FISSION CROSS SECTION OF $^{181}$Ta FOR PROTONS IN THE ENERGY RANGE 200–1000 MeV

V. I. Yurevich$^a$, V. A. Nikolaev$^b$, R. M. Yakovlev$^b$, I. B. Vorobiev$^b$

$^a$Joint Institute for Nuclear Research, Dubna
$^b$V. G. Khlopin Radium Institute, St. Petersburg, Russia

The experimental estimation of fission cross section of $^{181}$Ta for protons in the energy range 200–1000 MeV was carried out by method of solid-state nuclear track detectors based on 6-$\mu$m lavsan film. A comparison of the obtained data with the available experimental results is performed.

1. DATA PROCESSING

A probability of formation of registered fragments and residues in reactions of fragmentation and spallation of heavy nuclei, such as tantalum and lead, begins to grow rapidly with increasing proton energy in a range $E > 1.0$ GeV. At lower energies a dominating process is a reaction of fission, and the first two processes give only insignificant contribution to the

1E-mail: yurevich@sunhe.jinr.ru
number of the registered tracks. Also, from the experimental results it follows that in the
energy range 200–1000 MeV the reactions of fragmentation and spallation give lower number
of counts in SSNTDs for tantalum than for lighter nuclei, for example, for cadmium target.

In our measurements the assemblies target–SSNTD–target (T–D–T) were used. Thus, the
registered number of counts in SSNTD is a sum of contributions from the first and second
targets surrounding the SSNTD:

\[ N = N_F + N_B, \]

where \( N_F \) is the number of the registered tracks from nuclear fragments leaving the target
in forward direction (a direction of proton beam), and \( N_B \) is a contribution from nuclear
fragments emitted in back hemisphere. A registration of fission fragments is possible only
in a limited angular interval. Therefore, the measured number of fission fragments is only a
part of their total number \( N_{tot} \) emitted in a total solid angle. At \( E > 200 \) MeV the angular
distribution of fission fragments becomes close to isotropic in a center-of-mass system, which
in a laboratory system corresponds to the distribution extended forward because fission nuclei
have a momentum after \( p−A \) interactions [8]. In the case of thin target, whose thickness
is much less than average path length of fission fragments in the target, the critical angle
of registration of fission fragments by 6-\( \mu m \) lavsan SSNTD is 29°, which is equivalent to
registration in the angular intervals 0–61° and 119–180° by the assembly T–D–T [7]. It was
shown that the total number of fission events (or fission cross section) is proportional to the
number of the registered fission fragments in the specified angular intervals [7]. In our case
of thick fission targets, the value of the effective critical angle increases and the effective
width of the angular intervals becomes narrower in comparison with thin targets due to worse
registration characteristics of fission fragments leaving the target surfaces.

For estimation of the fission cross section of \(^{181}\)Ta for protons in the energy range 200–
1000 MeV the following assumptions were used:

1. Fission fragments leaving tantalum and lead targets have the same registration properties.
2. Kinematic characteristics of fission fragments are such that a magnitude of ratio \( N/N_{tot} \)
is energy-independent in the studied energy interval.
3. The contribution to the total number of counts from the nuclear fragments arising
in other processes is small in this energy range and can be taken into account by a small
correction.
4. The value of this correction can be estimated from results obtained for lighter targets
(we used cadmium) where the process of fission can be neglected in comparison with the
contribution from reactions of fragmentation and spallation.

The result of these assumptions is a proportionality of fission cross section value \( \sigma_f \)
to the measured number of counts \( N \) after a deduction of the correction on contribution
from other background processes \( \Delta N \). The value of the correction was accepted equal
to half of the number of counts of the assembly Cd–D–Cd with the same value of error
\( \Delta N = 0.5N_{Cd} \) ± 0.5\( N_{Cd} \).

The value of the fission cross section of \(^{181}\)Ta was determined with the help of the following relation:

\[ \sigma_{fTa}^{Ta}(E) = \frac{N^{*Ta}(E)}{N^{*Pb}(1000 \text{ MeV})} \sigma_{fPb}^{Pb}(1000 \text{ MeV}), \]

where

\[ N^{*Ta} = N^{Ta} − \frac{1}{2}N^{Cd} \quad \text{and} \quad N^{*Pb} = N^{Pb} − \frac{1}{2}N^{Cd}. \]
The fission cross section for a natural mix of lead isotopes at a proton energy of 1000 MeV was used for normalization of the results of our measurements. The fission cross section for $^{nat}$Pb in the energy range from hundreds of MeV to several GeV was investigated in [1, 4, 9, 10], and these experimental results are in good agreement. The evaluation [6] gives the value $\sigma_{Pb}^{f} = 133.8$ mb at $E = 1000$ MeV, which coincides with an average value found on the experimental data in the interval 600–3000 MeV. The error of this magnitude, apparently, does not exceed 10%.

For the assembly Pb–D–Pb and flux of 1-GeV protons of $10^{10}$, 15750 ± 2360 counts have been obtained in SSNTD, which corresponds to $N^{Pb} = 15515 ± 2327$.

A list of main errors for the value $N^{Ta}$ is shown in Table 1.

<table>
<thead>
<tr>
<th>Error</th>
<th>Value, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>3–5</td>
</tr>
<tr>
<td>Determination of number of counts $N$</td>
<td>12</td>
</tr>
<tr>
<td>Determination of proton flux</td>
<td>20</td>
</tr>
</tbody>
</table>

The values $N^{Ta}$, $\Delta N = 0.5 N^{Cd}$ and $\sigma_{Ta}^{f}$ obtained by the formula are given for seven energies of protons in Table 2.

<table>
<thead>
<tr>
<th>$E$, MeV</th>
<th>$N^{Ta}$</th>
<th>$\Delta N$</th>
<th>$\sigma_{Ta}^{f}$, mb</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>381 ± 90</td>
<td>22 ± 22</td>
<td>3.09 ± 0.98</td>
</tr>
<tr>
<td>300</td>
<td>633 ± 150</td>
<td>30 ± 30</td>
<td>5.20 ± 1.60</td>
</tr>
<tr>
<td>400</td>
<td>707 ± 168</td>
<td>35 ± 35</td>
<td>5.79 ± 1.78</td>
</tr>
<tr>
<td>500</td>
<td>701 ± 166</td>
<td>52 ± 52</td>
<td>5.59 ± 1.72</td>
</tr>
<tr>
<td>600</td>
<td>1401 ± 330</td>
<td>82 ± 82</td>
<td>11.37 ± 3.59</td>
</tr>
<tr>
<td>800</td>
<td>1517 ± 360</td>
<td>101 ± 101</td>
<td>12.21 ± 3.86</td>
</tr>
<tr>
<td>1000</td>
<td>2050 ± 480</td>
<td>235 ± 235</td>
<td>15.65 ± 5.40</td>
</tr>
</tbody>
</table>

2. DISCUSSION OF RESULTS

For comparison of our results with other data on fission cross section of $^{181}$Ta($p, f$), a set of available experimental results and the evaluation [6] are shown in figure. The fission cross section monotonically rises with increase in proton energy up to 1 GeV. There are no any experimental data at higher energies. Our results are in close agreement with the prediction [6] in all the energy range studied. Also, good agreement with the results [1] and [3] below 1 GeV is observed. However, there is a large discrepancy between our result and data [4] at 1 GeV, where we have obtained the value $\sigma_{Ta}^{f} = 15.65 ± 5.40$ mb and
the authors of [4] gave the magnitude $27.0 \pm 1.5$ mb. This discrepancy much exceeds the experimental errors.

Fission cross section of $^{181}$Ta for protons: ● — present work; △ — [1]; ◯, ▽ — [2]; ○ — [3]; ■ — [4]; curve — [6]

REFERENCES


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