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THE TOTAL CROSS SECTION AND THE FISSION CROSS SECTION OF ^{241}Am IN THE RESONANCE REGION. RESONANCE PARAMETERS.

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The ^{241}Am total and fission cross sections have been measured in the resonance region, using the 60 MeV Saclay linac as a pulsed neutron source. The resonance parameters obtained by a single level shape analysis of the transmission data are given for 189 levels up to 150 eV neutron energy. The mean level spacing, corrected for 18 % of missed resonances in the 0 to 50 eV energy range, is (0.55 ± 0.05) eV. The s-wave neutron strength function value, in the 0 to 150 eV energy range, is equal to $(0.94 \pm 0.09)10^{-4}$. The average radiation width obtained from 43 resonances is (43.77 ± 0.72) meV. Only preliminary results of the fission experiment are available now ; 38 fission widths are given up to 32 eV neutron energy, with the average value $\langle\Gamma_f\rangle$ = 0.23 meV ; the statistical distribution of these fission widths corresponds to a X^2 law with 4 degrees of freedom. An area analysis of the Los Alamos fission data[1] has also been done, from which we obtain 36 Γ_f values in the 20 eV to 50 eV energy range ; the corresponding average value is : $\langle\Gamma_f\rangle$ = 0.52 meV ; the statistiral distribution obeys to a X^2 law with 15 degrees of freedom, in desagreement with the Saclay results.

The Total Cross Section Measurement and Analysis

Experimental Conditions

The total cross section has been obtained up to 1 keV neutron energy from the transmission measurements of three sample thicknesses of americium oxyde : 0.18 g/cm^2 ; 0.63 g/cm^2 and (0.63 + 1.24) = 1.87 g/cm^2. Three series of measurement were performed : the first at a 17 m flight path and the others at a 53 m flight path. The main characteristics of each series are given in the table 1. The best nominal resolution achieved was 0.8 ns/m.

Table 1

Energy range (eV)	Channel width (ns)	Electron burst width (ns)	Flight path length (m)	Sample thickness (g/cm^2)
0.8-3.5	640			
3.5-8.8	320			0.18, 0.63 and 1.87
8.8-20	160	100	17.9	
20-27	80			
27-90	80	100	53.4	1.87
90-150				
150-1000	50	10	53.4	1.87

Method of Analysis

A shape analysis of the experimental data has been done up to 150 eV neutron energy by a least square fit (the code used is described in reference 2), which gives the energies, the neutron widths and the total widths of the resonances. In this shape analysis, the theoretical function is a sum of single level Breit-Wigner formulae broadened by a gaussian Doppler function and by a gaussian resolution. Such a formulation of the cross section gives a good representation of the resonance shape since the interferences in the fission channels are negligible (very small value of the fission widths). The Doppler width is taken equal to 0.0209 $\sqrt{E}$ (E energy of the incident neutron) with an accuracy better than 2 %. The parameters obtained by this analysis are given in table 2. In this table $\Delta(2g\Gamma_n)_1$ corresponds to the statistical error and $\Delta(2g\Gamma_n)_2$ to the systematic error due to the background evaluation ; $\Delta(\Gamma_\gamma)$ is a statistical error.

Level Spacings

A number of 189 resonances is identified in the 0 to 150 eV energy range (including the resonances at 0.308 eV and 0.576 eV)[3].

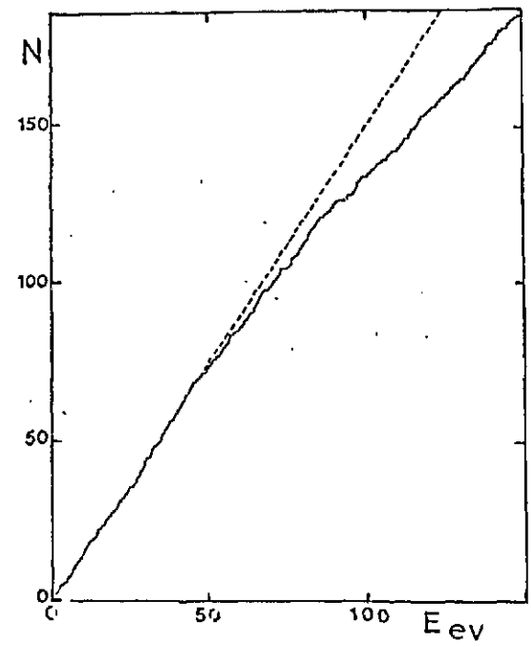

Fig. 1

Figure 1 shows the cumulative sum of the number of levels N versus the neutron energy E, in this energy range ; beyond 50 eV the variation of N is not linear ; there is a loss of resonances due to the increasing Doppler and resolution widths. So, a statistical study of the resonance parameters has to be limited to the 78 levels of the 0 to 50 eV energy range ; in this interval the observed mean spacing is equal to 0.65 eV.

Table 2

E (eV)	$2g\Gamma_n$ (meV)	$\Delta(2g\Gamma_n)_1$ (meV)	$\Delta(2g\Gamma_n)_2$ (meV)	Γ_γ (meV)	$\Delta\Gamma_\gamma$ (meV)
0.398	0.160	0.004			
0.576	0.075	0.007			
1.276	0.327	0.006	0.026	44.5	0.9
1.928	0.113	0.001	0.006	44.4	0.3
2.372	0.073	0.001	0.004	42.4	0.3
2.598	0.147	0.001	0.010	44.0	0.3
3.973	0.210	0.001	0.005	44.5	0.3
4.966	0.175	0.001	0.004	43.8	0.4
5.415	0.760	0.003	0.019	44.2	0.1
5.800	0.002				
6.117	0.124	0.001	0.002	43.8	0.7
6.745	0.024	0.001			
7.659	0.037	0.001			
8.173	0.108	0.001	0.001	42.7	1.2
9.113	0.369	0.002	0.009	44.2	0.6
9.651	0.406	0.002	0.009	43.9	0.6
10.114	0.026	0.001			
10.403	0.224	0.002	0.005	42.4	0.8
10.997	0.413	0.002	0.006	46.5	0.8
11.583	0.016	0.001			
12.137	0.007	0.001			
12.879	0.131	0.001	0.001		
13.874	0.012	0.001			
14.360	0.071	0.002	0.001		
14.682	2.482	0.011	0.075	40.3	0.5
15.689	0.244	0.003	0.003	39.3	2.9
16.398	1.277	0.005	0.034	41.5	0.9
16.849	0.646	0.004	0.012	41.2	1.5
17.729	0.391	0.004	0.006	37.3	2.4
18.167	0.017				
19.445	0.213	0.003	0.002		
20.333	0.034				
20.680	0.089	0.001			
21.740	0.081	0.003			
22.748	0.069	0.003			
23.079	0.417	0.012	0.005	42.2	4.0
23.337	0.445	0.012	0.006	42.5	5.8
24.192	1.304	0.017	0.028	39.2	1.5
25.008	0.014	0.001	0.001		
25.634	1.258	0.008	0.025	37.6	1.7
26.498	0.497	0.014	0.006	27.0	6.1
26.669	0.217	0.010	0.004		
27.575	0.165	0.021	0.002		
27.726	0.509	0.029	0.006	70.6	8.8
28.355	0.570	0.009	0.008	44.7	3.7
28.903	0.467	0.009	0.006	48.6	4.7
29.504	0.701	0.009	0.009	44.6	3.2
29.956	0.050				
30.822	0.150	0.010	0.002		
31.020	0.335	0.019	0.004		
31.251	0.996	0.019	0.015	42.6	4.2
32.030	0.300	0.010	0.003	47.4	8.6
33.510	0.060				
34.028	0.424	0.012	0.008	45.4	4.9
34.460	0.125	0.007			
34.928	0.612	0.012	0.006	42.9	5.4
35.445	0.427	0.012	0.004	50.5	8.1
36.220	0.167	0.007	0.001		
36.483	0.100				
36.979	2.995	0.017	0.075	52.0	1.5
38.366	2.260	0.015	0.044	47.0	2.0
38.830	0.055				
39.617	1.275	0.020	0.020	40.2	4.2
40.067	0.541	0.040	0.005	77.9	20.1
40.395	0.948	0.034	0.012	66.0	8.6
41.248	0.084				
41.791	0.355	0.009	0.003		
42.130	0.150	0.009	0.001		
43.254	0.805	0.033	0.010	18.0	8.9
43.574	0.582	0.035	0.006	34.2	13.6
44.416	0.119	0.009			
44.921	0.074	0.009			
46.073	0.665	0.018	0.007	43.9	8.6
46.566	0.371	0.018	0.003	22.8	14.0
47.535	1.053	0.017	0.012	41.6	5.2
48.765	0.713	0.018	0.007	40.0	8.0
49.332	0.220	0.011	0.002		
50.278	2.442	0.022	0.042	51.8	3.0
50.847	0.393	0.029	0.003	35.8	16.4
51.934	1.385	0.021	0.017	50.2	4.9
53.014	0.165	0.012	0.001		
53.493	0.124	0.012	0.001		
54.407	0.073	0.012			
54.990	1.443	0.025	0.002	108.5	6.9
55.595	0.713	0.014	0.002		
55.945	1.432	0.034	0.018		
56.158	0.949	0.034	0.010		
57.372	4.166	0.029	0.082	81.0	2.7
59.066	0.589	0.028	0.004	107.2	19.4
60.045	0.205	0.017			
60.381	0.140	0.017	0.001		
61.259	1.472	0.044	0.017	74.7	9.6
61.613	0.434	0.025	0.004		
62.569	0.222	0.016	0.001		
63.507	0.199	0.018	0.001		

E (eV)	$2g\Gamma_n$ (meV)	$\Delta(2g\Gamma_n)_1$ (meV)	$\Delta(2g\Gamma_n)_2$ (meV)	Γ_γ (meV)	$\Delta\Gamma_\gamma$ (meV)
64.019	4.042	0.049	0.076	47.1	4.6
64.530	1.954	0.052	0.025	39.3	9.2
65.164	5.197	0.049	0.163	49.7	3.7
65.733	1.390	0.066	0.010	18.8	14.0
66.314	1.035	0.052	0.010	75.2	19.6
66.874	2.105	0.044	0.025	71.9	8.1
67.525	0.431	0.019	0.003		
69.565	1.116	0.051	0.013		
69.824	2.661	0.053	0.040		
71.253	0.583	0.035	0.006		
71.453	1.109	0.079	0.011		
71.841	1.032	0.025	0.010		
72.276	0.225	0.021	0.001		
74.969	0.481	0.020	0.004		
75.715	0.374	0.034	0.003		
75.943	0.515	0.027	0.003		
76.779	0.102				
78.191	1.445	0.099	0.015	10.3	17.4
78.551	1.179	0.105	0.011	60.8	24.0
79.555	0.730	0.023	0.005		
80.050	0.546	0.029	0.004		
80.393	0.588	0.029	0.004		
81.077	0.106	0.039			
81.458	1.042	0.031	0.009	104.6	35.0
82.089	1.454	0.054	0.015	26.7	14.0
82.900	0.439	0.024	0.003		
83.370	0.431	0.024	0.003		
84.006	1.456	0.027	0.015	38.1	8.7
84.685	2.141	0.044	0.022		
86.610	0.275	0.025	0.001		
87.481	0.125	0.029			
87.984	3.919	0.053	0.055	70.7	6.3
89.297	0.332	0.061	0.002		
89.602	2.364	0.093	0.024	86.7	16.1
93.412	6.296	0.055	0.115	53.7	4.0
94.610	0.754	0.039	0.006		
95.205	0.350	0.035	0.003		
95.586	2.663	0.041	0.034		
96.100	2.906	0.048	0.037		
96.440	2.834	0.052	0.035		
97.423	0.277	0.030	0.001		
98.355	0.265	0.039	0.001		
100.156	1.075	0.033	0.009		
101.598	2.825	0.058	0.028	51.1	10.0
102.555	0.248	0.035	0.001		
103.203	6.980	0.063	0.120	40.2	4.5
104.780	2.196	0.059	0.022	40.2	12.8
106.148	5.824	0.185	0.136		
106.396	3.352	0.189	0.054		
107.615	1.925	0.038	0.019		
109.824	3.256	0.144	0.042		
110.093	3.337	0.144	0.043		
111.170	0.376	0.059	0.003		
111.627	5.200	0.102	0.068	94.3	10.4
112.752	0.414	0.042	0.003		
113.280	0.300				
113.907	1.741	0.078	0.014	77.6	23.0
115.084	1.400	0.081	0.014	79.3	23.8
115.777	0.731	0.049	0.004		
116.396	2.623	0.051	0.023	42.0	15.6
117.656	0.030				
118.527	0.806	0.046	0.005		
119.823	2.237	0.131	0.022		
120.123	1.930	0.131	0.026		
121.982	3.216	0.138	0.033	36.9	19.0
122.662	3.993	0.222	0.040	64.2	27.6
123.243	3.534	0.166	0.035	56.3	20.5
124.946	1.540	0.054	0.013		
125.919	1.035	0.055	0.007		
126.441	2.035	0.057	0.017		
127.415	0.250				
127.994	1.558	0.056	0.013		
129.677	0.225		0.002		
130.720	1.258	0.072	0.009		
131.319	3.121	0.132	0.032	56.0	23.2
132.180	0.875	0.052	0.006		
132.754	1.180	0.059	0.008		
133.657	1.764	0.100	0.014	52.1	30.5
134.967	8.015	0.317	0.104		
135.449	4.131	0.348	0.042		
136.435	5.757	0.145	0.068	45.7	14.1
137.103	1.294	0.077	0.009		
137.613	1.628	0.064	0.012		
138.774	3.886	0.138	0.040	40.6	15.4
139.963	1.253	0.071	0.008		
140.498	2.436	0.073	0.021		
141.310	4.229	0.109	0.055		
141.520	3.256	0.106	0.039		
143.036	0.331	0.056	0.002		
144.869	1.421	0.068	0.010		
145.438	0.350				
146.436	1.739	0.070	0.012		
148.031	12.302	0.138	0.190		
149.141	3.926	0.076	0.039		

Figure 2 shows the corresponding distribution of the level spacings ; the dashed line represents the Wigner distribution (two populations with spin and parity $J^\pi = 2^-$ and $J^\pi = 3^-$) normalized to the area of the experimental histogram. There is no agreement between the theoretical and the experimental distributions, which is an usual result for a nucleus with such a small level spacing ; the same kind of discrepancy is observed for ^{233}U, ^{235}U, ^{241}Pu, ^{237}Np ... and is mainly due to the resonance overlap hidding the small resonances.

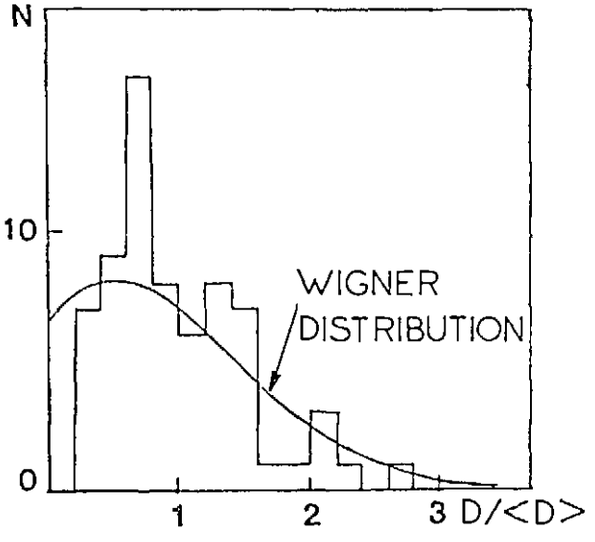

Fig. 2

Neutron Widths and S-Wave Strength Function

The distribution of the reduced neutron widths for resonances between 0 and 50 eV agrees relatively well with the Porter-Thomas law, if one assumes that about 15 % of levels are missed, corresponding to Γ_n^o values smaller than 0.1 times the mean value.

The strength function S_o is evaluated by the relation :

$$S_o = \sum_{E_1}^{E_2} \frac{2g\Gamma_n^o(E)}{2(E_2 - E_1)} \quad ;$$

the value obtained is not affected by the missed levels since in the shape analysis we take into account the total area of non resolved resonances. We obtain : $S_o = (0.75 \pm 0.12)10^{-4}$ in the 0-50 eV energy range and $S_o = (0.94 \pm 0.09)10^{-4}$ in the 0-150 eV energy range.

G.G. SLAUGHTER et al.[4] give a value of $(1.1 \pm 0.2)10^{-4}$ from an area analysis of the total cross cross section as measured by BLOCK et al.[5], up to about 45 eV. This value is significantly higher than ours ; the discrepancy is mainly due to three resonances or group of resonances (6.74 eV ; 9.17 eV and = 43 eV) for which SLAUGHTER proposed Γ_n values about ten times greatet than ours.

Capture Widths

The capture widths Γ_γ have been obtained for a large number of resonances by the relation : $\Gamma_\gamma = \Gamma - 2g\Gamma_n$, assuming that Γ_n and Γ_f are small enough. Up to 50 eV neutron energy the Γ_γ values are obtained with a relatively good accuracy ; beyond, the values are much more scattered, due to the facts that : i) the shape analysis cannot give accurate values of Γ when the Doppler and the resolution function widths are too large compared to Γ ; ii) the probability of observing unresolved resonances increases with energy, likewise the probability of observing abnormal large Γ values. The weighted average value in the 0 to 50 eV energy interval is : $\langle\Gamma_\gamma\rangle = (43.77 \pm 0.72)$ meV, which is mainly due to the very accurate values in the 0 to 10 eV energy interval ; a correction of 0.20 meV has been applied to the average value to take into account the fission widths.

Attempt to Determine the Number of Missed Levels

The examination of the level spacing and neutron width distributions shows that 15 % to 20 % of levels are missed in the experimental cross section. A more precise evaluation of the number of missed levels has been done by a Monte-Carlo method. Table 3 shows the results obtained for 9 calculated cross sections in the 0 to 50 eV energy range, which are supposed to have the same statistical properties as ^{241}Am.

Table 3

	N	D (eV)	N_{obs}	D_{obs} (eV)	$\frac{N-N_{obs}}{N}$
1	81	0.61	67	0.74	17 %
2	98	0.51	79	0.63	20 %
3	84	0.60	70	0.71	17 %
4*	88	0.57	74	0.67	16 %
5	89	0.56	74	0.67	16 %
6	102	0.49	80	0.62	22 %
7*	89	0.56	73	0.70	18 %
8*	95	0.53	75	0.67	21 %
9	91	0.54	72	0.68	21 %

N = number of levels for the calculated cross section.
N_{obs} = number of observed levels.

The cases n° 4, 7 and 8 have been particularly studied ; from a total number of 272 levels, 222 are observed, which means 18 % of missed levels ; the 50 non observed resonances correspond to 11 doublets (4 %) with large Γ_n^o values and 39 (14 %) with Γ_n^o values less than 0.1 $\langle\Gamma_n^o\rangle$; 13 % of the missed level spacing are smaller than 0.4 <D>.

The conclusion is : the observed mean spacing has to be corrected for (18 ± 4) % missed resonances ; then the right value of the average spacing would be : <D> = (0.55 ± 0.05) eV.

Fission Cross Section Measurements. Preliminary Results

Experimental Conditions

Due to the strong α activity of ^{241}Am, a fission fragment detector is not suitable for such measurement. We have built a new detector based on the fission neutron detection, using NE 213 as liquid scintillator. The γ-ray pulses are eliminated by a pulse shape discrimination method.[6] The rejecting rate for γ-ray pulses was 10^5. An anti pile up system has been used and only isolated pulses in 1 μs interval are taken into account. The detector has a cylindrical geometry and

contains 45 liters of liquid in 4 optically independent parts, each part being viewed by a XP 1040 photomultiplier. Internal shielding of lead and natural boron was used to protect against a large fraction of the γ-rays coming from the sample, and against neutrons thermalized in the liquid and backscattered. Due to the anti pile up system, the efficiency of the detector depends on the activity of the sample ; for ^{241}Am, it is about 8 %. The energy threshold for the detection of fission neutrons is 800 keV, and the time resolution 5 ns.

The results given in this section concern only a preliminary experiment, for which the experimental conditions are those shown in Table 4.

Table 4

Energy range (eV)	TOF analyser width (ns)	Linac electron pulse width : 100 ns Frequency pulse : 500 Hz
0.8-3.8	800	Sample thickness : 0.17 g/cm^2
3.8-9.7	400	
9.7-23.6	200	Counting-rate : 10 fissions/h in the 5.4 eV resonance peak
26.6-86.7	100	
86.7-152	50	Experiment duration : 200 h

Results

The normalization has been done in relation to the BOWMAN results[7] (spark chamber measurement) which were normalized to the value of 3.13b at 0.025 eV neutron energy ; the resonance areas were compared for 11 levels up to 15 eV ; a good agreement can be obtained for 7 resonances, but not for the resonances at 3.97, 4.97, 6.12 and 9.11 eV for which the areas obtained from the parameters published by BOWMAN are about ten times smaller than ours. Nevertheless, there is no apparent discrepancy in the fission cross sections in the vicinity of these resonances. The origin of the disagreement has to be find in some mistake in the resonance analysis.

Table 5 - Fission widths from Saclay data.

E	Γ_f	E	Γ_f	E	Γ_f
1.78	0.37	10.12	0.14	24.19	0.14
1.93	0.08	10.40	0.06	25.63	0.29
2.37	0.18	10.99	0.13	26.50	0.05
2.60	0.17	12.89	0.06	26.67	0.19
3.97	0.16	14.68	0.27	28.36	0.16
4.97	0.44	15.69	0.10	28.90	0.16
5.42	0.63	16.39	0.11	29.50	0.10
6.12	0.42	16.85	0.32	31.25	0.22
6.74	0.22	17.73	0.30	32.03	0.28
7.64	0.10	19.44	0.03	36.98	0.51
8.17	0.12	21.74	0.27	38.37	0.30
9.11	0.18	23.08	0.27	39.62	0.23
9.85	0.95	23.34	0.17		

Table 5 shows the Γ_f values obtained for 38 resonances up to 32 eV ; these values were calculated by the relation : $\Gamma_f = \Gamma_x(A_f/A_t)$; A_f and A_t are the fission and the total areas ; Γ and A_t correspond to the parameters of Table 2. The average fission width is : $\langle\Gamma_f\rangle = 0.23$ meV. The integral distribution shown in figure 3 is well represented by a X^2 law with 4 degrees of freedom. That mean that there is a quite large number of channels contributing to the ^{241}Am sub-threshold fission, which is not impossible, since the ^{242}Am compound nucleus is and odd-odd one.

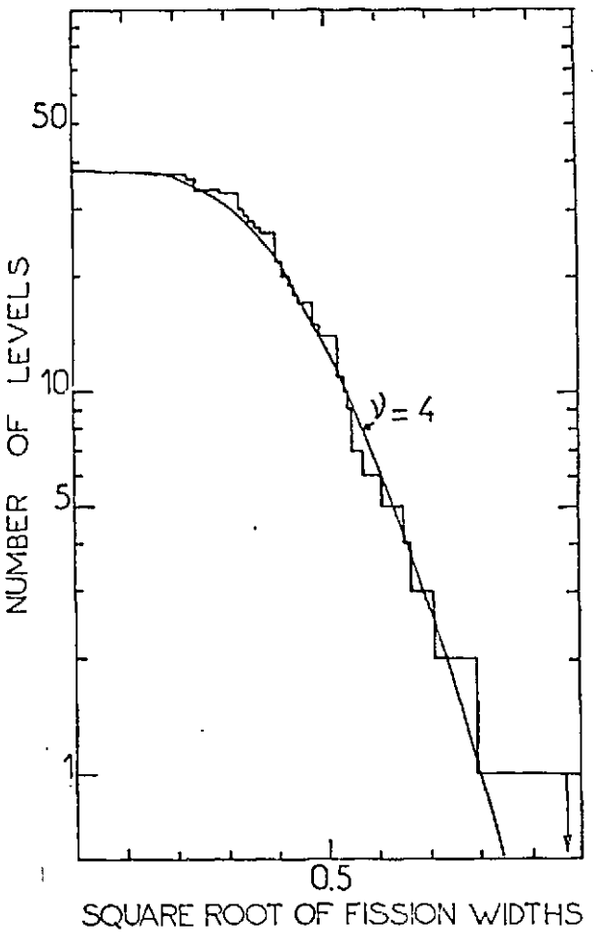

Fig. 3

The Fission Widths Deduced of the Los Alamos Fission Cross Section[1] in the 20 eV to 50 eV Energy Range

No fission widths have been published up to now from the Los Alamos fission data. We have analysed these data (provided by the CCDN at Saclay) between 20 eV and 50 eV . Table 6 shows the fission widths we

Table 6 - Fission widths from Los Alamos data.

E	Γ_f	E	Γ_f	E	Γ_f
22.75	0.58	30.82	1.20	40.07	0.79
23.09	0.77	31.02	0.51	40.41	0.34
23.34	0.31	31.25	0.57	43.29	0.35
24.19	0.48	32.03	0.56	43.57	0.49
25.63	0.82	34.03	0.22	46.07	0.27
26.50	0.47	34.46	0.74	46.57	0.28
26.67	0.48	34.93	0.41	47.54	0.25
27.57	2.54	35.49	0.36	48.76	0.49
27.73	0.44	36.25	0.57	49.33	0.54
28.36	0.55	36.99	0.46	50.28	0.37
28.90	0.36	38.37	0.53	50.65	0.47
29.50	0.45	39.62	0.56	51.98	0.38

obtained for 36 resonances. The corresponding average value is : $\langle \Gamma_f \rangle$ = 0.52 meV, which is larger than the Saclay average value by a factor 2.3. The distribution of these fission widths is shown in figure 4 ; it corresponds to a χ^2 law with 15 degrees of freedom, not in agreement with the fission channel theory.

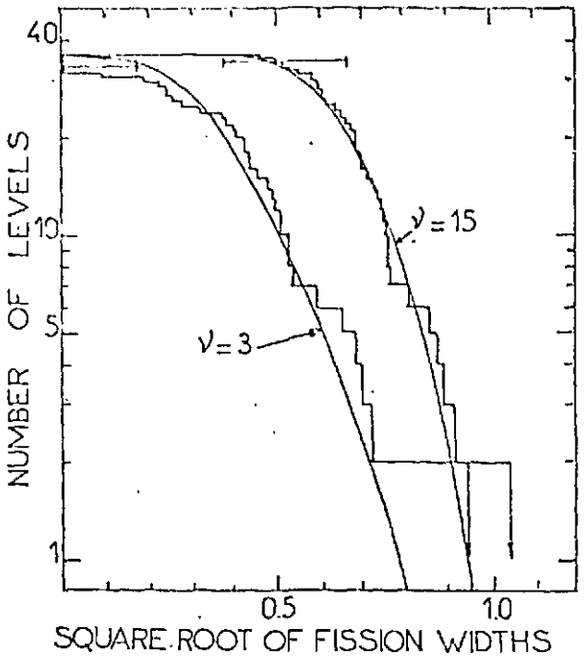

Fig. 4

The discrepancy between the average fission widths could be explained by a defect of normalization. As a matter of fact, the fission integral in the 22.5 eV to 28.7 eV energy range is equal to 2.32b-eV ; 2.80b-eV or 6.48b-eV when evaluated from Saclay, BOWMAN or Los Alamos data, which means that no severe discrepancy would appear in the average fission width if the Los Alamos results were renormalized to the Saclay or BOWMAN data. But such a renormalization will not change the shape of the Los Alamos fission width distribution ; particularly, the number of degrees of freedom will remain the same. Another explanation is a possible contamination by capture events in the Los Alamos experiment ; but to explain the observed discrepancy the contamination would be relatively important ; we have shown on the figure 4 how a correction of 0.30 meV on each fission width would modify the fission width distribution, which then would correspond to about 3 degrees of freedom. In this case, the Los Alamos measured cross section would be a mixing of 40 % fission and 60 % capture (in the average) ; however this capture contribution represents only 0.7 % of the total capture.

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