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Investigation of the Neutron Spectrum in the SCHERZO System BFS-39 by means of Proton Recoil Proportional Counter Spectrometers

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Summary

In the centre of the core configuration BFS-35 of the fast critical assembly BFS-I the neutron spectrum has been measured by means of proton recoil proportional counter spectrometers of the FEI Obninsk and the ZfK Rossendorf.
The experimental results have been compared between each other and with the results of calculations in order to estimate the reliability of the measurements and to check different data sets. In general the agreement is rather good...
BFS-35 is one of the realizations of the international fast calibration spectrum SCHERZO. Therefore our measurements could be compared with French measurements at the SCHERZO system UK-5 HARMONIE.
The experiments at BFS-35 made it possible to measure the SCHERZO spectrum down to energies of about 2 keV. That means a noticeable improvement with regard to the experimental results to be submitted until now.

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1. Introduction

The British Atomic Energy Authority UKAEA suggested series of measurements in an international frame to be carried out at a pure uranium system characterized by $k_{\infty} \approx 1$. In 1973 the summarized results of British, French and Westgerman investigations have been presented on the fast reactor conference in Tokyo /1/. It turned out that $k_{\infty} = 1$ is reached for an uranium enrichment of 5.56%. The moderation of the fission neutrons is mainly caused by inelastic scattering in uranium and the resulting fast spectrum is comparatively hard. Therefore such systems were called SCHERZO 556 or simply SCHERZO. The results of measurements of neutron spectrum, reaction rates and reactivities are presented in a Westgerman-French report /2/ and in a British report /3/.

SCHERZO represents a calibration spectrum which can be reproduced easily at different places. The results of French and Westgerman measurements of the neutron spectrum by means of proton recoil counters do not agree too good; partly they deviate remarkably from each other and from calculations. Moreover the low energy limits of the French (about 10 keV) and especially of the Westgerman (about 40 keV) measurements are not low enough; the strong decrease of the hard neutron spectrum below 25 keV could not be caught and estimated. Therefore joint neutron spectrum measurements using proton recoil counter spectrometers developed in the USSR and in the GDR have been carried out at a SCHERZO system at Obninsk - at the core configuration BFS-35 of the fast critical assembly BFS-I.

quantifying the compositions and dimensions, in particular the plutonium

2. Construction of BFS-35

A cross-section of the complete assembly is presented in fig. 1. The test zone - that means the SCHERZO system itself - is comparatively enlarged. The volume of the BFS-35 testzone amounts to almost 350 l, whereas the testzones of the westgerman SNEAK-8 and the French UK 5 HARMONIE have voulmes of almost 200 l and almost 300 l, respectively. But in BFS-35 the concentration of nuclei is somewhat lower, because in BFS-I pellets were used instead of platelets in the other assemblies. The density of nuclei is given in Table 1. The difference of the nuclear densities of Fe, Ni and Al is caused by the following circumstance. The uranium platelets (the uranium rods in the case of UK 5, respectively) are coated by Ni and covered by stainless steel, whereas the pellets are arranged in Al tubes.

The elementary cell of the BFS-35 testzone is given as a package of two natural uranium pellets (thickness of 10.6 mm each), one enriched uranium pellet (enrichment 36%, thickness 5.6 mm) and another natural uranium pellet. The elementary cell of the BFS-35 driver zone is given as a package of two natural uranium pellets and one enriched uranium pellet (enrichment 90%, thickness 5.6 mm) in between.

The BFS-35 testzone approximates the atomic uranium enrichment of the ideal SCHERZO closely, but because of the void fraction and the dilution by Al the value of k_∞ is slightly below unity.

3. Methods of experimental and calculational determination of the neutron spectrum

The neutron spectrum has been experimentally determined by means

for each of the basic heterogeneous cells using 2000 group FGL5 data [2].

of proton recoil proportional counter spectrometers created at PEI Obninsk and at ZfK Rossendorf. These spectrometers have already been applied during joint measurements at earlier BFS configurations /4/. Above 1.4 MeV spectrum measurements have been carried out using the Obninsk scintillation method (stilben scintillator).

The apparatus and the evaluation method of the Rossendorf spectrometer have already been published /5, 6/.

Cylindrical (PEI Obninsk, ZfK Rossendorf) as well as spherical (ZfK Rossendorf) counters have been used. The measurements took place in the central channel at half height of the testzone. The power level was characterized by slight subcriticality (about 30 cents) and source multiplication. The measuring series carried out with the Rossendorf spectrometer are described in table 2; the given informations and data correspond to those mentioned in preceding BFS reports /7/.

In most cases the calculations refer to the 26 group ABBN scems. Different group sets have been used, actually ABBN-64, ABBN-70 and ABBN-72 /8, 9, 10, 11/ as well as NAPP.B /12/. The Rossendorf calculations are characterized by fundamental mode method; all mentioned data sets were used. The Obninsk calculations are taking into account the whole critical assembly including driver and blanket zones in onedimensional approximation, but only the group set ABBN-70 was used.

The comparatively coarse ABBN subdivision does not reach the experimental energy resolution. Therefore a numerical fine spectrum calculation has been carried out additionally. The method was deduced from the well known continuous slowing down procedure. The calculation programme is called NSC code /13/. In the calculations data from the KEDAK nuclear data library /14/ have been used.

4. Results and discussion

The results of Rossendorf spectrometer measurements using cylindrical counters have been presented in table 3, as well in the fine intergals (Δu = .05) of the evaluation procedure as also summed up to group fluxes regarding the ABBN scheme.

The Rossendorf measurements cover the energy range 2...1200 keV, the Obninsk measurements cover the energy range 8...1400 keV. The Rossendorf results have been extrapolated up to 1400 keV applying a fit to a calculated spectrum (fundamental mode, ABBN-72). Within the energy range 10...1400 keV (ABBN groups 11...5) both measurements have been related to each other in the sense of equal flux integral; the normalization integral is given by

$$\int_{1400\,keV}^{10\,keV} \Phi(u)\,du = \sum_{i=5}^{11} \Phi_i(u)\,\Delta_i u = 14.64$$

The normalized experimental results are shown in fig. 2 and fig. 3. In fig. 2 the lethargy flux $\phi(u)$ is presented in a linear scale, in fig. 3 in a logarithmic scale. In fig. 4 the Rossendorf experimental results are compared with selected points of the FSC calculation corresponding to $\Delta u \approx .05$, i.e. to the experimental energy resolution at about 500 keV. In table 4 the group averaged experimental results are compared with each other and with different calculations. The comparison was carried out in such a way that for each group number i the deviation $(a_i/b_i - 1)$ is given; in the table the corresponding columns are labeled by a/b. In the experiment-calculation comparison always $(C/E - 1)$ is given.

Both measurements agree satisfactorily. In the energy range 50...500 keV (ABBN groups 9...6) - where about 75% of the integrated neutron flux is concentrated - the Obninsk measurements show a spectrum which is systematically softer than for the Rossendorf measurements. In groups 8 and 9 the Obninsk experiments show 10...20% more neutrons than the Rossendorf ones, in group 6 the Obninsk measurements show about 10% less neutrons. That is somewhat outside the agreement which was reached for the system BFS-33 /4/ and the internationally accepted error limits of 5...10%, respectively.

Fig. 3 shows that both measurements cover the low energy range of the steep slope with sufficient agreement. Only the Obninsk results are not so strongly smoothed as it requires the real counte resolution below 20 keV.

In table 4 the comparison of measurements and calculations was continued using mainly the Rossendorf results (see columns 3...8 of table 4). In general the agreement is good or even very good. Restrictions have to be made with regard to the following circumstances. Calculations using NAPPMB group set deliver too soft spectra and those using ABBN-64 too hard spectra. As far as it concerns NAPPMB this tendency is well known from the literature /15/. The NAPPMB calculation gives a k_∞ value of .911 also remarkably deviating from the expected value which is e.g. closely approximated by means of the ABBN-72 calculation delivering k_∞ = .958.

In group 11 and generally below 20 keV the Rossendorf measurement delivers too many neutrons. This is a systematic effect and can be explained as well by experimental as by calculational reasons.

Between summer of 1975 and end of 1976 - that means also during the measurements at BFS-35 in June 1976 - the electronic n-γ-discrimination sceme of the Rossendorf spectrometer had been changed slightly. The unit extending the impulse peak value had

F8/F5 values with an rms error of + 4% and F5/F9 values with an rms error

been replaced by a real stretcher which estimated the n- and the γ -events somewhat differently in the case of high counting rates. The results of repeated spectrum measurements at the Rossendorf fast system SEG-2 in autumn of the years 1976 and 1977 show that this tendency has been overcome since summer 1977 by installing a n-γ-discrimination sceme including an analoguous division unit /16/.

It should be pointed out that the agreement of Rossendorf experimental results with calculations using group sets ABBN-70 and ABBN-72 as well with the NSC procedure is rather good.

The NSC calculation enables a detailed comparison of spectra which is shown in fig. 4. Above 20 keV the agreement between the Rossendorf experiment and the NSC calculation shows a remarkable good impression. Of course the NSC calculation delivers a more structured spectrum because a smoothing in the sense of experimental energy resolution was not carried out.

Below 20 keV the already mentioned effect appears that the Rossendorf experiment delivers too many neutrons. Furthermore the NSC calculation has been carried out without taking into account Ni and therefore no structure can be seen at 12.5 keV and 15.5 keV Ni resonances whereas the measurement shows a point of inflexion at about 15 keV. Regarding the Al resonance at 5.9 keV the measurement shows too strong a structure because the smoothing was not sufficient for such low energies.

The tendency of deviations between experiment and NSC calculation below 20 keV might also be understood from a calculational point of view. For the NSC calculation the cross section values of the KEDAK library will be used averaged over the energy without taking into account any block effect. In the region of the unresolved resonances of ^{238}U this causes an overestimation of

^{238}U absorption. Furthermore in future the application of newly estimated inelastic scattering cross sections (KEDAK-3 library /17/) should lead to an increased neutron fraction in the low energy part of the spectrum.

Below 4 keV in the range of resolved uranium resonances no MSC calculations are existing as yet. Another experimental result is also not available, because at BFS-35 no spectra measurements have been carried out using the time of flight method. Therefore it is difficult to judge the Rossendorf experimental results in the range below 5 keV. For the groups 13...10 (energy range 2...45 keV) in table 5 Rossendorf experiments are compared with these cases of calculations which showed good agreement in table 4. It can be seen that in groups 12 and 13 (energy range 2...10 keV) the calculations themselves considerably vary. Taking into account that below 20 keV only 3% of the neutrons are present and below 10 keV only less than 1% it is thoroughly satisfying that in group 13 the deviation between Rossendorf experiment and ABBN-72 calculation is not larger than a factor 2.

Comparing the Rossendorf experiment at BFS-35 and the French measurements at UK 5 HARMONIE it can be estimated whether and how the different realizations of the SCHERZO conception could be refered to in spite of the somewhat deviating nuclear densities and k_{∞} values. In fig. 5 both measurements are presented, again normalized to each other in the energy range 10 keV ... 1.4 MeV. The optical impression of the agreement of both spectra is rather satisfying if one neglects the circumstance that the UK 5 HARMONIE spectrum has strong dips in the energy range 10...30 keV because of elastic resonance scattering of Fe and Ni. A quantitative comparison involving an ABBN-72 calculation for both systems is given in table 5. The data of the third column show that the experiments at the two systems deviate hardly more from each other than the corre-sponding calculations. In this sense it is justified the experiments at BFS-35 and at UK 5 HARMONIE to refer to each other, and a good agreement has been reached.

5. Conclusions

The investigated system BFS-35 is a further realization of the hard fast calibration spectrum SCHERZO which differs from the hitherto existing systems by the fact that Al is used instead of stainless steel as unavoidable dilution material. The influence on the spectrum is a distribution without so many dips between 10 keV and 30 keV as before.

The spectrum measurements were carried out using the technique of proton recoil proportional counters. It was shown that this method could be applied even to a very hard spectrum as SCHERZO where the lethargy flux spectrum decays from 50 keV to 2 keV by almost three orders of magnitude. If the procedure of measuring and evaluating is refined enough then the spectrum in the low energy range can be found out. So far the carried out investigations deliver an improved knowledge of the calibration spectrum SCHERZO especially in the low energy range.

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corresponding F9 value is averaged over the plutonium in the cell.

nuclide	ZEBRA-3H	SNEAK-8	UK 5 HARMONIE	EFS-35
U-235	24.59	23.75	26.48	17.65
U-238	379.7	380.9	374.9	297.0
Fe	31.23	39.68	31.03	4.23
Cr	8.64	11.12	9.916	.734
Ni	4.83	12.96	16.34	.343
Al	.24	.24	.32	83.45
C	4.33	3.76	3.19	5.57
Mn	.64	.87	-	.058
Mo	.08	.18	-	-
V	.05	-	-	-
Ti	.16	-	-	.027
Si	2.16	.45	-	-
Cu	.04	-	.30	-
H	.40	.18	-	.19
O	.43	-	-	-
N5/(N5+N8)	6.08%	5.87%	6.60%	5.61%
k_∞	1.0300 ±.0027	1.0065 ±.0013	1.0630 ±.0025	≈ .97

Table 1: Nuclear densities ($10^{20}/cm^3$) and further informations about different SCHERZO systems

No. of measuring series	Counte-	High voltage [kV]	Electronic arrangement	n-γ-discrimination	Evaluation using SUBTRA-code	A [keV/channel]	B [channels]
82	ZP1	2.15	.25 µs gaussian forming in spectroscopic amplif. 7 µs integration in the spectroscopic branch of the gated integrator 11 µs paralysis time	twodimensional differentiation and stretcher in the discrimination branch	normalization of the γ-background to the (n+γ)-measurement at the flank side of the γ-distribution	.0438	.5
83	"	"				.0855	0
84	"	"				.169	0
85	"	"				.440	0
81	"	"				1.29	-.3
86	"	1.7				.551	-.6
87	"	"				1.086	-.6
88	ZP3	2.2				1.56	-1
89	"	"				3.09	0
810	ZP4	3.0				2.87	-.65
811	"	"				5.65	-.65
812	SP2-10	3.6				2.69	0
813	"	"				5.21	0
814	SP2-4	2.4				1.525	-.5
815	"	"				2.98	0
816	SP9	1.25				.540	0
817	"	"				1.06	0

Table 2: Informations refering to the Rossendorf measuring series at BFS-35

E/keV/	Φ(u)	E/keV/	Φ(u)	E/keV/	Φ(u)	E/keV/	Φ(u)
1402	1.17	180	4.519	23.2	1.428	2.98	.6294(-2)
1332	1.25	171	4.111	22.0	1.352	2.83	.5910
1265	1.35	163	3.693	20.9	1.173	2.69	.6028
1202	1.47	154	3.497	19.9	1.021	2.55	.6310
1142	1.636	147	3.813	18.9	.8806	2.42	.6552
1085	1.794	139	4.481	17.9	.7914	2.30	.6467
1031	1.983	132	4.903	17.0	.7535	2.19	.6060
979	2.180	125	4.856	16.2	.7218	2.08	.5493
930	2.396	119.5	4.393	15.4	.6991	1.97	.4795
884	2.571	113.5	3.908	14.6	.6767	1.875	.4190
839	2.746	108	3.563	13.9	.6505	1.78	.3826
798	2.937	102.5	3.141	13.2	.6152	1.69	.3611
758	3.171	97.4	2.673	12.5	.5782	1.61	.3350
720	3.459	92.5	2.472	11.9	.5397	1.53	.3044
684	3.718	87.9	2.700	11.3	.4875	1.45	.2663
650	3.921	83.5	3.296	10.7	.4419	1.38	.2161
617	4.061	79.3	3.925	10.2	.3938	1.31	.1535
586	4.181	75.3	4.279	9.68	.34[illegible]		
557	4.309	71.6	4.289	9.20	.3023		
529	4.470	68.0	4.071	8.74	.2448		
503	4.618	64.6	3.791	8.30	.2022		
477	4.723	61.4	3.495	7.89	.1517		
454	4.771	58.3	3.246	7.49	.1174		
431	4.875	55.4	3.073	7.12	.9144(-1)		
409	5.023	52.6	2.870	6.76	.6371		
389	5.187	50.0	2.628	6.42	.3518		
369	5.313	47.5	2.309	6.10	.1607		
351	5.310	45.1	1.942	5.80	.1104		
333	5.220	42.9	1.672	5.51	.1605		
317	5.054	40.7	1.453	5.23	.2271		
301	4.980	38.7	1.328	4.97	.2282		
286	5.132	36.7	1.278	4.72	.1973		
272	5.396	34.9	1.294	4.49	.1605		
258	5.541	33.2	1.386	4.25	.1328		
245	5.597	31.5	1.514	4.05	.1173		
233	5.[illegible]49	29.9	1.646	3.85	.1055		
[illegible]	4.734	28.4	1.733	3.65	.9579(-2)		
[illegible]	4.599	27.0	1.729	3.47	.8567		
20[illegible]	4.616	25.7	1.649	3.30	.7811		
190	4.549	24.4	1.546	3.13	.7020		

i	$\Phi_i(u)$
5	1.946
6	4.227
7	5.113
8	4.143
9	3.276
10	1.522
11	.690
12	.111
13	.0087

Table 3: Rossendorf experimental results for the BFS-35 system; direct measuring results Φ(u) spaced in lethargy intervals Δu ≈ .05 as well as group fluxes $\Phi_i(u)$ with regard to the ABBN subdivision

i	E-PEI/ E-ZfK	C-PEI/ E-PEI	C-PEI/ E-ZfK	C-KAP/ E-ZfK	C-AB64/ E-ZfK	C-AB70/ E-ZfK	C-AB72/ E-ZfK	C-NSC/ E-ZfK
5	-27	30	0	-10	17	9	6	-9
6	-10	17	5	-5	15	3	7	-3
7	3	0	3	-7	7	-6	2	2
8	12	-3	4	7	1	1	1	2
9	20	-18	-2	11	-18	-4	-5	10
10	-26	23	-9	22	-25	9	-11	-2
11	-23	-24	-41	-32	-26	-1	-17	-33

Table 4: The comparison of experiments and the comparison of experiments and calculations; deviations given in percent

i	C-PEI/ E-ZfK	C-ABBN-70/ E-ZfK	C-ABBN-72/ E-ZfK	C-NSC/ E-ZfK
10	-9	9	-11	-2
11	-41	-1	-17	-33
12	-66	97	-12	-68
13	20	625	115	–

Table 5: Comparison of Rossendorf experiments with chosen data sets and calculational methods in the low energy range 2 keV...45 keV; deviations given in percent

i	Experiment E-BFS-35/ E-HARMONIE	Calculation ABBN-72 C-BFS-35/ C-HARMONIE	Difference of (1st column - 2nd column)
5	4	-9	13
6	-2	-8.5	6.5
7	-11	-5	-6
8	-11	-2.5	-8.5
9	17	12	5
10	26	32	-6
11	58	97	-39

Table 6: Comparison of experiments and calculations at BFS-35 and UK 5 HARMONIE; deviations given in percent

Subscription of Figures

Fig. 1: Construction of the BFS-35 system

Fig. 2: Presentation of the results of Rossendorf and Obninsk measurements at BFS-35; linear neutron flux axis

Fig. 3: Presentation of the results of Rossendorf and Obninsk measurements at BFS-35; logarithmic neutron flux axis

Fig. 4: Comparison of the Rossendorf spectrum measurement at BFS-35 with the NSC calculation

Fig. 5: Comparison of the Rossendorf spectrum measurement at BFS-35 with the French spectrum measurement at UK 5 HARMONIE

The neutron spectrum has been experimentally determined by means

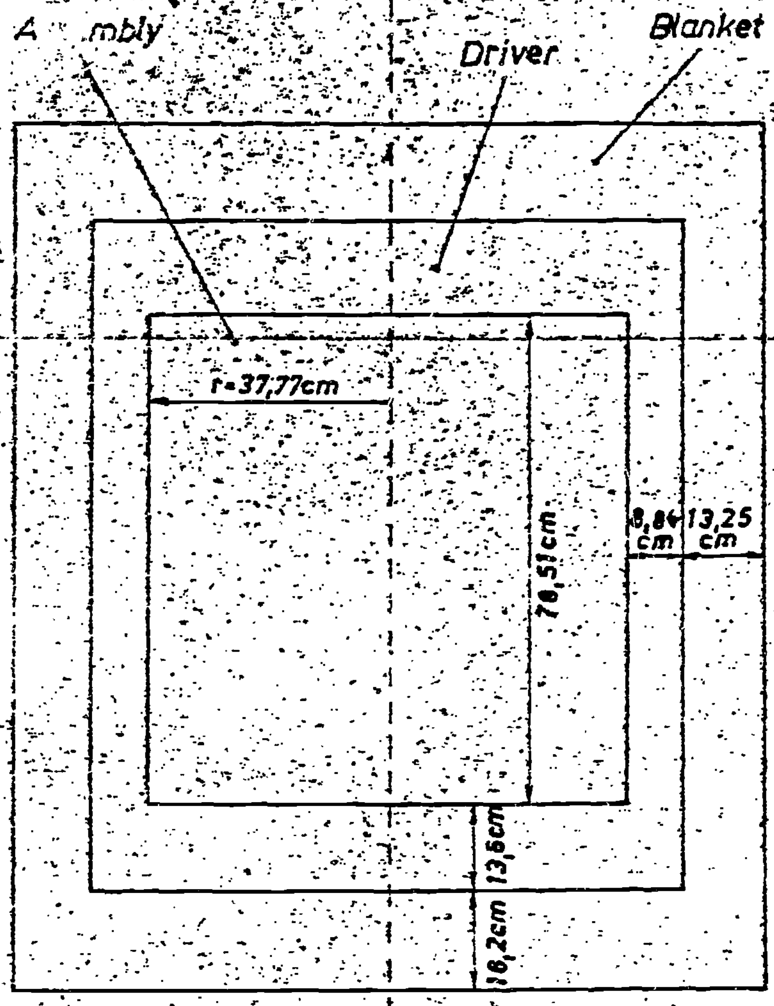


fig. ~~Abb.~~ 1

calculations data from the KEDAK nuclear data library /14/ have been used.

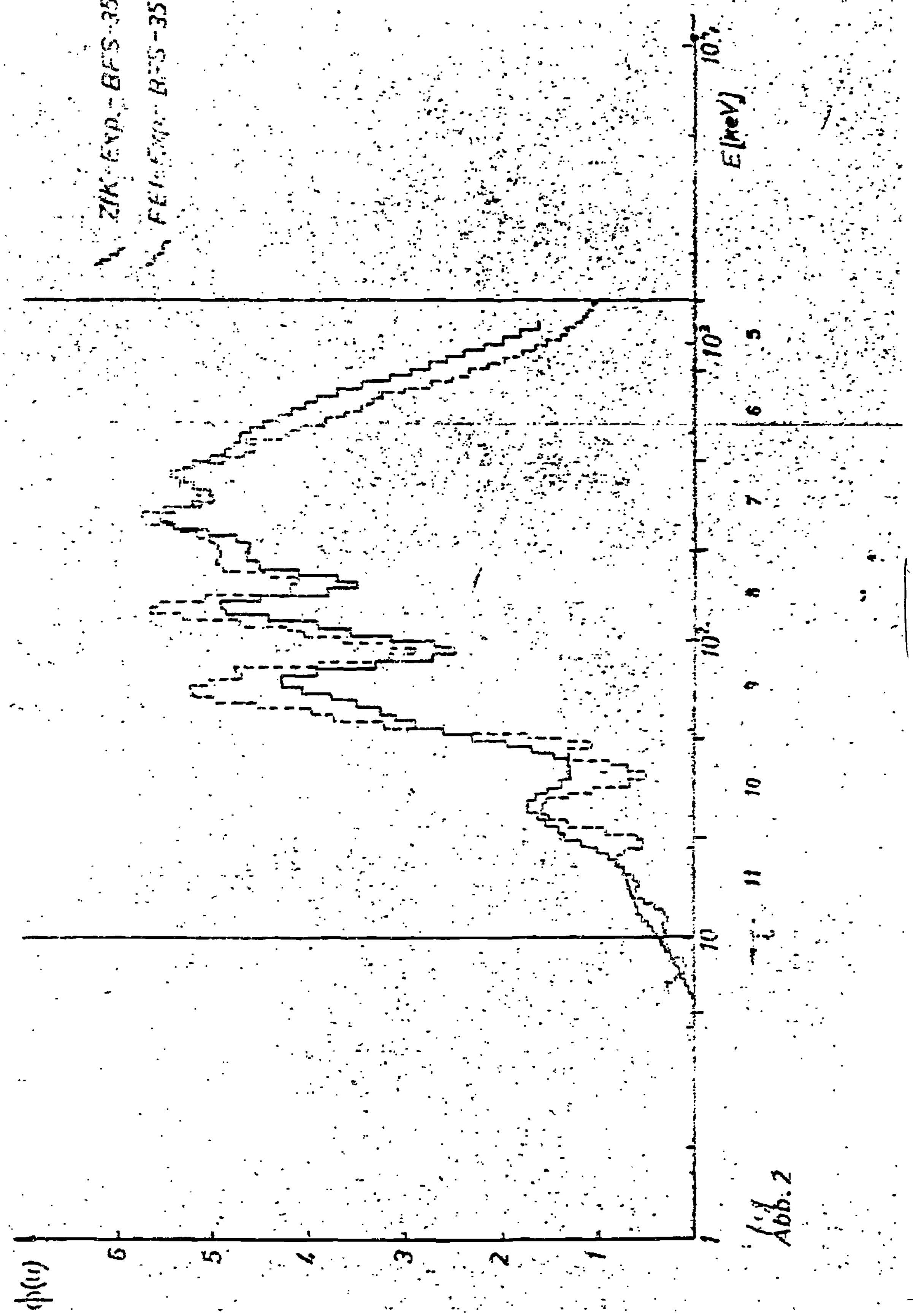


Abb. 2

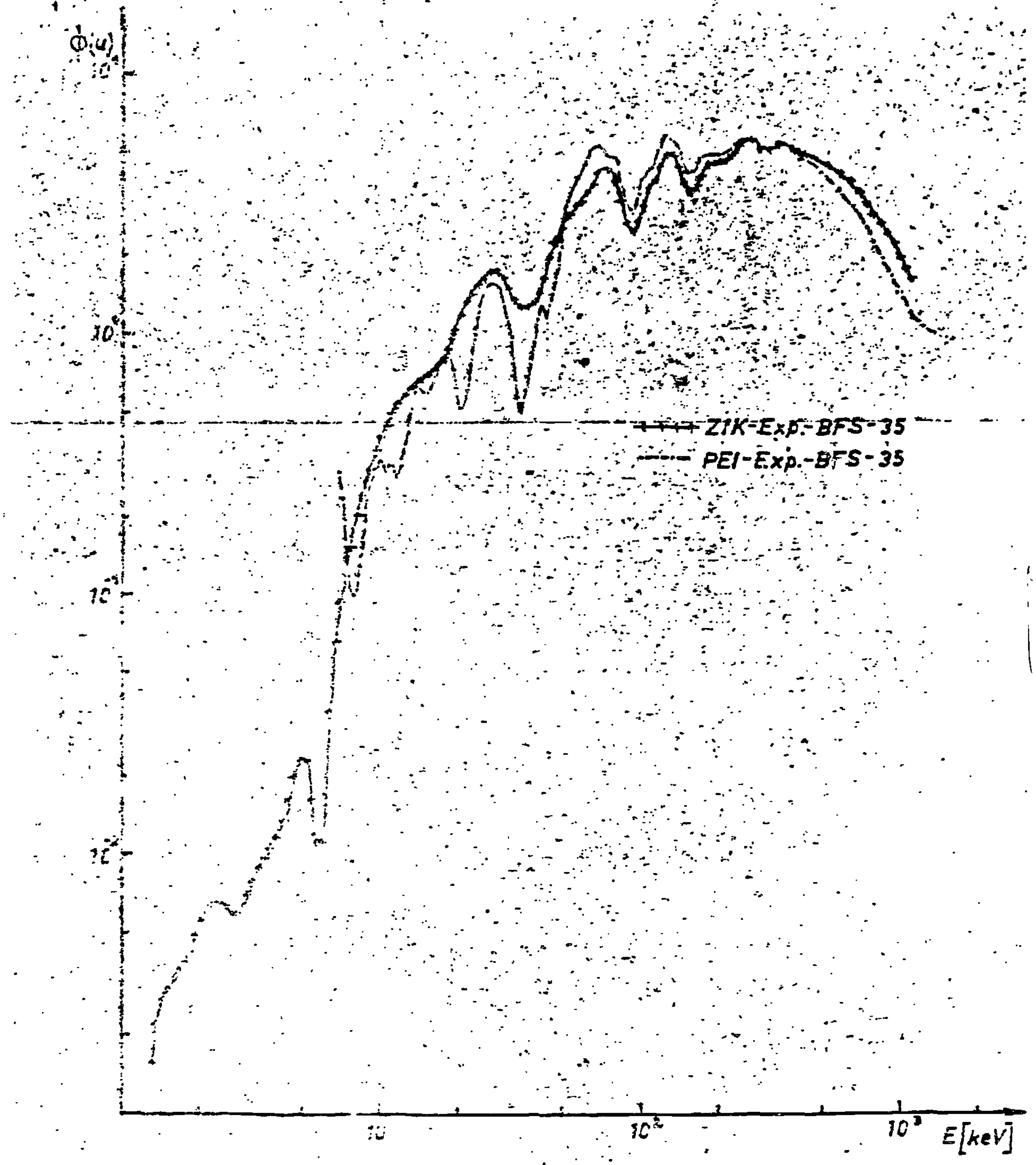
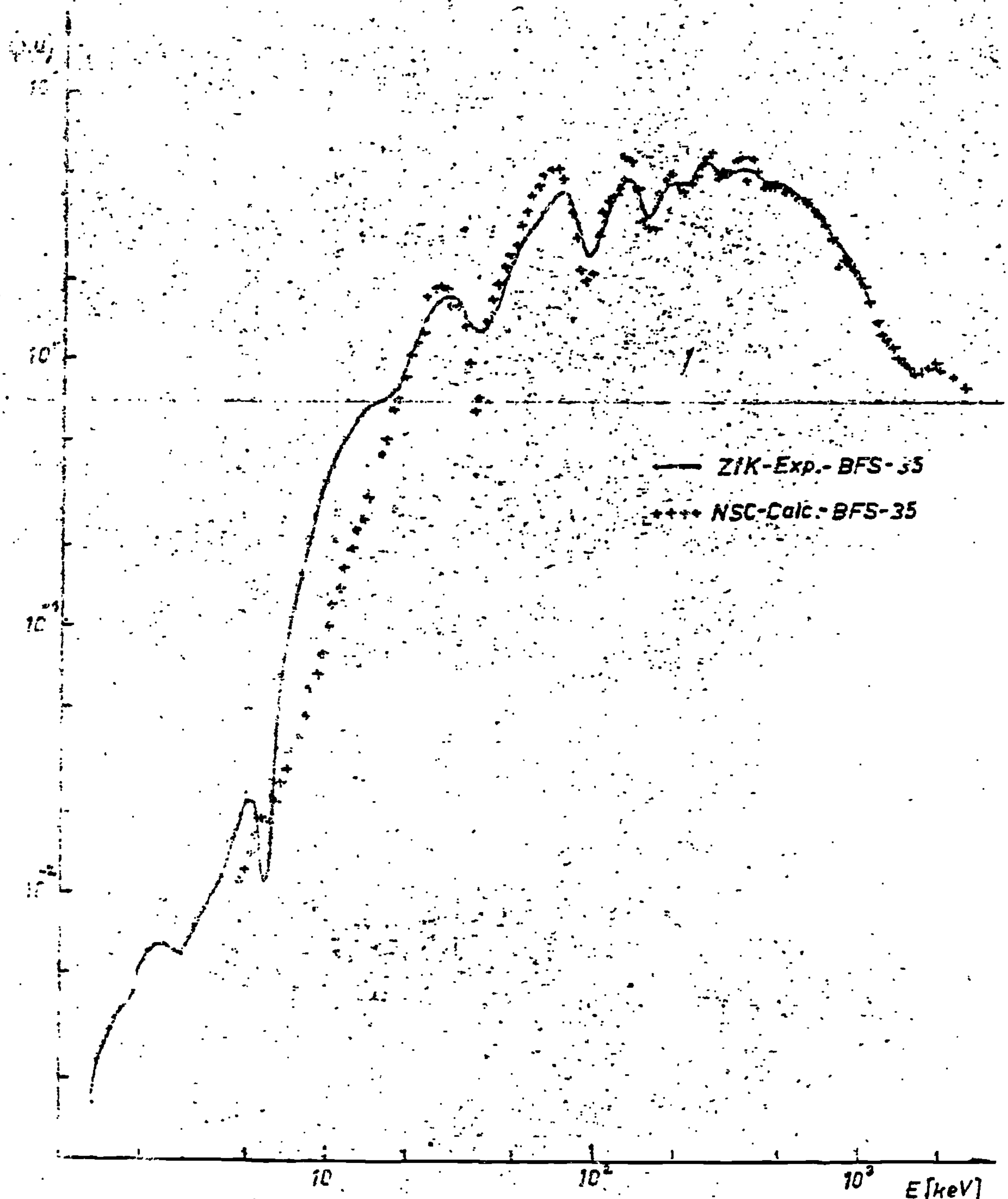


Abb.3

changed slightly. The unit extending the impulse peak value had



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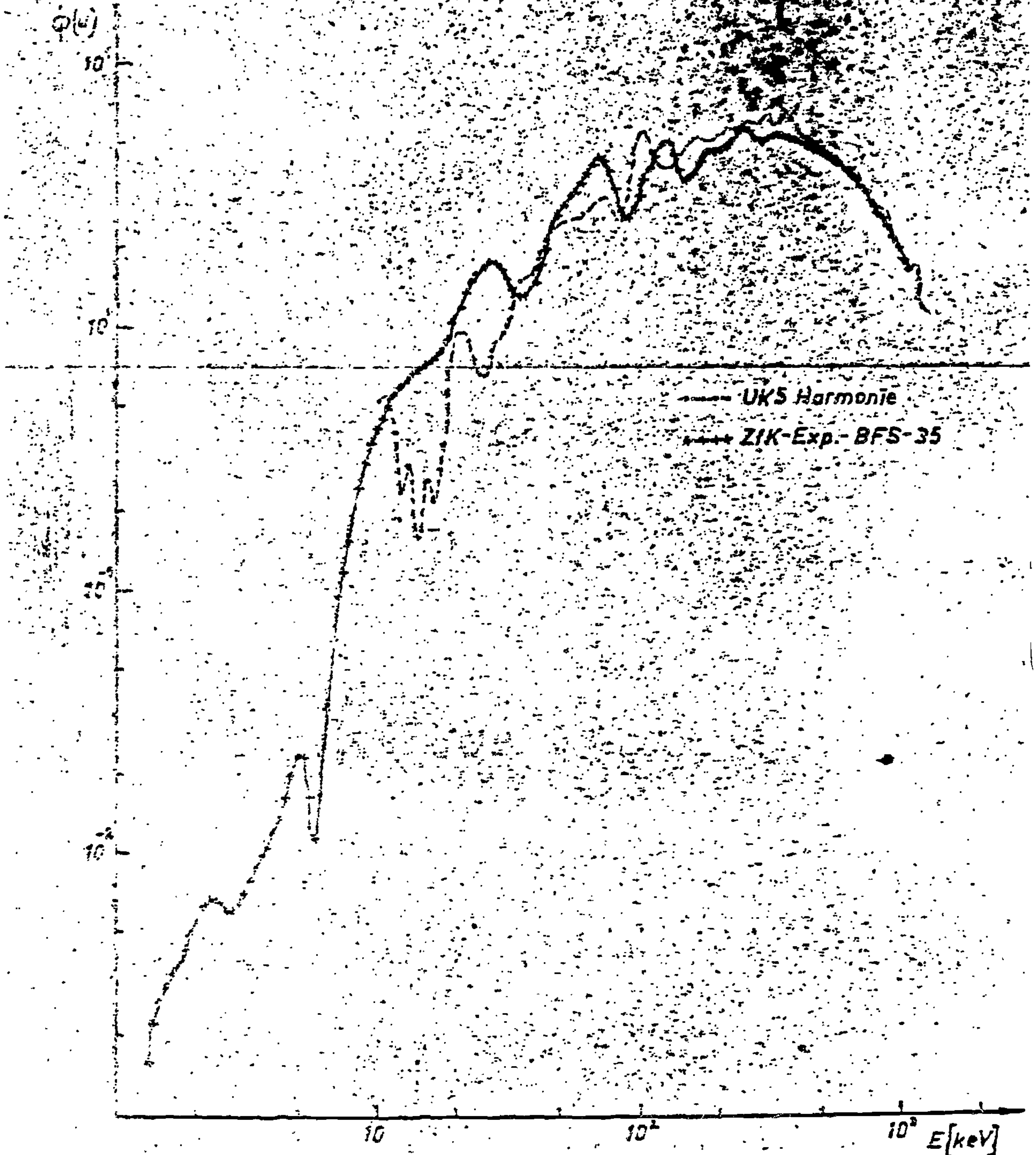

Abb.5