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MEASURED SPECTRA OF NEUTRONS ESCAPING FROM IRON SPHERES

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1. INTRODUCTION

Comparison of measured and calculated results of neutron penetration through a given medium is very often difficult on account of incorrectly defined source of radiation used in the experiment, and sometimes also due to geometry, which may be rather complicated from the viewpoint of calculation. It is the reason why in the recent years the basic testing of the calculational methods has been carried out experimentally using Cf 252 as a well-defined source of neutrons and spherical geometry of the medium involved.

It may be said that iron is one of the fundamental materials used in reactor technology. But its properties, namely its high scattering cross section as well as the striking resonance character of its total effective cross section, involve problems in calculating the penetration of neutrons. The authors of /1/ and /2/ have measured the penetration of neutrons emitted by Cf 252 through iron in a spherical geometry, and compared the results with calculation. Because their results exhibit a rather high scattering, we have performed another measurement by means of iron spheres with diameters 20, 30, and 50 cm.

The measurement of neutron spectra in such verifying experiments is carried out using differential spectrometric methods which offer to obtain sufficiently fine neutron spectra. These methods are usually based on the scatter of neutrons on hydrogen nuclei and detection of recoil protons. Our measurement has been performed using a stilbene crystal scintillation spectrometer, and the SP-2 proportional counter filled with hydrogen (392.4 kPa). The energy range of measured spectra has been from 10 keV up to 10 MeV.

3. THE METHOD OF MEASURING AND THE EVALUATION OF NEUTRON SPECTRA

The neutron spectra have been measured using a differential spectrometric method based on the registration of recoil protons, the gamma background being discriminated electronically. Spectra of neutrons with energy ranging from 0.5 to 10 MeV have been measured using a stilbene crystal scintillation spectrometer. Spectra of neutrons with energy in the region from 10 keV to 800 keV have been measured by means of hydrogen-filled SP-2 spherical chamber with a diameter of 40 mm, the hydrogen being under 392.4 kPa of pressure. Functional arrangement of the measuring setup is shown in fig. 2. The separation of pulses from neutrons and photons is based on different front edge of pulses from protons (neutrons) and electrons (photons). The separation signal is processed in the case of the scintillation spectrometer in dependence on pulse rise time, and in the case of the hydrogen chamber in dependence on pulse rise speed. The dependence of pulse rise time on energy necessitates to divide the spectrum obtained by the scintillation spectrometer into two components (a soft component and a hard one). Due to an escape of electrons from the hydrogen chamber there occurs a so-called physical threshold of photon discrimination. It is the highest energy which electrons can impart to the detector. For the SP-2 chamber filled with hydrogen (392.4 kPa) this energy equals to some 120 keV. For this reason we divide the measurement of spectra of neutrons by means of hydrogen chamber into two components. The hard component (100 keV up to 800 keV) is measured without discrimination of photons, while the soft one (10 keV up to 150 keV) is measured with discrimination. Furthermore, insufficient difference of rise times from proton and electron pulses from the hydrogen chamber makes it necessary to adopt an additional discrimination of photons connected with measuring a pure source of photons (Ra 226). This procedure has been described at a greater length in /4/.

spectra, the neutron spectra are evaluated on the basis of their smoothed derivative, cubical parabola with 7 points of fitting being used for the smoothing. The division of spectrum energy scale is logarithmic with 40 points in one decade.

4. ANALYSIS OF MEASURED RESULTS

Measured spectra of neutrons emitted by the source Cf 252 and neutrons escaping from the surfaces of iron spheres dia 20, 30, and 50 mm, are presented in fig. 3 and in table 1. The values are normalized to one neutron emitted by the source, the normalizing constant being $S_0/4\pi r^2 = 7.8 \times 10^3 s^{-1} cm^{-2}$. The statistical error of the measured results has been markedly influenced by the separation of measured spectral data from the background of scattered neutrons. The small separation of the effect from the background has made it practically impossible to evaluate the spectrum of neutrons from Cf 252 with energies under 100 keV. Furthermore, statistical scatter in the energy region between 100 and 300 keV has been increased for the same reason. In measuring on iron spheres, this small separation has resulted again in a marked statistical scatter of measured values in energy regions 10 - 20 keV and 30 - 50 keV. Achieving a better accuracy would necessitate to decrease the distance between the detector and the neutron source, in which case the influence of the background caused by scattered neutrons would be reduced.

Comparison of measured neutron spectra (fig. 3) suggests a rapid decrease of neutron flux density for $E > 1.5$ MeV with increasing iron thickness. The energy region between 0.8 and 1.5 MeV is transitory; after an initial increase of spectrum values they start to decrease as early as from small iron thicknesses. The third important region is for neutron energy below 0.8 MeV. Here the neutron flux densities grow in the whole range of measured iron thicknesses. Because the rate of growth is highest in the regions of least effective cross section, the resonance character of the spectrum is more and more expressive. For energy over 3 MeV the measured spectrum of Cf 252 exhibits a very good concordance with theory /8/.

the differences are in the limits which are adequate to different philosophy of measurement and data processing (e.g. division of the neutron spectrum from the viewpoint of energy). The deviations for energy below 800 keV result partly from different energy resolution of the detectors, partly from data processing. In addition, the shift of resonances towards lower energies /2/, which is especially marked in fig. 7 (sphere, dia 50 cm), may serve as an evidence of different calibration (from the viewpoint of energy) of the detectors.

5. CONCLUSIONS

In comparing our results with /1/ and /2/, we have found satisfactory concordance of the spectra of neutrons escaping from the surfaces of iron spheres only in the region of E = 100 - 650 keV (in case /1/) and for E> 800 keV in case /2/. The differences in the findings of individual authors cannot be attributed only to different energy resolution of the detectors or to different division of the neutron spectrum. Of great impact are also systematic errors occurring both in measurement and in data processing. The main sources of the errors consist in inaccurate energy calibration and in the bond between individual components of the spectrum. Because results of these measurements are used for testing the calculational methods, while the results in themselves are not considered as reliable, it seems justified to start in the verification of the calculation from experimental results of as many authors as possible. Beyond this, comparing experiments should be done which could help in eliminating the systematic errors of measurements of all experimental teams involved.

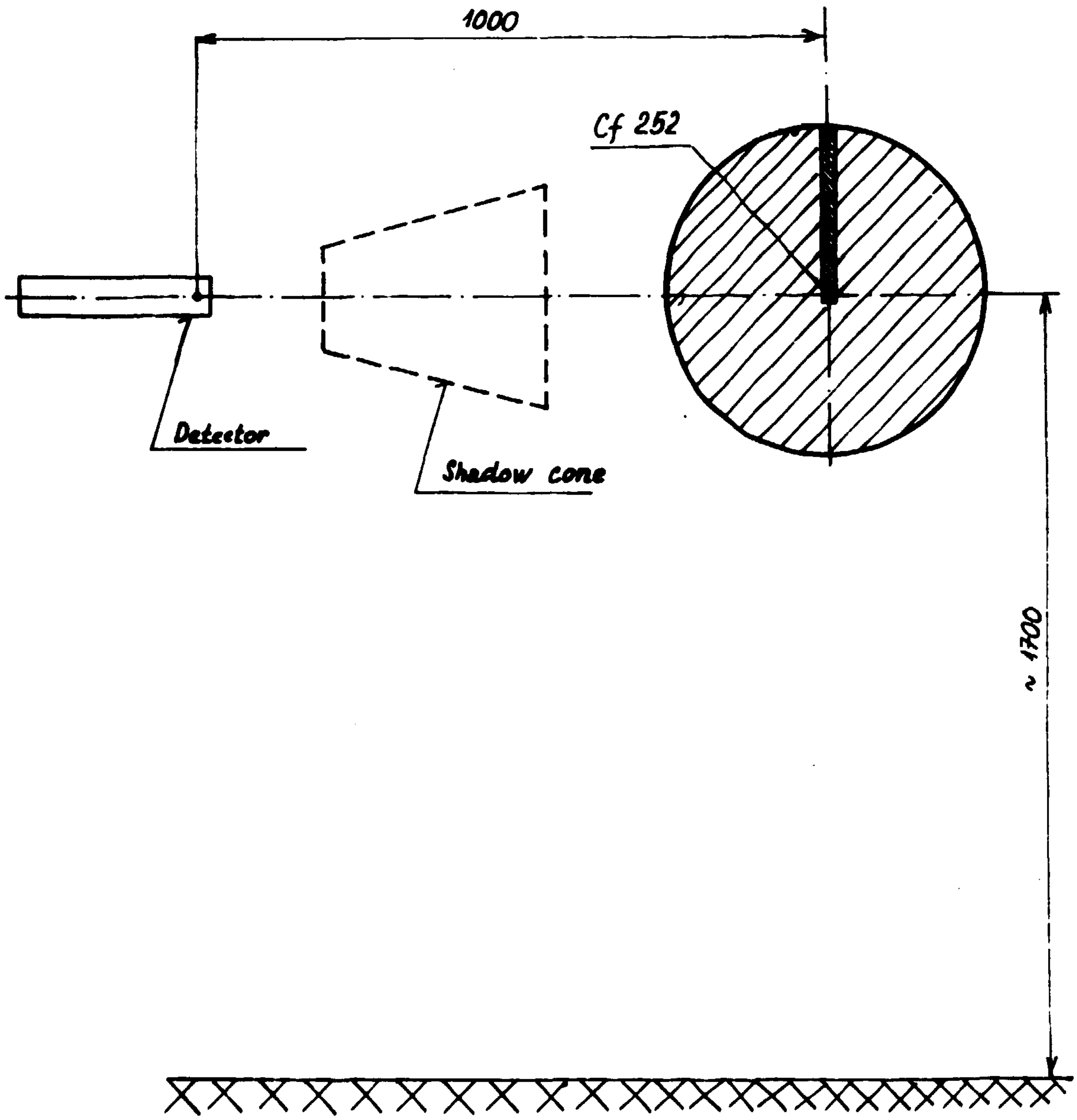
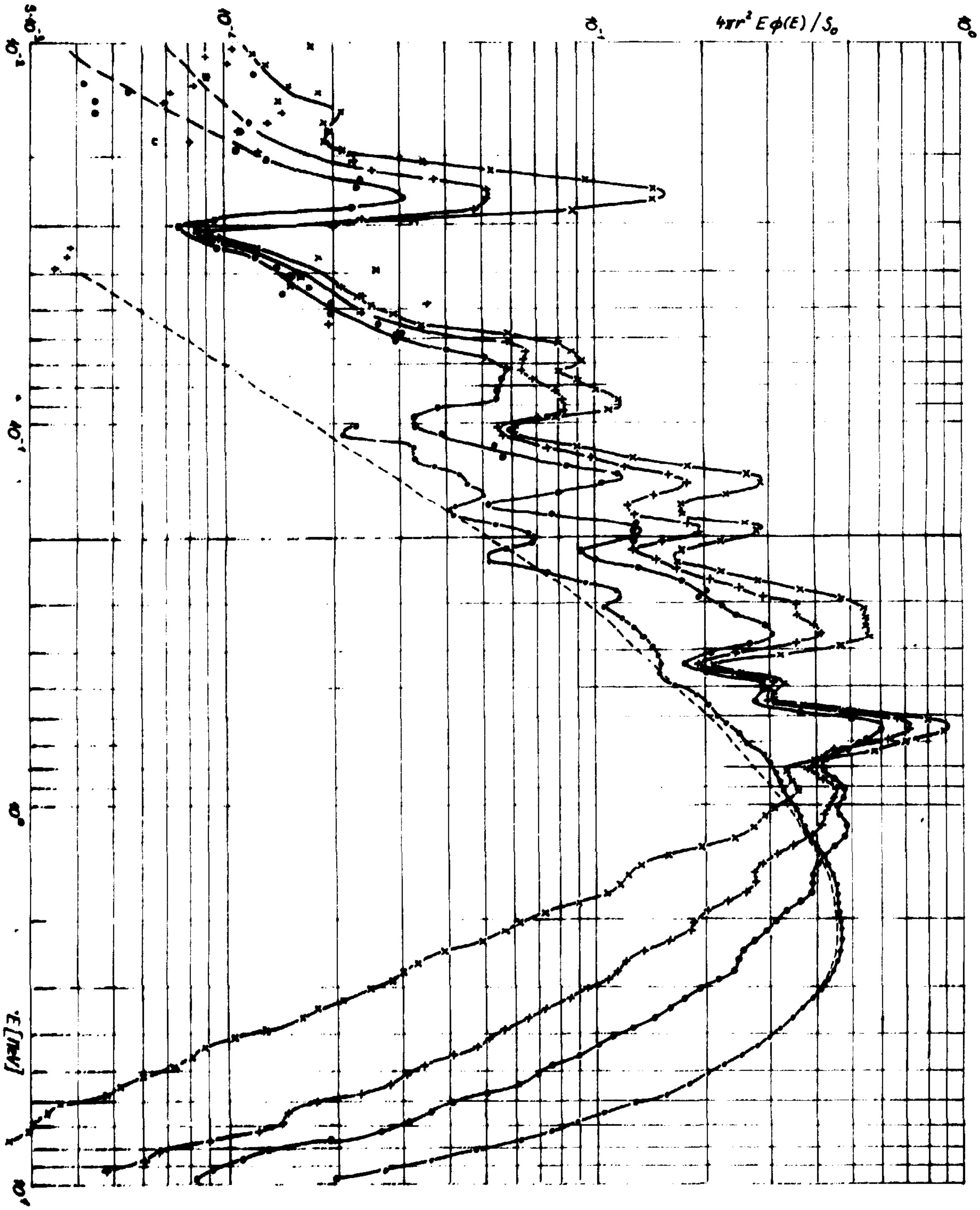


Fig. 1. Arrangement of the experiment

Fig. 3. The spectrum of neutrons emitted by fission of Cf 252 (•), and the spectra of neutrons escaping from iron spheres dia 20 (•), dia 30 (+), and dia 50 (x). Broken line denotes theoretical spectrum of Cf 252 /8/. Values normalised to one neutron emitted by the source.



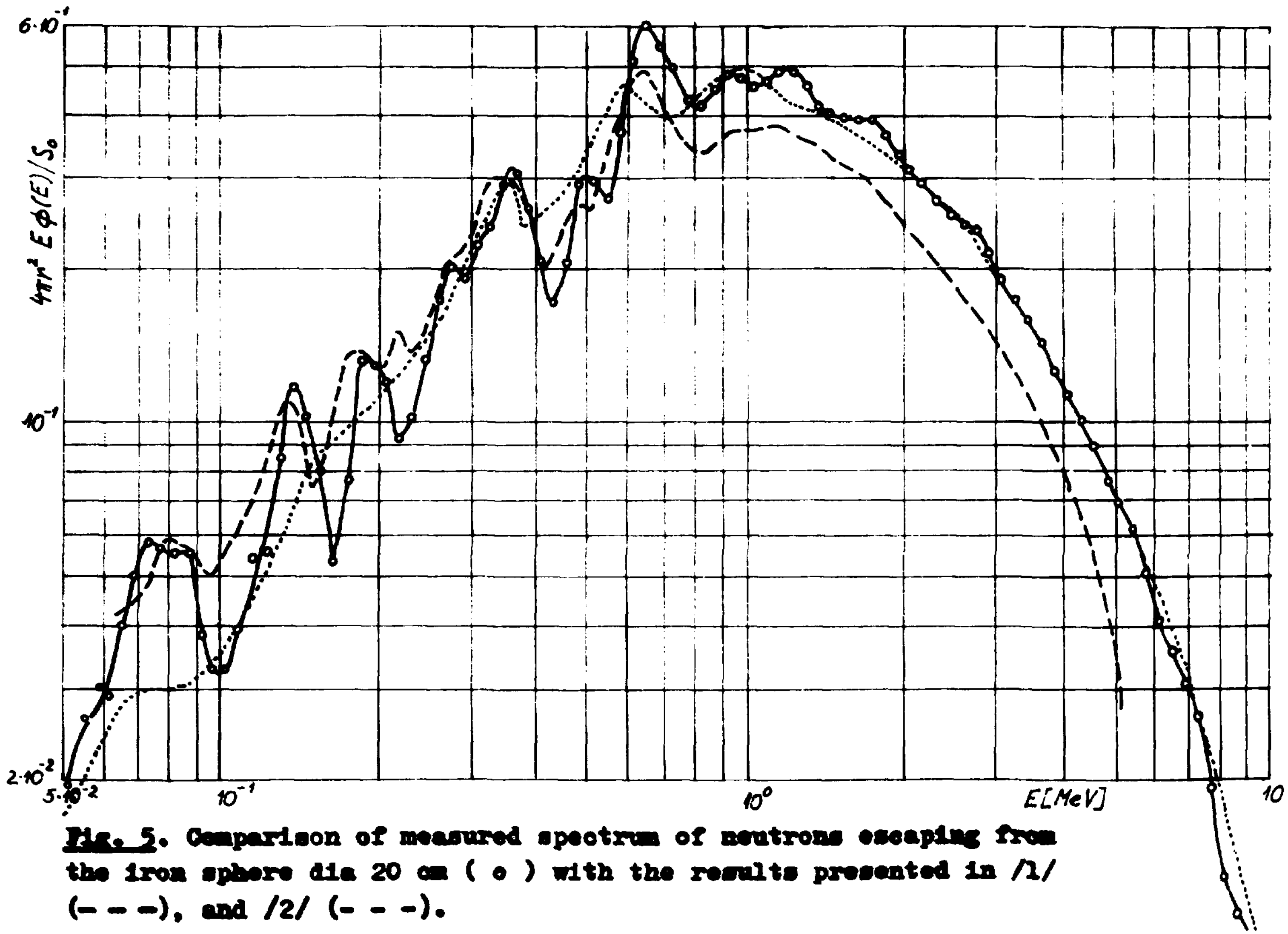


Fig. 5. Comparison of measured spectrum of neutrons escaping from the iron sphere dia 20 cm (o) with the results presented in /1/ (– – –), and /2/ (- - -).

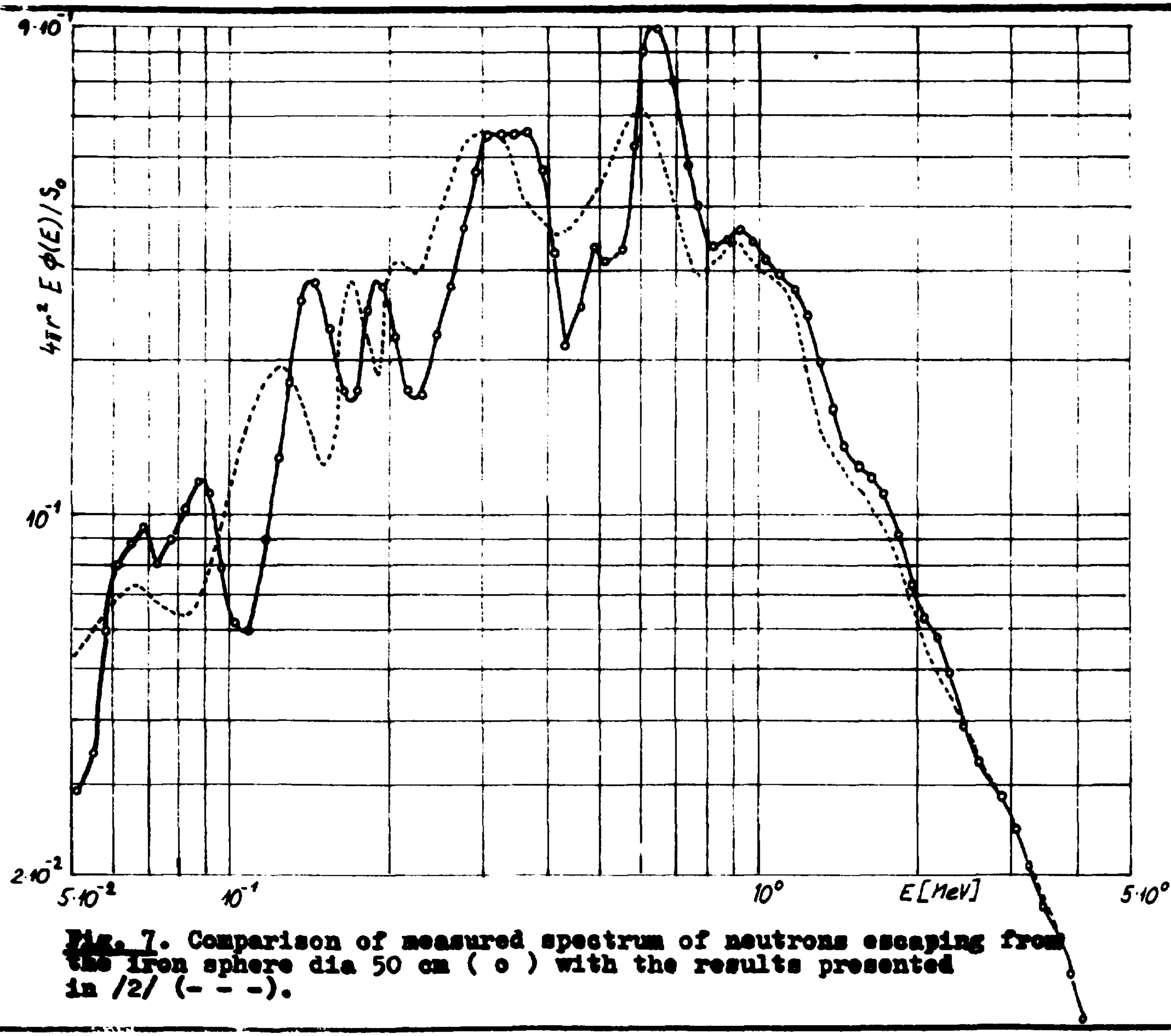


Fig. 7. Comparison of measured spectrum of neutrons escaping from the iron sphere dia 50 cm (o) with the results presented in /2/ (- - -).

Table 1 - continuation

E(MEV)	CF-252 1.MEAS.	CF-252 2.MEAS.	CF-252 AV.	IRON SPHERES DIA 20CM	IRON SPHERES DIA 30CM	IRON SPHERES DIA 50CM
.729	.295	.289	.292	.500	.521	.575
.688	.256	.253	.255	.552	.637	.715
.650	.251	.249	.250	.609	.722	.896
.613	.228	.227	.228	.501	.666	.804
.579	.219	.216	.217	.368	.481	.525
.547	.206	.204	.205	.274	.297	.327
.516	.199	.181	.190	.290	.300	.314
.487	.155	.169	.162	.288	.308	.335
.460	.140	.162	.151	.204	.243	.255
.434	.155	.153	.154	.174	.194	.214
.410	.164	.138	.151	.211	.248	.328
.387	.159	.133	.146	.266	.359	.472
.365	.134	.140	.137	.309	.420	.560
.345	.124	.129	.127	.295	.397	.558
.326	.119	.119	.119	.243	.358	.557
.307	.101	.110	.100	.226	.356	.555
.290	.117	.124	.120	.193	.289	.471
.274	.122	.110	.116	.204	.252	.366
.259	.105	.826-01	.942-01	.174	.211	.281
.244	.811-01	.686-01	.748-01	.132	.172	.225
.281	.542-01	.492-01	.517-01	.101	.149	.170
.218	.483-01	.583-01	.533-01	.923-01	.127	.176
.205	.640-01	.730-01	.685-01	.129	.155	.223
.193	.529-01	.738-01	.633-01	.130	.193	.279
.183	.356-01	.551-01	.453-01	.134	.179	.257
.173	.391-01	.375-01	.383-01	.770-01	.130	.174
.163	.537-01	.360-01	.438-01	.524-01	.126	.173
.154	.440-01	.467-01	.456-01	.800-01	.146	.231
.145	.448-01	.396-01	.422-01	.106	.180	.285
.137	.375-01	.373-01	.374-01	.117	.161	.259
.130	.437-01	.223-01	.330-01	.843-01	.122	.181
.122	.375-01	.284-01	.329-01	.563-01	.981-01	.127
.116	.205-01		.205-01	.540-01	.654-01	.901-01
.109	.230-01		.230-01	.393-01	.567-01	.594-01
.103	.232-01		.232-01	.331-01	.548-01	.618-01
.972-01				.327-01	.704-01	.787-01
.918-01				.379-01	.833-01	.111
.866-01				.554-01	.809-01	.116
.818-01				.555-01	.779-01	.102
.772-01				.573-01	.677-01	.898-01
.729-01				.592-01	.634-01	.804-01
.688-01				.502-01	.640-01	.947-01
.650-01				.400-01	.647-01	.878-01
.613-01				.289-01	.583-01	.799-01
.579-01				.304-01	.295-01	.585-01

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ABSTRACT

The report describes measuring the spectra of neutrons escaping from the surface of iron spheres in energy interval from 10 keV up to 10 MeV. The measurement has been performed using a scintillation spectrometer having a stilbene crystal, and a proportional counter SP-2 filled with hydrogen under 392.4 kPa of pressure. Used spheres had diameters of 20, 30, and 50 cm, Cf 252 being used as a source of neutrons.

2. DESCRIPTION OF THE EXPERIMENT

The arrangement of the experiment is shown in fig. 1. The iron spheres have been suspended some 1.7 m above the floor of the laboratory, and the source inserted into the sphere through a cylindrical channel dia 20 mm. The channel has been then closed by an iron plug. The effective thickness of the iron for the penetration of neutrons has been therefore less than the actual radii of the spheres by half the size of the central hollow cavity dia 20 x 20 mm. Shielding cone filled with water containing 40 g/l of boric acid has served for the measurement and elimination of neutrons scattered from the construction and walls. The distance of 1 m between the source and the detectors guaranted practically point geometry of both the source and detector. Angular orientation of the detectors in relation to the source has been chosen in such a way as to place both the stilbene crystal axis and SP-2 hydrogen chamber anode on the line connecting the source with the detector. In order to suppress the soft gamma radiation, both types of used detectors have been provided with a 4 mm thick envelope of lead. This wrapping of detectors into lead we commonly use in fields with a high predominance of photons, and it is the reason why we have used it also here, even if it has not been absolutely necessary.

The spectrum of the Cf 252 neutron source has been measured twice, i.e. prior to and after the measurement with the iron spheres. The measurement has been repeated in order to verify the long-term stability of the measuring set. The measurement of one arrangement took approximately 10 hours so that the overall time of the experiment amounted to some 250 hours.

The background of the scattered neutrons measured with the shielding cone has been read off directly in the pulse height spectra. All results have been normalized to one neutron emitted by the source, the normalizing constant being determined from the preset neutron emission of $2.35 \times 10^6 s^{-1}$ from 1 μgram of Cf 252 /3/. The density of the neutron flux (the normalizing constant) corresponding to 420 μg of Cf 252 in 1 m from the source will be then $7.8 \times 10^3 s^{-1} cm^{-2}$.

Energy resolution of the hydrogen chamber SP-2 is 5.1 % (E = 770 keV) while that of the stilbene crystal scintillation spectrometer amounts to some 10 % (E = 1 MeV). The energy scale of the scintillation spectrometer has been carried out by measuring the Compton edges (Ra 226). The energy calibration of the hydrogen chamber has been performed directly with respect to striking resonances in the spectrum of neutrons behind iron.

The neutron spectra as obtained from pulse height spectra have been evaluated by means of programs "ENKA" and "SPE" or "SPEC", language FORTRAN ADT. The program "ENKA" serves for evaluating the energy calibration of detectors while the other two programs are used to the evaluation of neutron spectra. As distinct from "SPE", the program "SPEC" takes into account corrections of proton spectra as obtained by scintillation spectrometer for the escape of protons and for doubled scattering of neutrons in the crystal of stilbene /5/. Concerning crystal dia 10 x 10 mm, the influence of the abovementioned corrections is negligible. Proton spectra as measured by the hydrogen chamber are in both programs corrected for proton escape from the detector. In doing it, an analytical technique mentioned in /5/ and /6/ is used. According to /7/, corrections obtained calculationally differ significantly from those obtained by experimental means. This is attributable mainly to differences in the amount of gas amplification of the spherical detector along its anode because this results in the creation of practically unknown spaces of limited gas multiplication. Assuming the effective radius of the detector less by 10 % in comparison with actual value, the comparison of neutron spectra performed with due account to both experimental /7/ and calculated corrections gave a good agreement in the shape of the spectrum. In addition, if the comparison is based on using the effective radius, the absolute values of neutron spectra approach much closer the actual ones. Because the spherical hydrogen chambers cannot be regarded as detectors of absolute values of neutron flux densities, the spectra obtained by their means are normalized to values measured by the scintillation spectrometer in the region of their overlapping. After corrections of measured proton

An insignificant softening of the measured spectrum between 1 and 3 MeV may be attributable to neutron interactions in the suspension, source casing and mainly in the lead envelope of the detectors. In energy region below 1 MeV, the softening of the spectrum is more striking and it exhibits even a resonance nature. This fact has been found practically analogical in both measurements of the spectrum. It is assumed that also this effect is caused by parasitic scattering of the neutrons.

One of our goals consisted in comparing the results with those presented in /1/ and /2/. In /1/, the authors have measured iron spheres up to a diameter of 45 cm, while in /2/ no results of measuring Cf 252 source have been available. In /1/, the neutron spectra have been measured by means of cylindrical chambers filled with pressurized hydrogen (293.4 kPa and 147 kPa), crypton (147 kPa), and methane (293.4 kPa). In /2/, a combination method has been adopted, i.e. a stilbene crystal scintillation spectrometer and a cylindrical chamber. The chamber, denoted SNM 38, has been filled with 294.3 kPa of hydrogen. The lower limit of measured neutron spectra has been 60 keV in case /1/ and 50 keV in the latter.

Comparison of Cf 252 measured neutron spectra suggests (fig. 4) that spectrum according to /1/ deviates more from the theoretical one /8/ below 800 keV. On the other hand, our results performed on iron spheres dia 20, 30 cm (fig. 5 and 6) are in good concordance with /1/ both from the viewpoint of shape, and absolute values in the region between 100 and 650 keV. For the energy of some 650 keV the spectra exhibit a stepwise increase of deviation. For energies exceeding 650 keV the spectra have a similar shape, but their values are shifted by some 30 %. It is probable that the difference in the results occurred during "putting together" of individual components of the spectrum as obtained by various detectors.

Our results are in much better concordance with /2/ if considered from the viewpoint of absolute values of neutron spectrum (fig. 5, 6, and 7). For energies exceeding 800 keV

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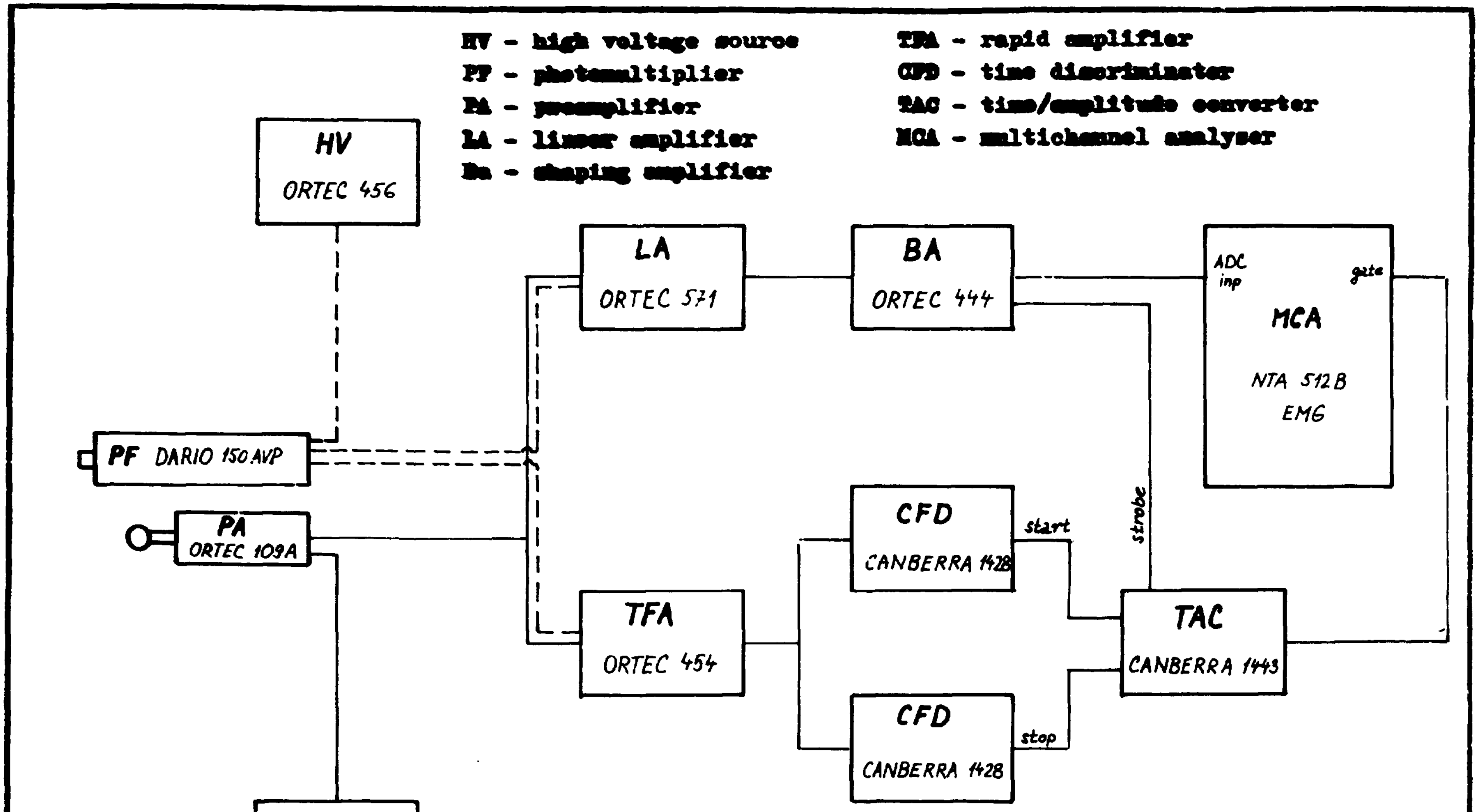
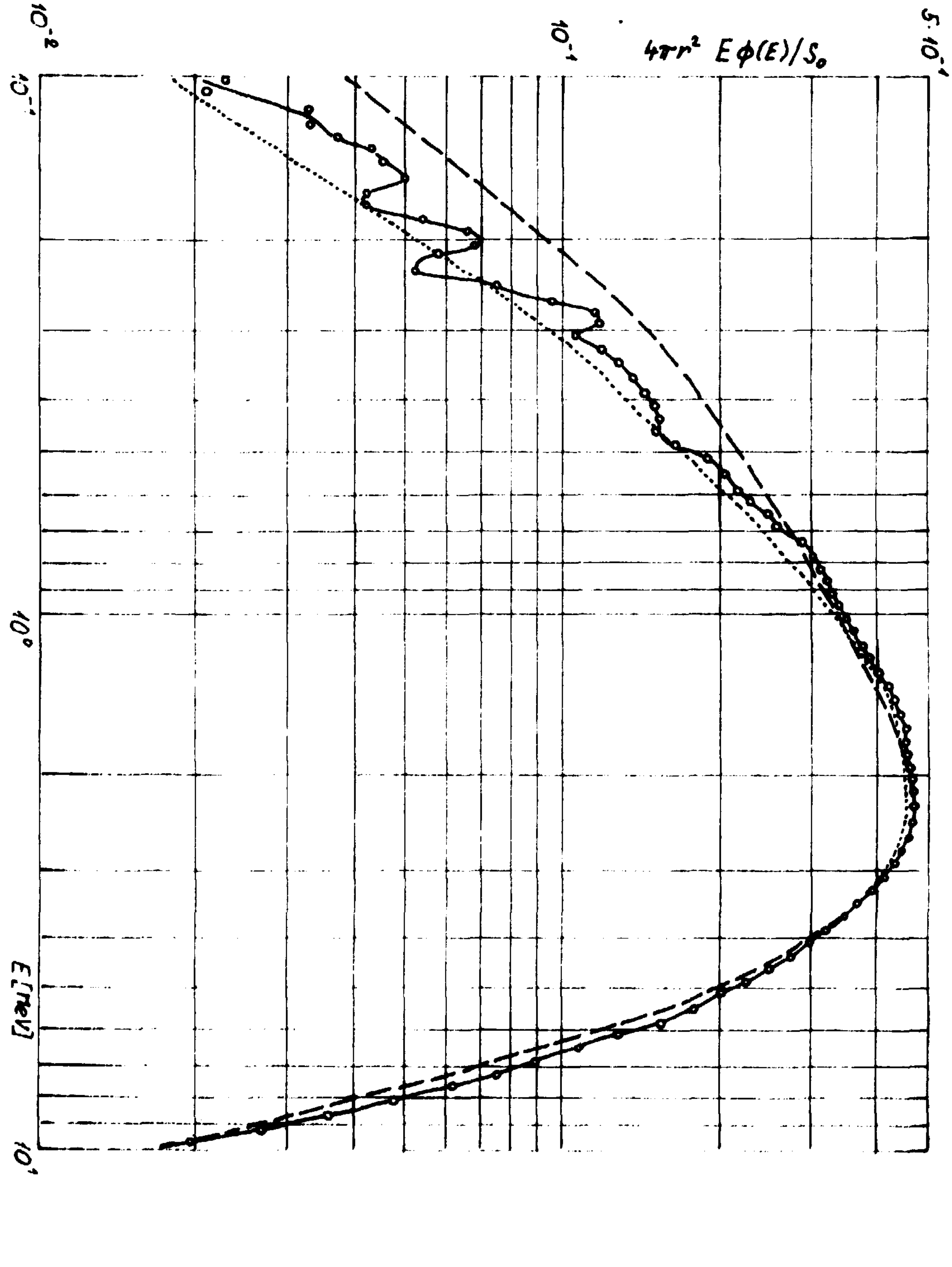


Fig. 2. Functional arrangement of the measuring setup (broken lines denote different connection of the scintillation spectrometer)

Fig. 4. Comparison of measured neutron spectrum of Cf 252 (o), with calculation; (- - -) - according to /8/, (— — —) - according to /1/.



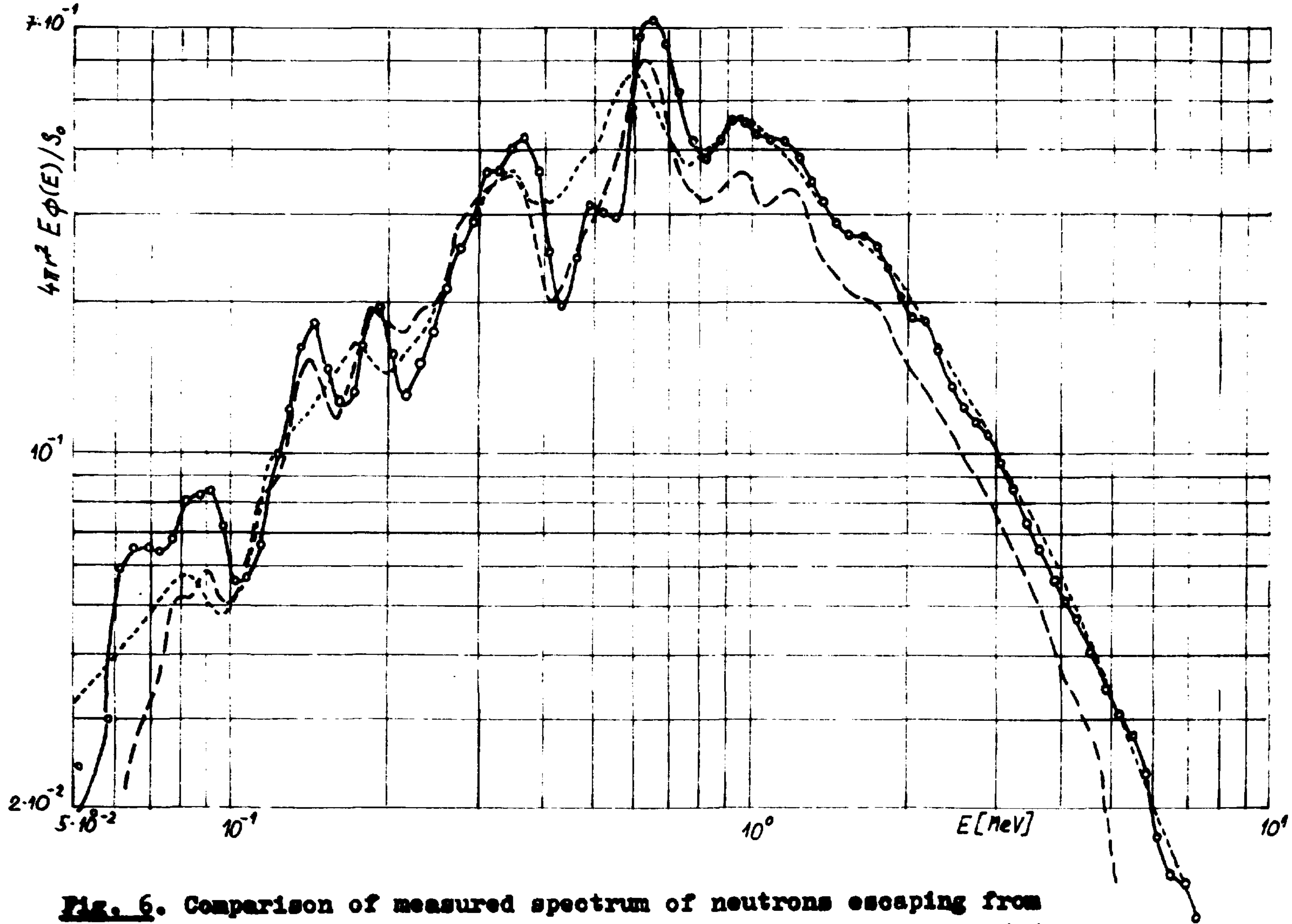


Fig. 6. Comparison of measured spectrum of neutrons escaping from the iron sphere dia 30 cm (o) with the results presented in /1/ (— — —) and /2/ (- - -).

Table 1. Spectra of neutrons $4\pi r^2 \cdot E \cdot \phi(E)$ normalized to unity yield of the source $(1/4\pi \cdot s)$, E denoting the average energy of the given group.

E(MEV)	CF-252 1.MEAS.	CF-252 2.MEAS.	CF-252 AV.	IRON SPHERES DIA 20CM	IRON SPHERES DIA 30CM	IRON SPHERES DIA 50CM
.972+01	.189-01	.200-01	.195-01	.814-02		
.918+01	.258-01	.273-01	.265-01	.925-02	.477-02	
.866+01	.345-01	.365-01	.355-01	.108-01	.606-02	.854-03
.818+01	.452-01	.479-01	.465-01	.129-01	.658-02	.195-02
.772+01	.580-01	.663-01	.621-01	.192-01	.902-02	.262-02
.729+01	.711-01	.816-01	.764-01	.265-01	.121-01	.294-02
.688+01	.846-01	.910-01	.878-01	.312-01	.140-01	.300-02
.650+01	.972-01	.112	.992-01	.357-01	.145-01	.330-02
.613+01	.119	.135	.127	.408-01	.175-01	.358-02
.579+01	.150	.157	.153	.503-01	.233-01	.486-02
.547+01	.176	.184	.180	.616-01	.278-01	.514-02
.516+01	.194	.206	.200	.693-01	.302-01	.603-02
.487+01	.223	.233	.228	.762-01	.343-01	.723-02
.460+01	.248	.256	.252	.898-01	.407-01	.810-02
.434+01	.263	.284	.274	.101	.476-01	.885-02
.410+01	.290	.308	.299	.112	.515-01	.103-01
.387+01	.312	.329	.320	.128	.563-01	.128-01
.365+01	.346	.351	.348	.144	.647-01	.160-01
.345+01	.364	.377	.370	.161	.733-01	.175-01
.325+01	.383	.402	.393	.175	.845-01	.207-01
.307+01	.409	.427	.418	.192	.958-01	.245-01
.290+01	.425	.446	.435	.219	.110	.284-01
.274+01	.449	.456	.452	.241	.114	.298-01
.259+01	.452	.464	.458	.246	.123	.333-01
.244+01	.463	.469	.466	.254	.137	.389-01
.230+01	.462	.474	.468	.273	.161	.494-01
.218+01	.471	.473	.472	.294	.186	.575-01
.205+01	.468	.476	.472	.312	.187	.626-01
.194+01	.450	.482	[illegible]	.334	.201	.731-01
.183+01	.454	.478	.466	.364	.230	.903-01
.173+01	.452	.472	.462	.392	.259	.109
.163+01	.455	.455	.455	.393	.273	.117
.154+01	.444	.442	.443	.393	.274	.123
.145+01	.430	.430	.430	.402	.288	.135
.137+01	.417	.421	.419	.419	.318	.160
.130+01	.400	.410	.405	.455	.351	.197
.122+01	.382	.390	.386	.484	.389	.242
.116+01	.376	.378	.377	.487	.418	.275
.109+01	.367	.366	.366	.463	.421	.291
.103+01	.358	.363	.360	.456	.433	.318
.972	.347	.345	.346	.476	.451	.342
.918	.338	.336	.337	.480	.460	.361
.866	.337	.319	.328	.451	.421	.345
.818	.319	.313	.316	.418	.385	.335
.772	.310	.308	.309	.431	.420	.401

Table 1 - continuation

	CF-252	IRON SPHERES		
E(MEV)		DIA 20CM	DIA 30CM	DIA 50CM
.547-01		.263-01	.189-01	.345-01
.516-01		.195-01	.235-01	.289-01
.487-01		.195-01	.257-01	.252-01
.460-01		.143-01	.238-01	.231-01
.434-01		.172-01	.109-01	.152-01
.410-01		.155-01	.151-01	.161-01
.387-01		.140-01	.345-02	.260-01
.365-01		.122-01	.371-02	.181-01
.345-01		.972-02	.380-02	.111-01
.326-01		.893-02	.970-02	.928-02
.307-01		.756-02	.199-01	.833-02
.290-01		.948-02	.235-01	.324-01
.274-11		.225-01	.476-01	.874-01
.259-01		.311-01	.512-01	.145
.244-01		.232-01	.507-01	.144
.231-01		.236-01	.372-01	.948-01
.218-01		.132-01	.252-01	.536-01
.205-01		.10[illegible]-01	.227-01	.346-01
.194-01		.649-02	.123-01	.211-01
.183-01		.113-01	.795-02	.186-01
.173-01		.118-01	.108-01	.197-01
.163-01		.541-02	.135-01	.186-01
.154-01		.456-02	.144-01	.214-01
.145-01		.450-02	.673-02	.137-01
.137-01		.557-02	.702-02	.181-01
.130-01		.418-02	.834-02	.147-01
.122-01		.123-01	.907-02	.901-02
.115-01		.156-01	.102-01	.131-01
.109-01		.133-01	.906-02	.118-01
.103-01		.113-01	.106-01	.175-01
.972-02		.925-02	.101-01	.168-01
.918-02				.146-01
.866-02				.126-01
.818-02				.931-02