{1cm} (1)

and the Doppler broadening by the following:

$$\Delta = 2(mE_r/kT)^{1/2} = 0.168\text{eV}$$  \hspace{1cm} (2)

An approximate value of $\Gamma$ is obtained to be 2.92V by utilizing the data of Table 3, because the absorption c.s. of the Mn level in the Table 3 gives merely the absorption by the self indication. True natural width $\Gamma$ becomes to be 2.06V often the correction method of Bethe and Placzek (B2). The neutron width $\Gamma_N$ (including the factor $1 + \frac{1}{2i+1}$) is given as follows:

$$\left(1 + \frac{1}{2i+1}\right)\Gamma_N = \sigma_0 E_r \frac{1}{1.30 \times 10^{-18}} = 1.9 \times 10^{-3}\text{eV}$$  \hspace{1cm} (3)

Using these values, the scattering c.s.'s for Mn are calculated by the following expression given by Bethe (B1, (551)).

$$\sigma = 4\pi R^2 + \frac{3}{2} \chi \Gamma_N \frac{4R(E-E_r) + \chi \Gamma_N}{(E-E_r)^2 + \frac{\chi^2}{4}}$$  \hspace{1cm} (4)

The results are shown in Table 7 and plotted by a broken line in Fig. 3A.

<table>
<thead>
<tr>
<th>E (\text{eV})</th>
<th>0</th>
<th>10</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>20</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_0$ (\times 10^{-24}\text{cm}^2)</td>
<td>-0.05</td>
<td>-0.14</td>
<td>-0.29</td>
<td>-0.35</td>
<td>+0.03</td>
<td>+0.4</td>
<td>+0.3</td>
<td>+0.14</td>
<td>+0.05</td>
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<table>
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<th>Literature</th>
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<tbody>
<tr>
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<td>(G1) Goldsmith and Rasetti; Phys. Rev., 50 (1936) 328.</td>
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<tr>
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