Cross section of the reaction $^9\text{Be}(\gamma, n)$ near threshold

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Six kinds of radioisotopes were used to measure cross sections of the $^9\text{Be}(\gamma, n)$ reaction near its threshold. The results obtained were $0.88 \pm 0.16, 1.33 \pm 0.24, 1.10 \pm 0.20, 0.73 \pm 0.13, 0.47 \pm 0.09$, and $0.18 \pm 0.04 \text{ mb}$ at $1674.7, 1705.2, 1724.9, 1778.9, 1836.0$, and $2167.6 \text{ keV}$, respectively. The cross sections measured show a sharp peak near the threshold, and its width is narrower than that observed by Jakobson with Bremsstrahlung X-rays. Comparison of the present results with theories based on the valence neutron model indicates that the agreement is only qualitative.

On a utilisé six sortes de radioisotopes pour mesurer les sections efficaces de la réaction $^9\text{Be}(\gamma, n)$ près de son seuil. Les résultats obtenus sont $0.88 \pm 0.16, 1.33 \pm 0.24, 1.10 \pm 0.20, 0.73 \pm 0.13, 0.47 \pm 0.09$ et $0.18 \pm 0.04 \text{ mb}$ à $1674.7, 1705.2, 1724.9, 1778.9, 1836.0$, et $2167.6 \text{ keV}$, respectivement. Les sections efficaces mesurées présentent un pic prononcé au voisinage du seuil, et la largeur de ce pic est plus étroite que celle qu’a observée Jakobson avec des rayons X de freinage. La comparaison de ces résultats avec les théories basées sur le modèle du neutron de valence indique que l’accord est seulement qualitatif.

1. Introduction

The nucleus $^9\text{Be}$ has an unusually low threshold energy for the $(\gamma, n)$ reaction, viz. $1666 \text{ keV}$, and because of this characteristic, beryllium can be used to make a convenient monoenergetic neutron source in combination with an appropriate radioisotope. Since the characteristic is intimately related to the picture that $^9\text{Be}$ consists of a core $^7\text{Be}$ and a last neutron loosely bound to a potential attributable to the core, accurate measurements of the cross section near the threshold are important not only for quantitative applications of this reaction, but also for the investigation of the nuclear structure of $^9\text{Be}$. There are some early measurements with radioisotopes of the $^9\text{Be}(\gamma, n)$ reaction (1-3), when, however, our knowledge of the radioisotopes was deficient. Jakobson (4) measured an excitation function ranging from threshold to about $5 \text{ MeV}$ with Bremsstrahlung X-rays from a linear accelerator, but it seems that the energy resolution and accuracy were insufficient. Also with Bremsstrahlung X-rays, Berman et al. (5) measured cross sections near the threshold, but the measurements were only relative.

Measurements with radioisotopes have two important advantages: (a) the energy resolution is much higher than measurements with Bremsstrahlung X-rays, and (b) the incident photon flux can be measured fairly accurately. Hence it is worthwhile to perform careful measurements of the cross section with radioisotopes using the current knowledge of them and improved instruments. This paper describes measurements of cross sections near the threshold at six energies.

2. Method

Figure 1 shows the experimental arrangement of the present measurements. A $\gamma$-ray source S is placed at the center of the beryllium target, whose shape is a hollow cylinder $6 \text{ cm}$ in outer diameter by $6 \text{ cm}$ high, with walls of $1 \text{ cm}$ thickness. The neutrons generated by the $^9\text{Be}(\gamma, n)$ reaction are measured by four BF$_3$ counters embedded in paraffin. The efficiency of the BF$_3$ counter used is nominally $5 \text{.0 c/nu}$ for thermal neutrons. The exterior of the neutron detector is covered with cadmium sheets, $0.5 \text{ mm}$ thick, in order to minimize the reentry of slow neutrons scattered from the surroundings. Table 1 shows the $\gamma$-ray sources used and nuclear data (6) relevant to the present measurements: in the 3rd column is shown the energy $E_{\gamma}$ of the $\gamma$-ray participating in the reaction, in the 4th column the emission rate $\delta$ of the $\gamma$-ray, and in the 5th column the energy $E_n$ of the neutrons being generated. In the case of $^{103}\text{Ru}$, $\gamma$-rays of $1698.1$ and $1721.4 \text{ keV}$ participate in the reaction; the emission rates are $0.0784$ and $0.0346\%$ respectively. The $\gamma$-ray energy is regarded here as the weighted average, viz. $1705.2 \text{ keV}$, with an emission rate of $0.113\%$. The $^{57}\text{Co}$ and $^{85}\text{Y}$ sources were supplied from The Radiochemical Centre, Amersham (RCC) and the others were made by irradiating high purity samples in a reactor.

The cross section $\sigma(E_{\gamma})$ is approximately given by
where \( C(S) \) is the counting rate of neutrons due to the source \( S \), \( I(S) \) the source intensity (Becquerels), \( \varepsilon(E_n) \) the efficiency of the neutron detector, and \( K \) a constant which depends only upon the shape of the Be-target. Supposing the Be-target to be a hollow cylinder of dimensions of 5 cm \( \phi \times 5 \) cm with very thin walls, we can estimate \( K = 37.5N \) from a simple calculation, \( N \) being the number of \(^{10}\text{Be} \) nuclei in the actual target. In [2.1] the effect of Compton-scattered \( \gamma \)-rays was neglected because, for the 1674.7 keV \( \gamma \)-ray of \(^{57}\text{Co} \), the lowest energy among the \( \gamma \)-rays used, the scattering mean free path (SMFP) in beryllium is calculated according to the Klein–Nishina formula to be about 16.3 cm, which is much larger than the thickness (1 cm) of the Be-target. \( I(S) \) is measured as described in the next section. \( \varepsilon(E_n) \) is read from an efficiency curve which is derived by normalizing a calculated curve at \( E_n = 262 \) keV with a \(^{24}\text{Na}–\text{D}_{2}O \) neutron source.

3. Measurements

3.1 Intensity \( I(S) \) of source

The source intensity at the time of commencement of measuring the \(^{9}\text{Be} \left( \gamma, n \right) \) reaction was estimated from the intensity measured at a later time, when the activity of the source has decayed down to the order of \( 10^5 \) Bq, with a Ge(Li) detector. Efficiencies of the Ge(Li) detector were measured with standard sources of \(^{133}\text{Ba} \), \(^{137}\text{Cs} \), \(^{56}\text{Mn} \), \(^{60}\text{Co} \), and \(^{88}\text{Y} \), which were supplied by RCC. Their absolute intensities have been guaranteed within \( \pm 6\% \). The resultant error of the efficiency thus measured was \( \pm 8\% \) at most, which consists of the standard deviation of the mean value for five measurements of the peak area and the maximum error \( \pm 6\% \) of the standard sources. The photo peaks of the following \( \gamma \)-rays and the corresponding emission rates were adopted to estimate \( I(S) \): \(^{57}\text{Co} \) (810.8 keV, 99.44\%), \(^{109}\text{Ru} \) (724.2, 48.1), \(^{60}\text{Ni} \) (1481.4, 23.58), \(^{28}\text{Al} \) (1778.9, 100), \(^{88}\text{Y} \) (898.0, 91.36), \(^{32}\text{Cl} \) (1642.2, 31.03). Each peak area was successively measured five times to get the mean value, a correction for the half-life being applied when necessary. The measured results of \( I(S) \) are shown in the 2nd column of Table 2, where the errors attached consist of the standard deviations of the mean values of the peak areas and the maximum error \( \pm 8\% \) of the Ge(Li)-detector efficiency.

3.2 Counting rate \( C(S) \) of neutrons

Neutrons were measured with the apparatus shown in Fig. 1 in a room made of concrete 100 cm thick. Backgrounds were measured by replacing the Be-target with a graphite target of the same dimensions. The reasons for using graphite are: (a) its density is near that of beryllium, and accordingly the effects of the \( \gamma \)-rays can approximately be considered the same, and (b) the \(^{12,13}\text{C} \left( \gamma, n \right) \) reactions cannot be caused by any sources used, since the threshold energies are 18.717 MeV for \(^{12}\text{C} \) and 4.948 MeV for \(^{13}\text{C} \). The background was measured to be 38 \( \pm 3 \) counts per 5 min for all sources, where the error attached is the standard deviation of the mean value for twenty measurements (hereafter errors shown denote the standard deviations of the mean values, unless otherwise noted). As to natural backgrounds, counting rates measured without the source in the Be- and C-target were \( \text{BG(Be)} = 39 \pm 2 \) per 5 min and \( \text{BG(C)} = 38 \pm 2 \) per 5 min, respectively, and accordingly the effects of the \( \gamma \)-rays from the sur-
The gamma-ray sources and nuclear data relevant to the present measurements are shown in Table 1. The measurements of source intensities and neutron counts are shown in Table 2.

### Table 1. Gamma-ray sources and nuclear data relevant to the present measurements

<table>
<thead>
<tr>
<th>S</th>
<th>(T_{1/2})</th>
<th>(E_{\gamma}) (keV)</th>
<th>(\delta(E_{\gamma})) (%)</th>
<th>(E_n) (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{58}\text{Co})</td>
<td>70.8 days</td>
<td>1674.7</td>
<td>0.53</td>
<td>8</td>
</tr>
<tr>
<td>(^{103}\text{Ru})</td>
<td>4.44 h</td>
<td>1705.2</td>
<td>0.113</td>
<td>34</td>
</tr>
<tr>
<td>(^{60}\text{Ni})</td>
<td>2.52 h</td>
<td>1724.9</td>
<td>0.39</td>
<td>52</td>
</tr>
<tr>
<td>(^{38}\text{Al})</td>
<td>2.24 min</td>
<td>1778.9</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>(^{88}\text{Y})</td>
<td>106.6 days</td>
<td>1836.0</td>
<td>99.34</td>
<td>152</td>
</tr>
<tr>
<td>(^{38}\text{Cl})</td>
<td>37.14 min</td>
<td>2167.6</td>
<td>42.4</td>
<td>446</td>
</tr>
</tbody>
</table>

### Table 2. Measured results of source intensities and neutron counts

<table>
<thead>
<tr>
<th>S</th>
<th>(I(S)) (MBq)</th>
<th>(C(S)) (counting period)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{58}\text{Co})</td>
<td>(34.21 \pm 3.22)</td>
<td>(713 \pm 6) (5 min)</td>
</tr>
<tr>
<td>(^{103}\text{Ru})</td>
<td>(18.82 \pm 1.56)</td>
<td>(121 \pm 3) (5 min)</td>
</tr>
<tr>
<td>(^{60}\text{Ni})</td>
<td>(19.15 \pm 1.72)</td>
<td>(345 \pm 4) (5 min)</td>
</tr>
<tr>
<td>(^{28}\text{Si})</td>
<td>(6.22 \pm 0.60)</td>
<td>(1861 \pm 13) (30 s)</td>
</tr>
<tr>
<td>(^{88}\text{Y})</td>
<td>(1.12 \pm 0.13)</td>
<td>(2104 \pm 11) (5 min)</td>
</tr>
<tr>
<td>(^{38}\text{Cl})</td>
<td>(8.11 \pm 0.96)</td>
<td>(2343 \pm 12) (5 min)</td>
</tr>
</tbody>
</table>

The natural background effects of the 1836 keV gamma-rays from the sources do not affect the measurements. They were then normalized to the efficiency measured with a standard source. The decrease of the 1836 keV gamma-ray, as will be seen later in Fig. 3, with these considerations, the effects of those gamma-rays on the neutron detector were considered negligible, since their SMFP in heavy water is about 3 cm, while the radius of the source was 0.85 cm. The neutron yield of the \(^{24}\text{Na-D}_2\text{O}\) source was measured by the water bath method (7), in which a small BF\(_3\) counter with an effective volume of about 1 cm\(^3\) was used to measure thermal neutron distribution in a water bath 100 cm in diameter and 100 cm high. The absolute efficiency of this BF\(_3\) counter for thermal neutrons was calibrated in a standard graphite pile of the Electrotechnical Laboratory (8). The rate of the neutron yield thus measured was \((4.87 \pm 0.34) \times 10^7\) n/s/4\(\pi\). The error attached consists of a 2% error in the absolute efficiency of the BF\(_3\) counter and a 5% error in the thermal neutron measurements. The counting rate for the \(^{24}\text{Na-D}_2\text{O}\) source installed at the center of the cylindrical paraffin wall, 6 cm in diameter and 6 cm high, was 3.00 \pm 0.03 \times 10^7\) cpm, from which the efficiency for the 262 keV neutrons was determined as

\[
\epsilon(262) = (9.2 \pm 0.7) \times 10^{-2}
\]

Besides the 2754 keV gamma-ray, a gamma-ray of 3867 keV energy is emitted from \(^{24}\text{Na}\) with an emission rate of 0.06%, by which 817 keV neutrons are generated from the \(^{3}\text{Be}(\gamma, n)\) reaction. However, the emission ratio \((3867)\sigma(3867)/(2754)\sigma(2754)\) of the 817 keV neutrons to the 262 keV neutrons is estimated to be about 0.06% according to Hulthen–Nagle’s theoretical values (9) for the cross section of the reaction. Therefore, the effect of the 817 keV neutrons on \(\epsilon(262)\) can be neglected. In the actual geometry used for the \(^{3}\text{Be}(\gamma, n)\) reaction, neutrons are not emitted from a point-like source, but from the cylindrical Be-target. However, the gamma-ray flux incident upon a unit area of the cylindrical paraffin wall of 5 cm \(\times\) 5 cm, to which neutron generation is proportional, depends upon the corresponding solid angle, which is nearly equal to the solid angle of the \(^{24}\text{Na-D}_2\text{O}\) neutrons impinging upon a unit area of the cylindrical paraffin wall of 6 cm \(\times\) 6 cm.
Therefore, the efficiency $\epsilon(262)$ measured above is considered approximately correct. Figure 3 shows the efficiency curve thus obtained. Necessary efficiencies were read from this curve, taking account of $\pm 8\%$ error due to $\epsilon(262)$.

4. Results and discussion

From the measured results described in Sect. 3, cross sections are calculated by $[2.1]$, and are shown in Table 3. Figure 4 shows a comparison of the present results (solid circles) with previous data (solid squares). Reference 1 is a measurement with a $^{129}$Sb source, in which only a lower limit of the cross section was estimated because only uncertain knowledge of $^{129}$Sb was then available. It is known today that $^{129}$Sb has a complex decay scheme and more than two kinds of $\gamma$-rays participate in the $^9$Be($\gamma$, n) reaction. In ref. 2 a $^{129}$Sb and $^{88}$Y source were used to measure $\sigma(1691)$ and $\sigma(1836)$, respectively. An emission rate $\delta(1691) = (50.6 \pm 2.5)\%$ was adopted to estimate $\sigma(1691)$, which agrees with a recent value, $\delta(1691) = 49.05\%$, within the error. As to the effect of the 2091 keV $\gamma$-ray, however, the correction remained approximate for lack of accurate data of $\sigma(2091)$. For $\sigma(1836)$ the effect of the 2734 keV $\gamma$-ray was corrected with $\delta(2734) = (0.5 \pm 0.3)\%$ and $\sigma(2754) = (0.674 \pm 0.054)$ mb due to the 2754 keV $\gamma$-ray of $^{24}$Na, while the effect has been estimated to be less than 0.6\% and neglected in the present measurements. However, correction of this effect in the present measurement would slightly enlarge the discrepancy between ref. 2 and the present result. Reference 3 is a measurement with $2185$ keV $\gamma$-ray of $^{144}$Pr. Correction of the nuclear data adopted there with recent data and correction of the $\gamma$-ray flux estimation cancel each other, resulting in little modification to their value. Accordingly, the discrepancy between ref. 3 and the presently measured $\sigma(2167.6)$ remains unexplained. The broken line in Fig. 4 shows...
the Jakobson's excitation function (4), which was measured by the photon difference method in 50 keV steps. The peak was given as $\sigma = 1.15$ mb at $E = 1.70$ MeV. The full width at half maximum (FWHM) of the peak is estimated to be about 150 keV.

For the practical purpose of estimating the cross section at an arbitrary energy around the threshold, an empirical equation of the following form has been fitted to the present results, though there is no theoretical basis for it.

\[
\sigma(E) = \frac{A_i(E_i - 1666)^{A_1}}{1 + A_3\sqrt{E - 1666} + A_4(E_i - 1666)}
\]

where $A_i (i = 1 \rightarrow 4)$ are constants to be determined by the method of least squares. A computer code based upon a modified Marquardt algorithm (10) was used to obtain the optimum values of $A_i$ shown in Table 4. The solid line in Fig. 4 represents the equation [4.1] with these constants, and the fitting seems very satisfactory. It is seen from the figure that the present results show a peak narrower than that observed by Jakobson. According to [4.1] the peak position and the FWHM are estimated to be $E_r = 1695$ keV and 100 keV, respectively. It is noted that the shape and the FWHM of the present peak are very similar to those of the energy spectrum of protons inelastically scattered from $^9\text{Be}$ (11); if the excitation of the first $1/2^+$ excited state of $^9\text{Be}$ is assumed to be independent of excitation mode, both peaks are expected to be similar.

On the basis of the valence neutron model, Guth and Mullin (12) calculated cross sections of the $^9\text{Be}(\gamma, n)$ reaction, regarding the ground state of $^9\text{Be}$ as $P_{3/2}$ and taking account of the $E1$-interaction as a first approxi-
The broken line in Fig. 5 shows their calculation for the $P \rightarrow S$ transition. The potential used was of square well type with radius $r_0 = 5$ fm and depth $V_r = 3$ MeV for the final $S$ state of the neutron. The FWHM of the peak is estimated to be about 300 keV, which is fairly broad in comparison with the present result of 100 keV. According to their theory, the cross section for the $P \rightarrow D$ transition becomes of considerable magnitude when the $\gamma$-ray energy exceeds 2000 keV, and consequently the discrepancy between the present measurement and the theory at $E_\gamma = 2170$ keV would be further increased by the $P \rightarrow D$ effect. When a value $r_0 = 3$ fm is adopted for the potential radius, a figure derived from the electron scattering experiment (13), the depth $V_r = 3$ MeV does not reproduce the trend of experimental results at all. The optimum value of $V_r$ for $r_0 = 3$ fm is estimated to be 7.3 MeV, which still seems unreasonably small. In order to consider the effect of the nuclear surface, Francis et al. (14) used a Woods-Saxon potential with $r_0 = 3$ fm, $V_r = 32$ MeV, and diffuseness $a = 1.2$ fm to calculate the $P \rightarrow S$ cross section. The dash-dot curve in Fig. 5 shows their calculation. It is seen that the agreement between the present results and the theory is still poor. When an experimental value $a = 0.8$ fm (15) is adopted for the diffuseness, their theory gives unreasonably large cross sections. Since the cluster effect would be considerable in the light nuclei, the discrepancy between the experiments and the theories might suggest a limit to the effectiveness of the valence neutron model. Salyers (16) developed a method of calculating the cross sections near the threshold on the basis of a cluster model, according to which the peak of the cross section has a modified Breit-Wigner form and is estimated to have the FWHM of about 110 keV.

5. Acknowledgements

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