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NEW RESULTS OF ABSOLUTE CROSS-SECTION MEASUREMENTS FOR THE HEAVY NUCLIDE FISSION INDUCED BY FAST NEUTRONS

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Abstract: Absolute measurements of the ^{238}U fission cross section at the neutron energy of 5.0 MeV have been carried out using the TCAP--technique.

The results of the ^{235}U fission cross section absolute measurements obtained earlier have been revised on the basis of both experimental measurements of the fission fragment detection efficiency and more precise determination of the fission foil areal densities as well as their nonuniformities.

(fission cross section, ^{235}U, ^{238}U, TCAP-method, fission fragment registration efficiency, fast neutrons fission)

Introduction

Within the scope of collaboration of the V.G.Khlopin Radium Institute, Leningrad, USSR, and the Technical University of Dresden, GDR, absolute measurements of the fast neutron induced fission cross sections for the most important reactor fuel nuclides are carried out starting since 1975.

To perform the measurements, the time correlated associated particle method (TCAPM) was realized for a number of the neutron energy spot points in the range from 2 to 20 MeV corresponding to all fission chances.

This paper presents the results of measurements for ^{235}U at the neutron energy of 5.0 MeV completed recently.

The TCAPM is one of the most precise methods which provides in principle a high accuracy of measurements. At the present time the main source of the systematic error is the fission fragment efficiency because the improvements of the TCAPM we have carried out made it possible to reduce essentially other components of the total uncertainty. Up to now the correction for this effect was obtained by calculations based on the White's recommendations /1/ both in earlier works and in the great majority of measurements carried out by other authors. Obvious disadvantages of this method forced us to perform a direct experimental determination of this correction for every fission foil used. Such measurements have been carried out for the whole set of the ^{235}U foils.

^{238}U Fission Cross Section Measurement

The method of measurement and experimental set-up were described in detail /2/. Since the ^{238}U fission cross section for 5.0 MeV neutrons is rather small, the neutron flux was increased and a set of 9 fission foils was used instead of that of 5 foils. The conditions of the measurements were optimized carefully taking into account quite a number of conflicting requirements.

In the end of optimization the main parameters chosen were as follows:

- neutron energy of 5.0 MeV (instead of 4.45 MeV in /2/) at a 6.4 MeV deuteron energy;
- the angle between incident deuterons and the registered associated helions amounted to 35.5°;
- the target to the associated particle detector distance was equal to 136 mm, with a 9 mm - detector aperture;
- the thickness of $(CD_2)_n$-target was decreased to 0.4mg/cm^2; the thermomechanical strength of the target was improved by fast electron irradiation;
- ΔE detector of the telescope was 13 μm thick, 9 mm in dia.; the thickness nonuniformity was less than 200 keV when measured with the aid of alpha-particles.

The background in AP-channel was from 0.5 to 2.0 per cent. A correlated background in the ionization chamber did not exceed 0.01 per cent.

The ^{238}U fission cross section was found to be $(0.542 \pm 0.011) \cdot 10^{-24}$cm^2. This value is in good agreement with the ENDF/B-V evaluation $(0.533 \cdot 10^{-24}$cm$^2)$, and is to be considered as preliminary one as well as all our results for ^{238}U obtained earlier. The final values will be obtained after an additional investigation of fission foils.

Fission Cross Section of ^{235}U

Additional analysis of the ^{235}U fission foil characteristics comprised

- new measurements of the fission foil masses,
- careful measurements of the nonuniformity of the foil areal density,
- experimental determination of the fission fragment detection efficiency.

The results of all the ^{235}U fission cross section measurements performed earlier at the neutron energy of 2.6 MeV /3/, 4.45 MeV /2/, 8.4 MeV /4/, 14.7 MeV /5/ and 18.8 MeV /2/ were then corrected on the basis of this analysis.

Fission foil masses

When the fission samples were assayed earlier, their areal densities were determined as averaged ones over the whole sample area. However, as the neutron cone profile measurements showed, the main part of the neutron cone, including 80 to 90 per cent of neutrons, occupied only a central part of the sample area with a diameter of about 10mm. Therefore, new measurements of the sample area density were carried out by alpha-scanning with a small aperture detector (a 4.174mm dia. diaphragm on the sample surface).

The following recommended half-lives were used to calculate the samples masses:

$T_{1/2}(^{234}U) = 2,446.10^5$ y /6/,
$T_{1/2}(^{235}U) = 7.037 \cdot 10^8$ y /6/,
$T_{1/2}(^{236}U) = 2.346 \cdot 10^7$ y /7/.

Total areal densities of sample sets used in 5 measurements mentioned are given in Table 1 in comparison with the former values.

Uniformity of areal densities

In our earlier papers /2-5/ the ^{235}U sample uniformity was estimated using two diaphragms 10 and 19mm in dia., which was found to be better than 1%. It was not analysed more accurately because the corrections for this effect were not introduced and nonuniformity was taken into account as a component of the total uncertainty. Then it was measured in detail by two ways:

- by a counting of alphas emitted from the sample surface limited by a 8 mm diameter diaphragm,
- by the method of Rutherford backscattering (RBS) of 1.7 MeV alphas from a Van-de-Graaf accelerator, the spot diameter being 3 mm /8/.

A spot in the sample center and 8 peripheral spots over 45° on the middle

Table 1. Total areal densities of ^{235}U foil sets

Neutron energy, MeV	Foil No.	Total areal density ($\mu g/cm^2$)		Difference, (per cent)
		New value	Former value	
2.6	IV,V	674.8(±0.99%)	678.1(±1.00%)	-0.50
4.45	I,II,IV,IX,X	1747.2(±0.72%)	1773.7(±0.93%)	-1.51
8.4	I,IV,V,VII,IX	1714.4(±0.82%)	1738.6(±0.96%)	-1.47
14.7	II	258.4(±0.70%)	256.7(±0.75%)	+0.64
18.8	I,II,IV,IX,X	1747.2(±0.72%)	1773.7(±0.93%)	-1.51

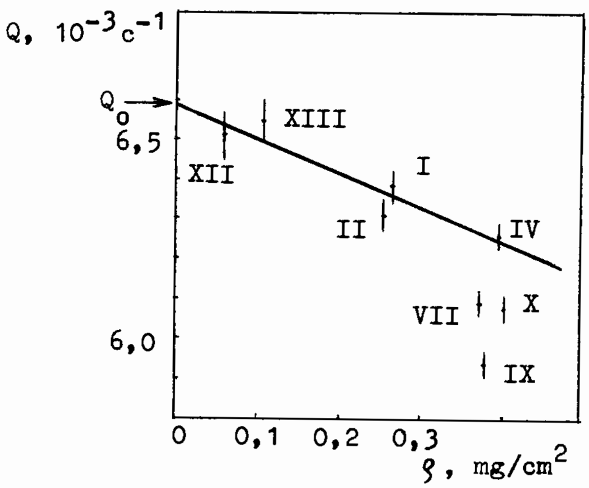

Fig.1 Fission counting rates in the ^{235}U samples related to their alpha-activities and to the neutron flux vs. sample areal densities

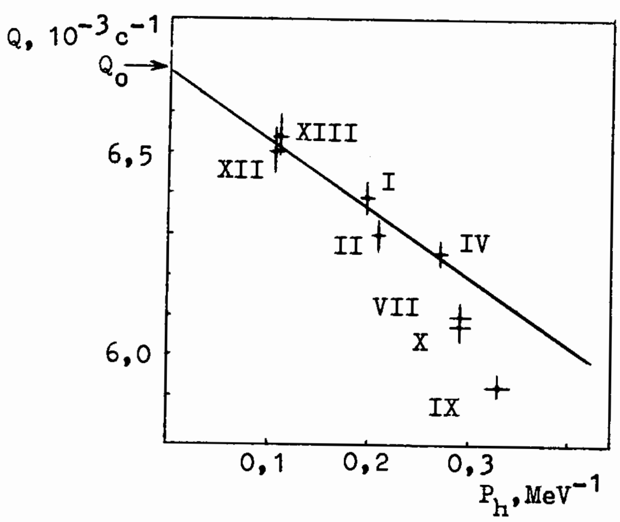

Fig.2 Fission counting rates in the ^{235}U samples related to their alpha-activities and to the neutron flux vs. heights of the fragment pulse-height spectrum plateau P_h

circle were measured /9/.

The results of various measurements confirm on the whole the nonuniformity to be less than 1%.

Fragment detection efficiency

Two methods were used to measure the fragment detection efficiency.

In the first one fission rates in the samples investigated related to their alpha-activities and to the neutron flux were measured vs. sample areal densities ρ (Fig.1) or vs. the heights of the fragment pulse-height spectrum plateau (Fig. 2) /10/. In this case the plateau height is assumed to be the ratio of an integral over the fragment pulse-height spectrum in the plateau region for a 1 MeV energy interval to an integral over the total spectrum area (in per cent). Calculations performed in Technical University showed this parameter to be in direct dependence on the fragment self-absorption in the sample layer.

In both cases the sets of experimental points were fitted by straight lines extrapolated either to zero areal density or zero plateau height. These extrapolated points corresponded to 100 per cent detection efficiency (all the fragments escape the layer). The correction value $\mathcal{E}_{abs}$ for i-th foil was calculated as follows

$$\mathcal{E}_{abs} = A_i - \mathcal{E}_{extr\ i},$$

where

$$A_i = \frac{Q_0 - Q_i}{Q_0}$$

$\mathcal{E}_{extr\ i}$ - is the correction for extrapolation to zero of fragment pulse-height spectrum for i-th foil.

The values of corrections obtained are given in Table 2.

The second method of the fragment detection efficiency determination was based on the fission rate measurements both in 2π-geometry ($N_{2\pi}$) and in a small solid angle (N_Ω). $N_{2\pi}$-values were corrected for extrapolation to zero of the fragment pulse-height distribution (N_{ex}). The solid angle Ω_{eff} was determined using a calibrated ^{252}Cf spontaneous fission source and was found to be 0.04554 with an uncertainty of 0.32%.

The corrections $\mathcal{E}_{abs}$ obtained using this method are given in Table 3.

As can be seen from Tables 2 and 3, the results of the correction determinations are in a rather good agreement besides those for VII, IX, X foils. These foils were prepared simultaneously, are of a worse layer quality and probably contain some impurities not observed in the α- counting. The weighted mean values of corrections are given in Table 4.

In this Table the effective fragment ranges R were calculated using fragment losses obtained $\mathcal{E}_{abs}$ according to White's expression $\mathcal{E} = \frac{t}{2R}$, where t is foil areal density in mg/cm^2.

The corrections obtained were measured using thermal neutrons. For the fast neutron induced fission these values were corrected for transfer velocity brought in by incident neutron and fission anisotropy according to a method proposed in /11/. The corrected values are given in Table 5.

Results of ^{235}U fission cross section measurements

In the upper part of Table 5 the fis-

Table 2. Corrections for fragment counting losses (per cent). First method.

Foil No.	Total losses below a threshold of 8.7 MeV: Based on $Q(\rho_0)$	Based on $Q(P_h)$	Correction for zero extrapolation	Correction for fragment losses due to self-absorbtion	
	A_a	A_d	$\mathcal{E}_{ex}$	$\mathcal{E}_{abs}$	$\Delta\mathcal{E}_{abs}$
I	3.41	5.04	1.75	2.49	1.05
II	4.18	5.89	1.82	3.22	1.06
IV	5.12	6.83	2.37	3.62	1.02
VII	7.48	9.08	2.53	5.77	1.04
IX	9.79	11.40	2.87	7.74	1.06
X	7.74	9.39	2.52	6.06	1.10
XII	1.09	2.86	0.94	1.04	1.31
XIII	1.44	2.77	0.96	1.15	1.23

Table 3. Corrections for fragment counting losses (per cent). Second method.

Foil No.	N_Ω	$N_{2\pi}$	N_{ex}	$\mathcal{E}_{abs}$,%	$\Delta\mathcal{E}_{abs}$,%
I	33374	700187	10451	3.03	0.68
II	63113	1326864	17968	3.05	0.56
IV	158918	3272255	67323	4.49	0.57
VII	146785	3034056	58777	4.22	0.56
IX	132928	2723232	66556	4.61	0.64
X	141445	2901770	64137	4.72	0.58
XII	65659	1429622	6729	0.38	0.51
XIII	61969	1337865	7308	1.16	0.52

Table 4. Weighted mean fragment counting losses obtained from the measurements made by two methods.

Foil No.	I	II	IV	VII	IX	X	XII	XIII
$\mathcal{E}_{abs}$, %	2.93	3.09	4.28	4.56	5.45	5.01	0.47	1.16
$\Delta\mathcal{E}_{abs}$,%	0.57	0.49	0.50	0.50	1.30	0.51	0.48	0.47
R, (mg/cm^2)	4.57	4.18	4.70	4.15	3.52	4.07	6.70	4.87

Table 5. Corrections and uncertainty components for ^{235}U fission cross section measurements (per cent).

Corrections and uncertainty components	Neutron energy (MeV)				
	2.56 /3/	4.45 /2/	8.46 /4/	14.7 /5/	18.8 /2/
I. Values published earlier					
Nonuniformity	±0.40	±0.72	±0.9	±0.50	±0.72
Cone geometry	0.25±0.05	0.05±0.05	0.15±0.05	±0.20	0.12±0.08
Statistics	±0.80	±1.26	±1.52	±0.46	±1.01
Random coincidences	8.47±0.45	1.40±0.17	7.46±0.55	3.00±0.10	2.82±0.21
Extrapol. to zero	1.36±0.35	1.18±0.26	2.25±0.67	0.50±0.10	1.67±0.16
Fragment absorbtion	2.11±0.30	2.00±0.85	1.97±0.30	0.28±0.20	1.73±0.78
AP-channel background	2.37±0.50	2.32±0.67	2.82±0.23	0.30±0.10	5.62±1.35
Neutron flux attenuation	0.97±0.25	0.25±0.40	0.23±0.40	2.50±0.30	0.44±0.40
Correlated background	-	-	-	-	1.72±0.04
σ_f (b)	1.215	1.057	1.801	2.085	1.999
$\Delta\sigma_f/\sigma_f$ (per cent)	1.53	2.10	2.29	1.18	2.25
II. New values					
Nonuniformity	±1.08	±1.02	±1.00	±0.29	±1.02
Fragment absorbtion	3.46±0.56	3.73±0.67	3.34±0.68	1.32±0.48	3.33±0.69
Cone geometry		0.00±0.00			0.00±0.00
Final σ_f (b)	1.238	1.093	1.853	2.094	2.065
$\Delta\sigma_f/\sigma_f$ (per cent)	1.94	2.07	2.34	1.09	2.37
σ_f ENDF/B-V (b)	1.263	1.115	1.782	2.101	1.958

sion cross sections as well as corrections and uncertainty components are given as obtained and published earlier. The new values obtained in this work are given in the lower part of Table 5. It can be seen that the former values and the new ones are in the error bar limits.

It should be emphasized in conclusion that a careful experimental determination of the fission fragment detection efficiency is a very important and necessary condition to provide a high accuracy and reliability of the fission cross section measurement results.

It is obvious now that the determination of fission detection efficiency by the calculation procedure we used earlier gave the underestimation of fragment losses. It is also clear that these corrections are to be determined experimentally for every target used.

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