FORSCHUNGSZENTRUM
ROSSENDORF e.V.

FZR

FZR 93 - 11
April 1993

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Neutronic Problems of a Compact 14 MeV Plasma Neutron Source

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Abstract

Some neutronic problems connected with the design of a compact 14 MeV neutron source for fusion material research based on a plasma mirror are treated.

Contents

1. Introduction

The development of proper materials for manufacturing the various components of future fusion reactors is a major issue of fusion technology. Such materials should be able to withstand the neutron fluence of the 14 MeV DT-neutrons and their secondaries during the life span of the reactor (10-30 MeV a m^{-2} as a near term goal) without too serious deterioration of their mechanical properties. Fusion reactor materials are furthermore demanded to become only weakly activated when exposed to the fast fluence, in order to mitigate the problems of radioactive waste disposal and of radiation hazards during maintenance.

Fusion material research has widely tackled the above mentioned problems in the past. But progress is largely hampered by the lack of a sufficiently intense source of 14 MeV neutrons, the source strength of existing neutron generators beeing at least five orders of magnitude below the demand. Thus, material researchers were forced to resort to the simulation of radiation damage by irradiation of samples in fast fission reactors as well as by irradiation with accelerated charged particles. But the weight of the main damage mechanisms (by displacement of atoms in scattering collisions and through gas production in n, ^{4}He and n,p-reactions) is much different in fission neutron fields and 14 MeV fields. Thus it is not straightforward to translate results from simulation irradiations to fusion reactor conditions. Therefore, an intense source of fast 14 MeV neutrons would be valuable for executing comparison experiments ("calibrations") with microsamples, even if the intensity of the source is insufficient for end-of life tests. But one can hardly imagine that fusion power reactors will be built without numerous end-of-life tests of the involved materials. For confirmation of this assertion, the historic analogy of the commercialization of fission reactors may be cited: The present know-how in fission reactor materials is the result of irradiations in some sixty odd experimental reactors lasting tens of years. Hardly fusion material problems are much easier.

The solution of the second of the mentioned tasks, the selection of low activation materials is yet more dependent on the availability of an intense 14 MeV source. Sequential and exotic reactions as well as activation of low level impurities can neither be modelled by charged particles nor by neutrons of lower energy.

For the past decades several concepts for creating a neutron source dedicated to fusion material research have been discussed on a series of conferences (see e.g. 1,2). Most of the proposals are based on accelerators and targets using one of the neutron producing reactions, the preferred combination being a linear accelerator for an intense 35 MeV deuteron beam and a Li-target for the Li(d,nx) stripping reaction. The most serious program to realize such a project has been the american FMIT, started in 1978 and virtually abandoned a decade ago. Efforts for developing accelerator based neutron sources are continuing. Especially the Japanese ESNIT project of a D-Li source is pursued actively. Such a source would be extremely valuable, particularly for the purpose of the "calibration" mentioned above.

Nevertheless, more and more members of the community are coming to the conclusion, that accelerator based neutron sources will never be able to solve the problem of end-of-life tests of macrosamples and components. There is a number of reasons supporting such an attitude. First of all, the operations costs, in particular electricity costs, would be prohibitively high if the intensity could really be raised to about 1 MW neutron power. Secondly, irradiation volumes will be restricted too much. Last but not least, the spectrum of primary neutrons has only the right average energy of 14 MeV but not the proper shape of a line at this energy. This leads to ambiguities in the interpretation of results, especially in activation experiments. E.g. threshold reactions can have zero cross-section in the true fusion spectrum and finite yields in the D-Li spectrum.

Therefore, a final solution of the problem is rather to be expected from DT-plasma devices themselves. But by their very nature neutron producing Tokamaks are big and expensive machines. If one would wait for tokamaks to irradiate materials to end of life, this would postpone the introduction of fusion reactors by decades. This is why a more compact (higher flux) and less expensive plasma device is demanded. A possible candidate is the mirror machine. There is a number of proposals for neutron sources based on such machines /3-4/. The most attractive, from the point of view of its technical realization, is probably the Novosibirsk concept of the Gas Dynamic Trap GDT /3/, although its plasma physics data base is less proven than that of /4/. Only for the GDT an attempt for a technical predesign of a neutron source is known /6/. The present paper treats some neutronic problems pertaining to this design in particular and to plasma mirror sources in general. Indeed, it is by no means obvious that the sensitive parts of such a compact, high flux device can be shielded properly. After all, space for shields is yet more limited than in Tokamaks.

All the neutron-gamma transport calculations have been performed by the Los Alamos Monte Carlo transport code MCNP /7/ version 3B3. Extensive use has been made of the weight window variance reduction techniques. Generally statistical errors were kept below 3 %. As a neutron-gamma data base generally ENDF/B-IV was used, no more modern version of ENDF/B beeing at our disposal. As the gamma production data in B-IV appear to be obsolete, comparisons with results from ENDL-85 were carried out. No striking differences were detected.

2. General description of the source

Before dealing with the problems of shielding, a general description of the source must be given. Figure 1 taken from /3/ gives an idea of the left half of the device. A relatively cold (T = 0.5 - 1 keV) and dense (3×10^{14} cm^{-3}) DT plasma is confined by an axially symmetric magnetic field B shown below the draft. The field is generated by a series of superconducting coils 5 and, in its high intensity mirror part (25 T), by a hybrid magnet containing a superconducting outer coil 3 and water cooled inner coil 4. To maintain MHD stability the magnetic field as well as the plasma extend to the left beyond the mirror. Through the inclined beam duct shown on the figure an intense beam of neutral tritons, deuterons or a mixture of both is injected into the plasma. There the main part of the beam is ionized and trapped. The fast D and T ions gyrate around the magnetic field lines. Simultaneously they move along the field, as injection was effected at an angle of 30° with respect to the field direction. The ions are reflected from the mirrors and move many times to and fro. The maxima of neutron generation in reactions of the fast ions among themselves as well as between fast ions and cold plasma ions will be at the turning points, where the axial ion velocity is slowed down to zero. By means of the hump in the magnetic field arranged to the right of the maximum (see curve B of fig. 1), this turning point is shifted away from the mirror magnet. This is why the distribution of neutron source strength F shown in the lower part of the picture does not extend just to the mirror magnet. This is an essential feature of the concept, reducing the radiation charge to the mirror magnet. Another useful particularity is that the beam duct is not aimed at the source region, whereby undue irradiation of the source of neutrals is avoided. There is no need to have any feedthroughs, antennae nor other sensible parts in the immediate vicinity of the neutron source region.

3. Optimization of shield composition

The problem of optimizing the shield composition is still more important for a compact neutron source than it is for a Tokamak like ITER. It is well known that mixtures of a metal like iron or tungsten, a hydrogen containing moderator like water together with a boron compound for neutron absorption are to be favoured. Of course, in its general form the task has too many dimensions. Their number should be diminished by practical considerations. In the present paper the moderator and the neutron absorber were supposed to be an aqueous solution of 4 weight % boron acid (H_3BO_3) containing boron enriched to 80 % in ^{10}B. Similar solutions are applied in PWR for compensation of the reactivity reserve at the beginning of a fuel cycle. The chemical interactions of such kind of coolant with many materials under radiation conditions are well known. The selected concentration is well below solubility at room temperature.

Furthermore, the conditions of the optimization have to be fixed. However, as many as possible features typical for the task of shielding coils should be incorporated in these conditions. Since usually the admissible total dose (neutron + gamma) to the organic insulator determines the necessary thickness of the shield, the total dose W_{N+P} in epoxy resin was selected as the quantitiy to be minimized.
Eventually, penetration of a sphere reflected by copper of 0.8 natural density was chosen for the minimization. Figures 2-4 demonstrate the result of the optimization for iron and tungsten homogeneously mixed with the mentioned solution of boron acid in water. There are distinct minima at about 30 Vol % for Fe and about 15 Vol % for W on figs 2 and 3. Fig. 4 shows the attenuation of the total dose in epoxy after penetration of a sphere of radius r (apart from a geometrical factor $4\pi r^2$). The saving in thickness by using W instead of Fe amounts to 30-35 %. Whether this advantage is outweighed by the higher cost and much higher activation of W compared to Fe has to be decided in the frame of an overall design of the source. - In each of the pairs of close curves the upper one represents a homogeneous distribution of the aqueous solution in the metal, whereas the lower one represents a linear dependence of the volume content of water, with pure metal in the centre. This demonstrates, that the absolute minimum is not reached for a homogeneous distribution. But a search for the optimal distribution in a mathematical sense is certainly not worthwile in view of the expected marginal gain (about 3 % in thickness for the linear dependence), and in view of difficulties in realizing such a distribution. What remains is a hint to the designer to concentrate the metal near the first wall and to raise the water content near the coil.
A useful guide for the designer may be the following

DESIGNER'S RULE

The total dose at a point (the "detector") is approximately made up of two factors:

1 A geometry factor $1/4\pi r^2$, where r is the distance from the 14 MeV source to the detector.

2 Material attenuation factors $A(r) = 4\pi r^2 W_{N+P}$ as plotted for two materials in fig. 4, where r is the distance travelled by the neutron in the material on its way from the source to the detector.

The above rule has been checked for several complicated configurations. Sometimes it yields astonishing good results. Of course, it is not meant to replace true transport calculations. But it may be useful in estimating the effect of designer's variations of a starting configuration on the dose. Material attenuation factors for other materials as well as for other radiation loads besides the total dose (dpa in copper, fast fluence above 0.1 MeV) can be quickly produced for the shelf by calculations in spherical geometry.

4. Can the flux around 14 MeV be increased by reflectors?

Sometimes a positive answer to the question posed in the headline is claimed. In order to decide it, the following model was formulated as an input to the MCNP code:
An infinite source of 14 MeV neutrons is situated on the axis of an infinite cylinder. The surrounding reflecting material has an inner radius of 15 cm, outer radius 35 cm. The outer shield is pure iron up to 200 cm radius. Indeed, the results are virtually independent of the geometry and the composition of the outer shield.

For various neutron energy intervals the "gain", i.e. the ratio of the flux at the inner surface of the reflector to the flux of 14 MeV neutrons at that surface in the absence of any material has been calculated. Neutron data are extracted from the ENDL-85 library. Use of ENDF/B-IV does not change the picture.

Results are shown in the table 1. The second column demonstrates, that the gain in the 6.5 - 14 MeV interval is marginal, at maximum in the 10 % range. But only these energies are of interest for fusion material research.

The diagram fig. 5 shows as an example the spectrum for a lead reflector in lethargie representation (i.e. energy axis is in logarithmic scale, the number of neutrons in a certain energy interval is proportional to the area under the histogram). The spectra with all the other reflecting materials are of the same type. Generally, this kind of spectra with the 14 MeV peak, a valley beneath and a broad hill in the MeV range is well known from the so called deep penetration case. Evidently they are already typical in the vicinity of the source.

The next fig. 6 contains the spectrum of Fe together with the so called CTR-standard spectrum /9/, which material scientists would like to be realized in a neutron generator.

Thus, the task of approximating this spectrum leaves virtually no room for manoeuvring with reflecting materials in order to raise the flux in the high energy part.

The reason for the lack of a useful reflector for 14 MeV neutrons is simple: The share of the elastic scattering cross-section in the total cross-section is too low for all the nuclides. But elastic scattering is the only process turning the neutrons back to the source without significant loss of their energy.

Table 1

Gain of reflecting materials (14 MeV neutrons themselves excluded)

	6.5 - 14 MeV	0.1 - 14 MeV	0 - 14 MeV
C	.226	1.20	4.64
Na	.075	1.16	1.742
Ti	.123	3.25	4.17
V	.057	3.54	4.60
Cr	.107	3.16	4.52
Cu	.098	4.20	5.35
Zr	.055	5.03	6.92
Fe	.093	2.85	3.62
Ni	.102	2.16	2.66
Mo	.054	5.50	6.25
Ta	.095	4.05	4.15
W	.091	4.81	5.57
Pb	.083	6.66	8.71
Bi	.069	6.02	7.43

5. Radiation limits

Evidently, the most exposed parts of the projected neutron source are the superconducting winding of the coil generating the hump in the magnetic field of fig. 1, the superconducting part of the hybrid mirror magnet and the inner edge of the warm insert of this same magnet. The two SC coils mentioned will be made of Nb_3Sn or some future high field superconductor. The radiation limits of such coils are the subject of research in the frame of the ITER program /11/. The values adopted at present /8/ are shown in table 2.

Table 2

Radiation limits of superconducting coils

Total dose to electrical insulator	5×10^9 rad
dpa in copper stabilizer	6×10^{-3} dpa
neutron fluence to Nb_3Sn superconductor ($E_n > 0.1$ MeV)	1×10^{19} cm^{-2}

On the contrary, the radiation damage of the warm part of the mirror magnet is a particular problem proper to the neutron source, without any correspondence in the Tokamak development. On the one side the winding of the end magnet, made of a copper alloy and operated at room temperature, is less radiation sensitive than the materials of superconducting coils. Besides, being less precious, the inserts can be changed more frequently, say once a year. On the other side the possibilities of shielding the sealing magnets are much more restricted.

There are two radiation limits for the warm part of the mirror magnet to be established, for the insulator and for the conductor.

As the radiation resistance of insulating materials at room temperature is concerned, it has been the subject of broad research (see the reviews /12,13/). Considerable experience has also been accumulated in the construction of radiation resistant bending magnets for high energy accelerators /14,15/. In the last paper a rapid degradation of mechanical properties of polyimide preimpregnated glass cloth was observed beyond 4×10^{10} rad, with essentially no changes below this level. Inorganic insulators like cement can stand higher doses. But there is no example of a high field (in the range of 25 T) magnet with inorganic insulators. It is certainly hard to predict the dose limit, insulators in the warm end magnet will stand. Evidently conditions are not as hostile as they are in cryogenic magnets, where gaseous products produced by irradiation are frozen out during operation and evaporated during warm-up periods. The limit should therefore be between the 5×10^9 rad for SC magnets and the observed 4×10^{10} rad of /15/. We adopt 2×10^{10} rad.

The problem of radiation damage to the conductor of the mirror magnets is still less well defined. Certainly the windings are to be made of some high strength, well conducting copper alloy (see the recent review on high field stationary magnets /16/). Irradiation induces changes in volume (swelling), yield strength and conductivity. Small doses of the order of 10^{-2} dpa lead even to an increase in yield strength /17/ (radiation hardening), but high doses in the dpa range induce a strength reduction /18,19/. The electric conductivity of all the highly conductive alloys too is reduced by irradiation. Of course, it is rather difficult to evaluate, what a level of the three enumerated damage phenomena will lead to a failure of the warm mirror magnet as a whole. But looking at the body of damage data in copper alloys collected particularly in /18/, and having in mind that a 25 T dc magnet is operated not much below the limits set by tensile strength of its conductor, one has the impression that it would probably bear 2 dpa in copper. Of course, this is a subjective judgement.

6. Evaluation of radiation loads to magnets in a compact plasma neutron source

The neutronic model of the Efremov source predesign IN-1 used as input to MCNP is visualized in fig. 7. This is of course an idealization, even of the first tentative design. Nevertheless it should retain enough essential to neutronics features, in order to produce the base for a next step. The exact spatial distribution of the source strength is not essential. Anticipating problems with housing the necessary shields in the compact source design, tungsten was selected as the principal shield component, the other components beeing determined by the optimization of section 3. Certainly tungsten has the disadvantage of a high activation level. But anyway hands-on maintenance is excluded for the source, and remote handling is foreseen from the very beginning in /6/.

The most exposed parts of the magnet systems are (see fig. 7):

1. position 1, a ring on the bobbin of the SC magnet generating the field hump of fig. 1, located in the same plane as the centre of the source,

2. position 2, the ring-shaped edge of the SC part of the hybrid mirror magnet nearest to the source,

3. position 3, the innermost ring-shaped edge of the warm insert of that magnet.

As usual, a life span of 10 full power years (FPY) was assumed for the SC coils of positions 1 and 2. For the warm coil of pos. 3 a more frequent change can be accepted. We tentatively adopted 1 FPY.
Results are listed in the following table 3.

Table 3

Results of transport calculations for neutronic model fig. 7 (s. text)

	position 1 10 FPY	position 2 10 FPY	position 3 1 FPY
total dose in epoxy /rad/	3.0E9 (.60)	3.4E11 (68)	3.9E10 (2)
dpa in Cu	7.9E-4 (.13)	8.5E-2 (14)	1.3E-2 (.007)
n-fluence (E_n>0.1 MeV) /cm^{-2}/	1.6E18 (.16)	2.3E20 (23)	1.4E19

In parentheses the ratio of the calculated result to the limit of the corresponding quantity at the corresponding position as established in section 5 are noted.
Obviously, the radiation loads to pos. 1 are well within admitted limits.
On the contrary, charges to the SC part of the mirror system pos. 2 exceed limits by two orders of magnitude - a factor of 68 for the insulation. The reason is rather manifest. In the present design neutrons penetrate from the irradiation zone 6 (fig. 7) via the coil structure 4 to the winding 3. This inadequacy can certainly be removed in a further stage of the design by covering the penetration channel with an adequate shield. Of course something most be sacrificed. Either the irradiation zone will be reduced or axial dimensions will be stretched, or a bit of both. In any case measures are expected to be tolerable.

As radiation damage to the warm insert at pos. 3 is concerned, no harm is predicted for the conductor itself, displacements per atom beeing well within the region of radiation hardening. But the limit for the organic insulator is exceeded twice. Formally one could consider a corresponding reduction of the campaign of the warm coils. Possibly a revised design of the source might include an increased distance of the magnet from the source and / or a reinforced shield wrapping the edge. A radical solution would be the development of a magnet with inorganic instead of organic insulation - admittedly a challenging task. In any case the mirror magnets are to become the subject of a special technological development, not just of design. Radiation resistance of insulators as well as corrosion in the combined radiation and magnetic fields will be one of the boundary conditions of the task.

7. Performance of the plasma neutron generator as a thermal neutron source

Certainly, the main field of application of an intense 14 MeV-neutron generator will be fusion technology, principally fusion material research and tests of low activation materials. On the other side there is a rising demand for thermal neutrons in condensed matter physics, biochemistry and other branches of science. Since the construction and even the operation of high flux research reactors suffer from dwindling public acceptance, rising operation costs, legal limits on the fuel enrichment stemming from nonproliferation conceptions etc. Thus it seems not vain to evaluate the possible parameters of a thermal neutron source consisting of a 14 MeV plasma source of the considered type surrounded by an appropiate moderator.

One can hardly imagine to conciliate the demands of fast neutron users with those of thermal neutron researchers in a single irradiation zone. But fortunately a mirror plasma device possesses two sources of 14 MeV neutrons at the turning points of the sloshing ions at both ends of the machine. Indeed, the proposals on which the present paper is founded /3,6/, foresee the boosting of the source strength in one of the zones at the expense of the other one. This is achieved by arranging a shoulder of the magnetic field in front of one of the bottle necks. In this shoulder region the injected ions are delayed for a long time and therefore induce more numerous D-T reactions than at the other end of the machine where they are rapidly reflected at the steeply rising magnetic field. But if one wants to get two decoupled source zones of equal strength one has only to chose a magnetic field symmetric with respect to the midplane with shoulders in front of either mirror. In this case the two zones have equal source strengths, the disadvantage beeing the reduction in intensity of the formerly favoured zone by a factor of almost 2.

For an exact formulation of the problem of determining performance parameters of a thermal neutron source one has to anticipate some design features of such a set-up. A thorough comparison with the possibilities of research reactors should also refer to a definite layout of the experimental channel. Nevertheless the simple neutronic model chosen here and represented on fig. 8 should give a crude impression of the possibilities. This arrangement comprises in infinite cylindrical geometry a central void, the thick moderator, shells of neutron and gamma absorbers (B_4C,Pb) and an infinite Cu-reflector imitating the superconducting coil. In a real thermal neutron source the coil will consist of two parts and in the gap between them neutron conducts will extend in radial direction similar to the spokes of a wheel.

The calculation starts from a source strength of 0.75 MW of 14 MeV neutrons was adopted, half of the 1.5 MW of the Novosibirsk proposal. This source is uniformely distributed over the volume of a cylinder 50 cm long and 3 cm diameter. Indeed, the exact spatial distribution of the source is irrelevant. The inner diameter of the moderator was chosen to be 30 cm. This is a rather conservative choice, in favour of a sufficient lifetime of the first wall. A reduced value of this diameter would somewhat raise the flux.

In order to obtain maximum thermal flux, the outer diameter of the moderating assembly should be as large as possible. On the other hand costs limit the diameter of the superconducting coils, within which the moderator must be housed. As a reasonable compromise the following principle has been adopted: The outer diameter of the moderator was fixed at such a value, that the addition of a few centimeters of boron carbide and lead screens neutrons and gammas to such a level, that the maximum permissible radiation dose to the epoxy isolation (5×10^9 rad) is just reached. In that case damage to the superconductor itself and to the matrix material remains within stated limits.

Finally the moderating material itself is has to be selected. It turned out that the only two promising candidates are beryllium and heavy water. This is partly due to their good moderating and excellent reflecting properties known from research reactors, partly also due to the neutron multiplication by the (n,2n) reaction in D and Be. Other materials, e.g. light water or lead show disappointing results.
Thus, two cases at all, for D_2O and for Be moderators were calculated. The results are shown in table 4 and figure 9.

The diameter necessary for shielding the coil windings is somewhat less in the case of beryllium, the achievable flux being about twice as high as for heavy water. But whether the material problems connected e.g. with swelling of Be due to the considerable He-production by the (n,2n) reactions can be solved is an open question.

Moreover the lower two curves in the figure 9 demonstrate the ratio of fast flux (10^{-6} to 13.9 MeV) to thermal flux as well as the ratio of 14 MeV-flux (> 13.9) to thermal one. For a possible estimation of the perturbation by the fast components in scattering experiments one has to have in mind that the fast flux is practically isotropic, whereas the 14-MeV flux is strongly directed outward ($1/r^2$ dependence).

Table 4

moderator	D_2O	Be
diameter void /cm/	30	30
diameter moderator	240	201
thickness B_4C	2	2
thickness Pb	8	10
diameter overall R	260	225
neutron fluence at R/limit	0.34	0.44
dpa in Cu at R/limit	0.19	0.19
dose in epoxy at R/limit	1.0	1.0
maximal thermal flux $cm^{-2}s^{-1}$	5E14	9E14

Summarizing this paragraph it can be stated, that a DT-plasma source can be converted into a thermal neutron source by addition of a moderator. The resulting thermal flux corresponds to that of a good, but not of an excellent research reactor. The diameter of the necessary superconducting coils does not exceed the dimensions of coils beeing developed for big tokamaks.

8. Conclusions

It has been demonstrated, that in a compact mirror based neutron source for fusion material research established radiation limits to the magnet system can be observed.
It appears not possible to raise the flux in the high energy part of the spectrum by arranging reflecting materials.
If one of the neutron generating zones of the machine is equipped with a moderator, it can be converted into a thermal neutron source with a flux of about 5E14 n $cm^{-2}s^{-1}$.

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Figure Captions

Fig. 1 Schematic view of the left half of the neutron source based on the Novosibirsk concept of the gas dynamic trap /3/
1 - expander vacuum chamber; 2 - plasma absorber; 3 - superconducting part of mirror magnet; 4 - water cooled part of mirror magnet; 5 - one of the superconducting coils of the main magnetic field; 6 - shield; 7 - vacuum chamber; 8 - zone of moderate neutron flux; 9 - superconducting magnet generating the hump in the magnetic field shown on the diagram below; 10 - zone of high neutron flux
The diagrams below show the magnetic field B and neutron source strength F in dependence on axial position.

Fig. 2 Optimization of the composition of a homogeneous mixture of Fe with a solution of 4 weight % boron acid H_3BO_3 (boron enriched to 80 % ^{10}B) in water. On the abscisse is plotted the volume part x of aqueous solution in the mixture, on the ordinate the total dose (neutron + gamma) in epoxy after penetration of 14 MeV neutrons through spheres of radius r. Normalization is to spheres of pure iron (x = 0).

Fig. 3 Same as fig. 2 with Fe replaced by W.

Fig. 4 Total dose W_{N+P} in epoxy multiplied by geometric factor $4\pi r^2$ behind spheres radius r, consisting of mixtures of Fe or W with an aqueous solution of 4 weight % boron acid H_3BO_3 enriched to 80 % in ^{10}B. The volumetric part x of the solution is $x = 0.30$ in the case of Fe and $x = 0.15$ in the case of W. The spheres are reflected by copper of 0.8 natural density. The 14 MeV neutron source is located in the centre of the sphere.

Fig. 5 Neutron spectrum for a Pb-reflector in lethargie representation. Conditions see text.

Fig. 6 Neutron spectrum for a Fe-reflector (broken line) and CTR standard spectrum (continuous line), normalized to equal 14 MeV intensity.

Fig. 7 Cylindric neutronic model of the Efremov design of a plasma neutron source (right half of the device)

1 Plasma (neutronic vacuum)
2 warm coil of mirror hybrid magnet (Cu 0.8 natural density)
3 superconducting coil of mirror hybrid magnet
4 structure of this coil (steel 0.5 natural density)
5 shield consisting of 85 vol % W, 15 vol % aqueous solution of H_3BO_3 enriched to 80 % in ^{10}B
6 irradiation zone (steel 0.5 natural density)
7 sield, composition as 5
8 structure, composition as 4
9 superconducting coil generating the elevated field for reflecting injected fast ions (fig. 1)

The 14 MeV neutron source strength is distributed homogeneously in a cylinder 1.5 m length, 2.5 cm diameter, centred at the origin. Source strength is set to 1 MW of 14 MeV neutrons.

Most heavily exposed spots of the magnets are positions 1 to 3.

Fig. 8 Neutronic model for thermalization in neutron plasma source

Fig. 9 Results for heavy water (left) and Be moderators (right). On the abscissa is the radial distance from the cylinder axis. Main parameter characterising the potential of the source is the thermal flux (upper curves, right scales). The source strength of 14 MeV neutrons was taken as 0.75 MW. The lower two curves in each half show the percentage of fast (1 eV to 13.9 MeV) and 14 MeV (i.e. greater 13.9 MeV) neutrons in the spectra. These parameters too characterize the potential of the source for scattering experiments.

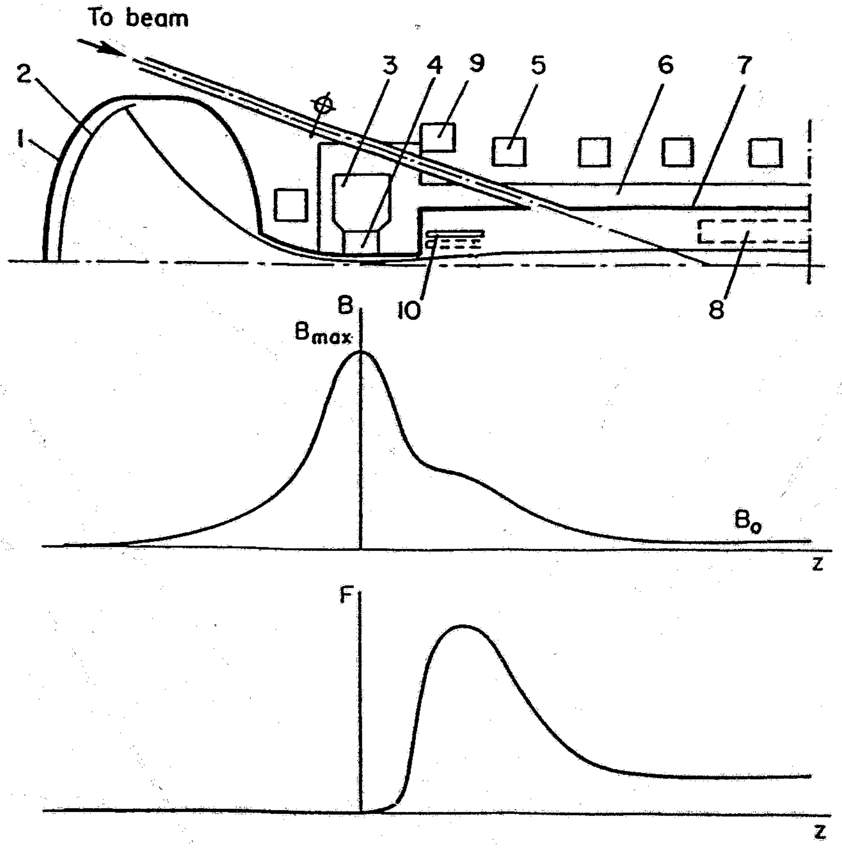


Fig. 1

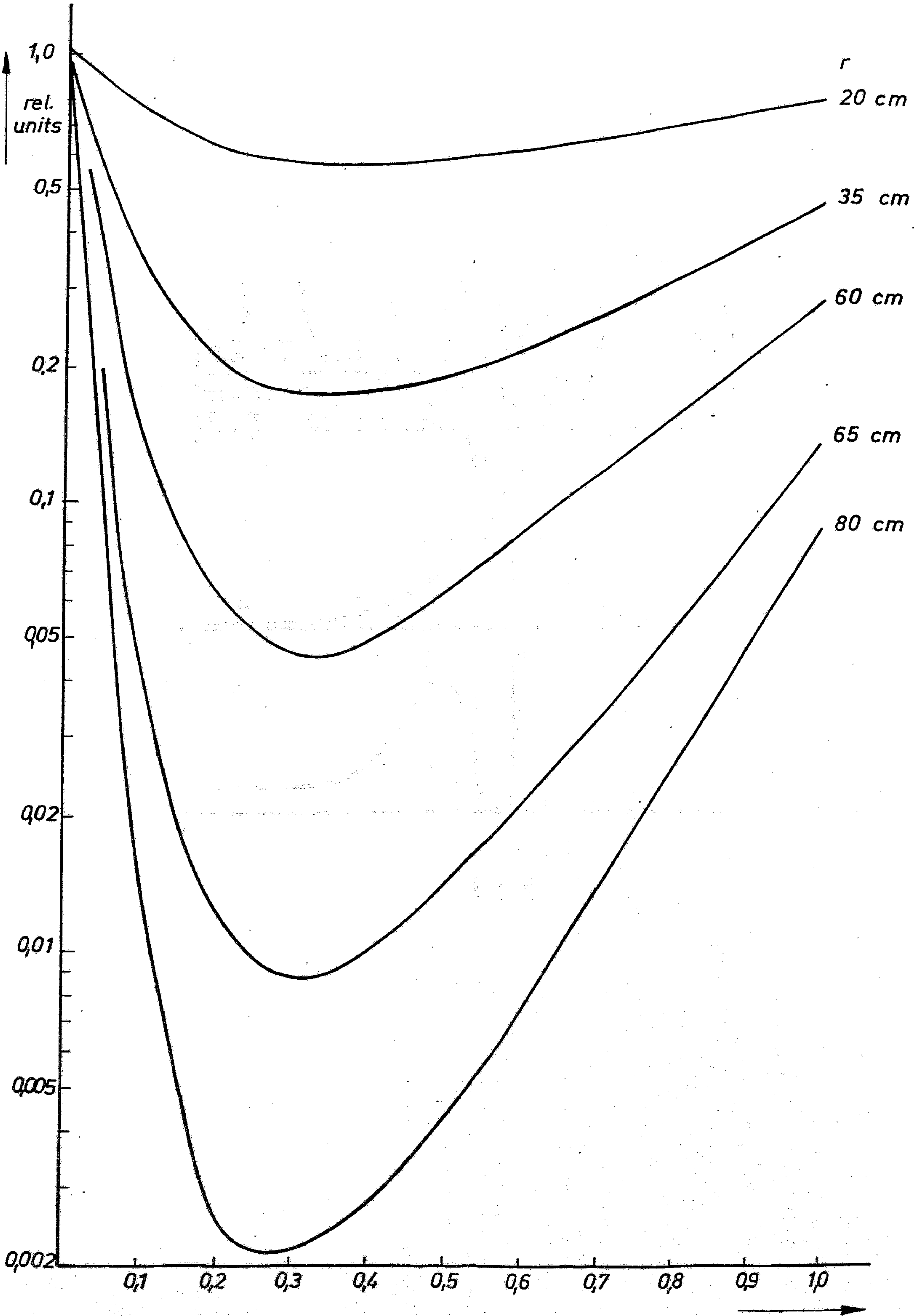

1,0
rel. units
0,5
0,2
0,1
0,05
0,02
0,01
0,005
0,002
r
20 cm
35 cm
60 cm
65 cm
80 cm
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1,0

Fig. 2

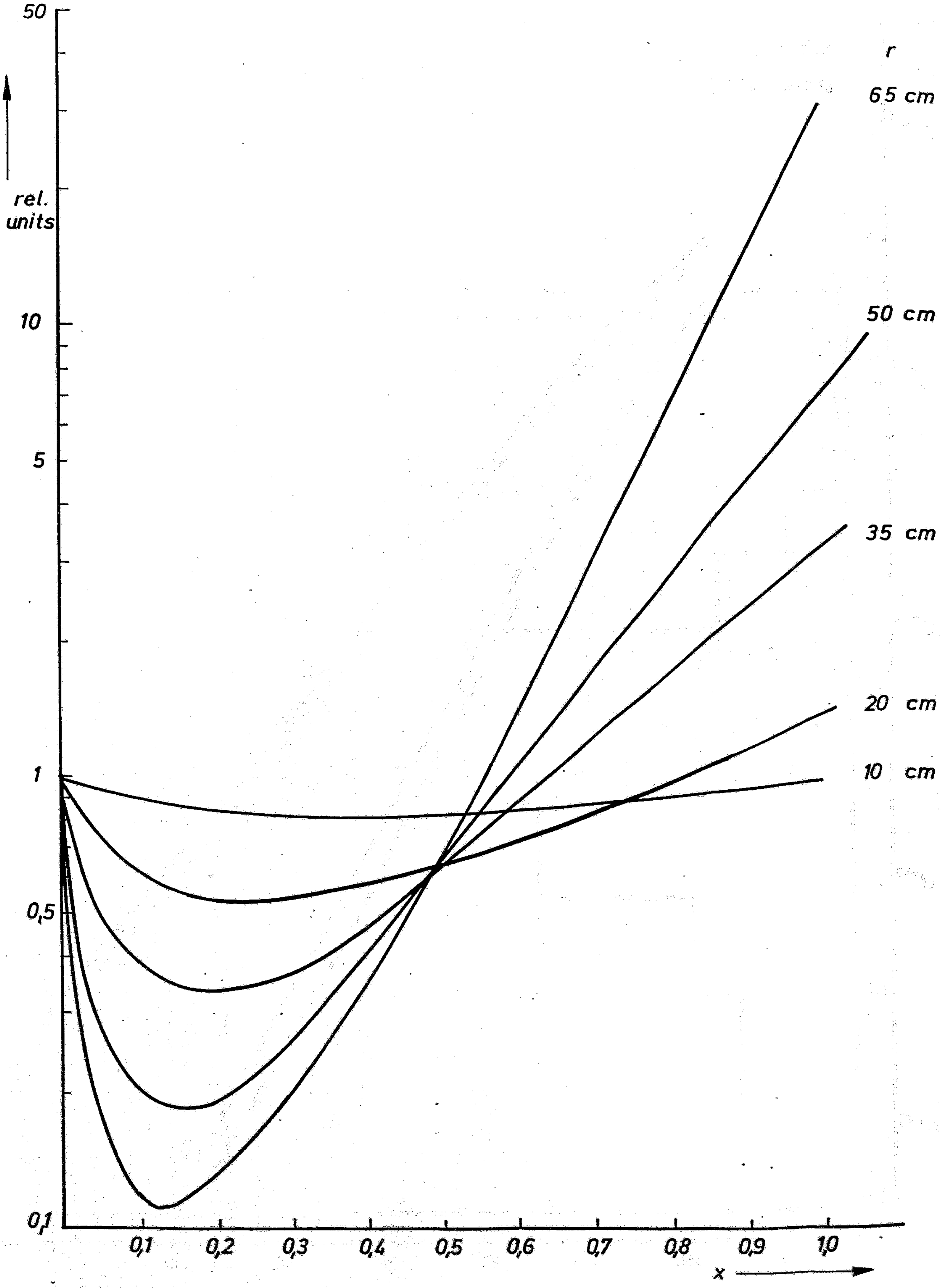

50
10
5
1
0,5
0,1
rel. units
r
65 cm
50 cm
35 cm
20 cm
10 cm
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1,0
x

Fig. 3

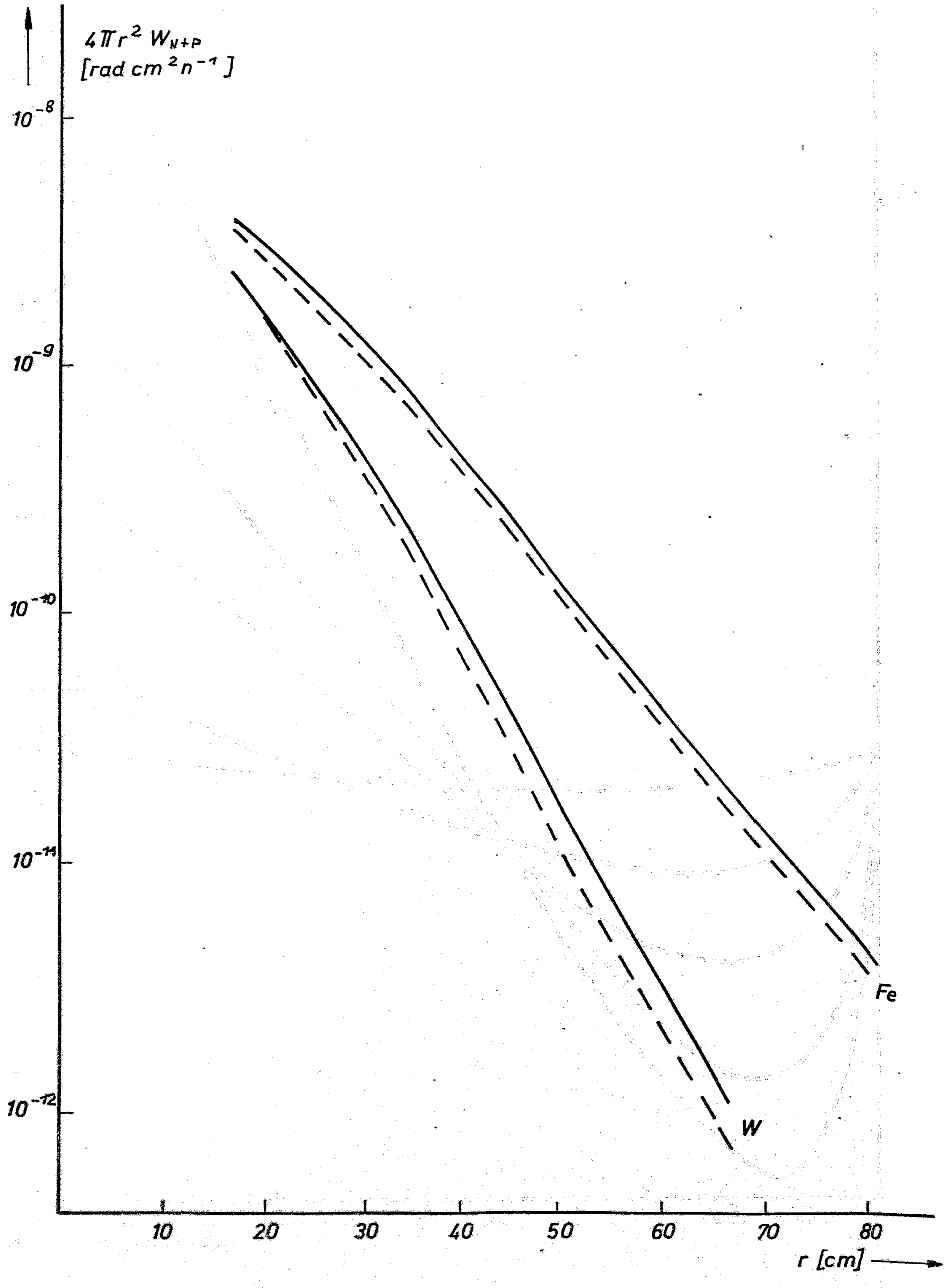

$4\pi r^2 W_{N+P}$
[rad cm^2 n^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10
20
30
40
50
60
70
80
r [cm]
Fe
W

Fig. 4

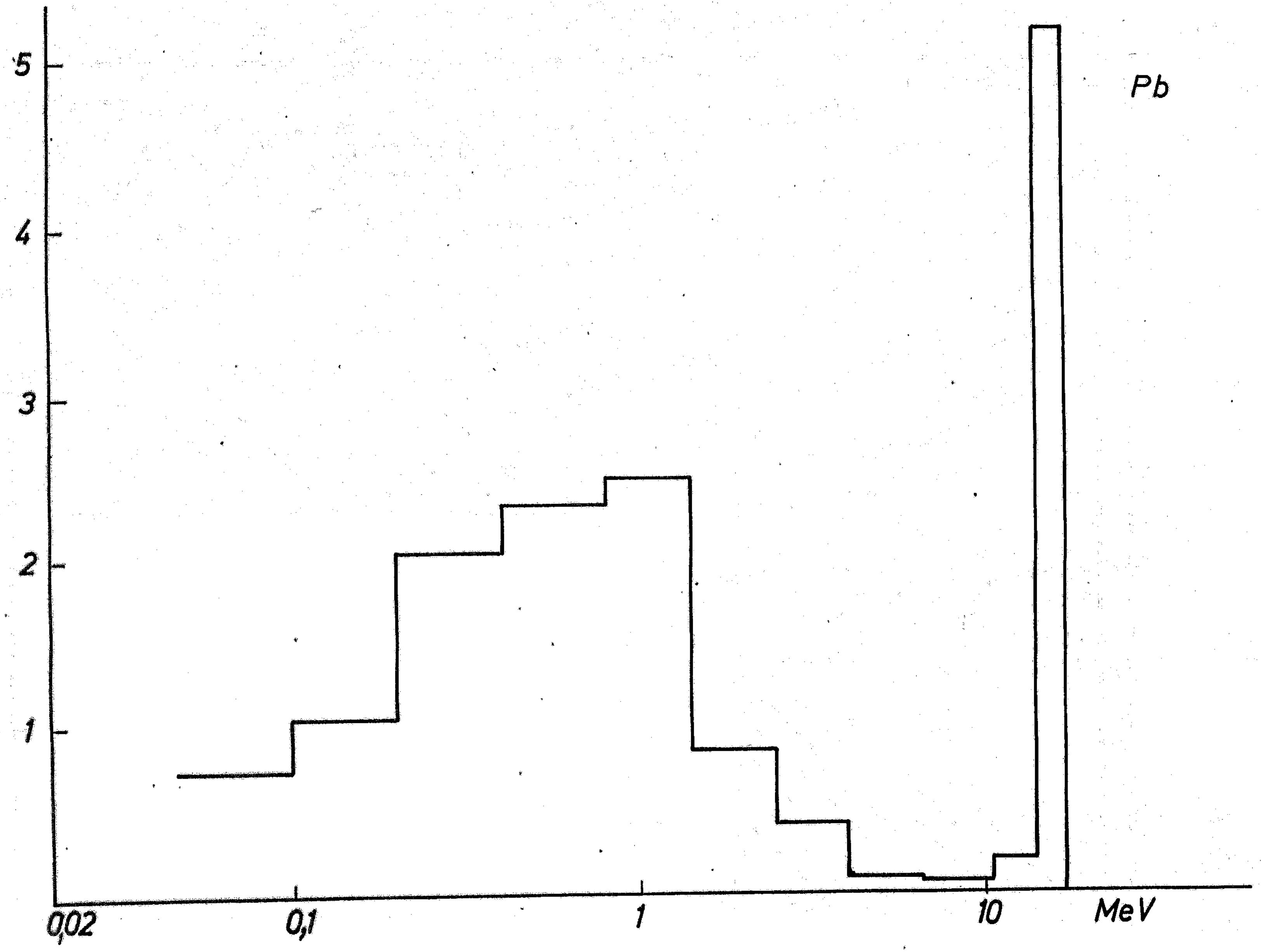


Fig. 5

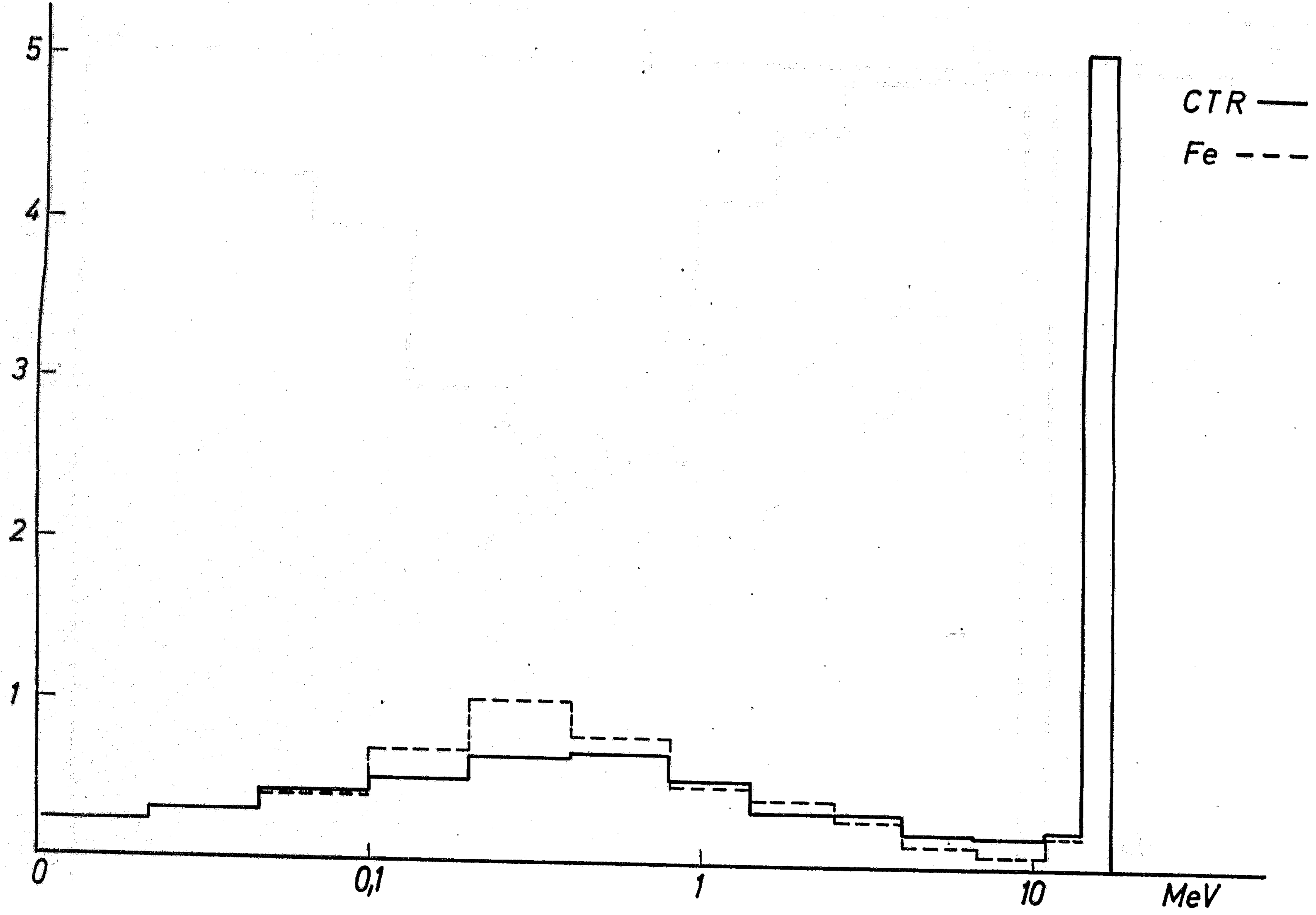
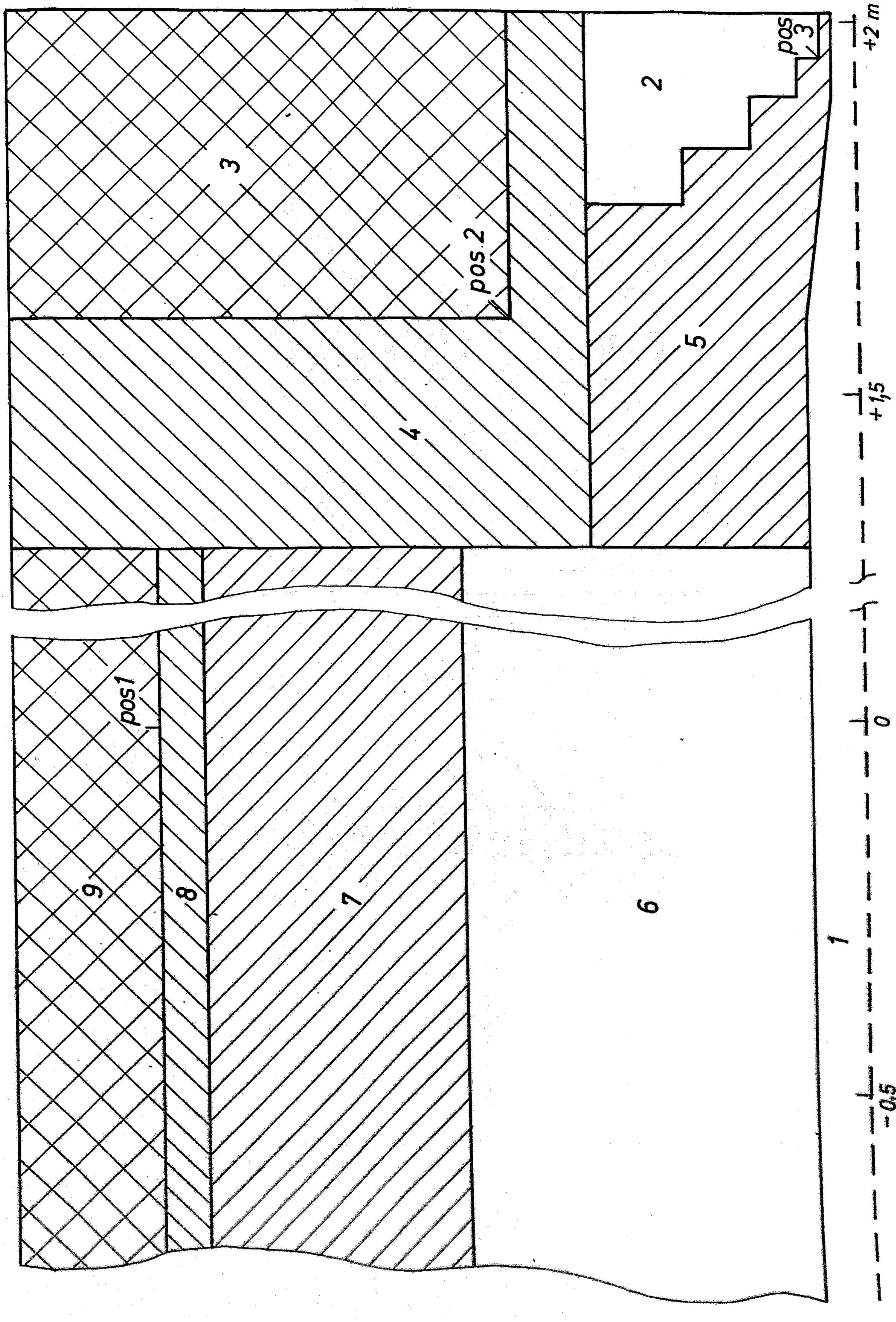


Fig. 6


3
pos.2
4
2
pos 3
5
+2 m
+1,5
0
-0,5
9
pos1
8
7
6
1

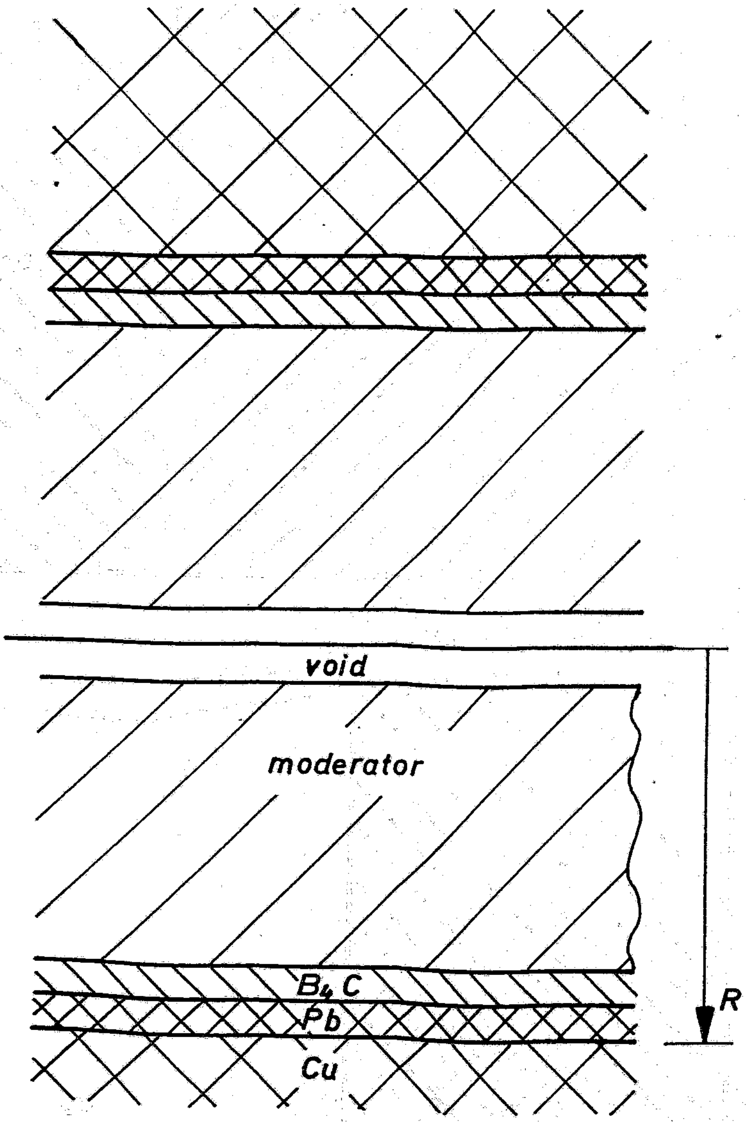


Fig. 8

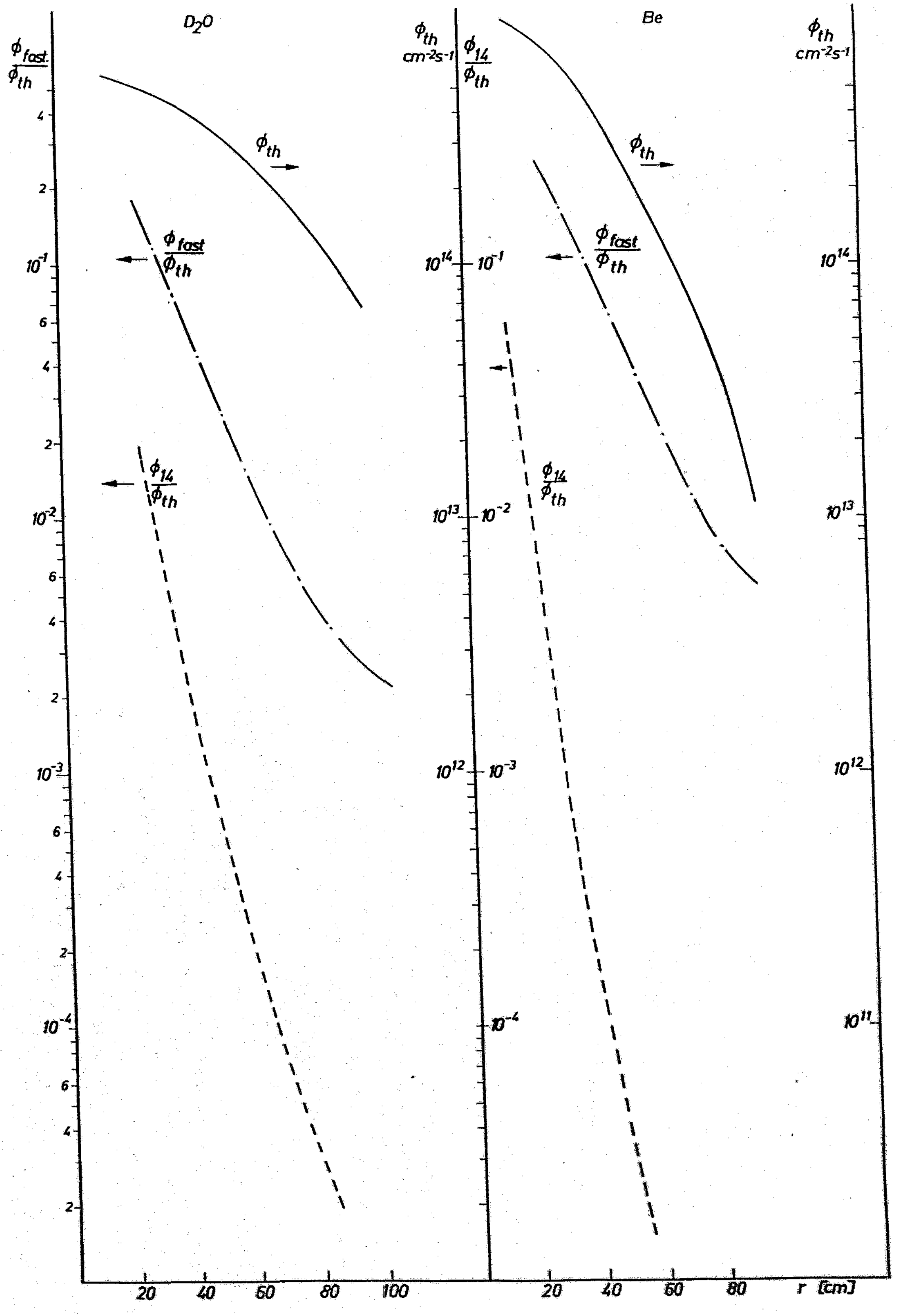

D$_2$O
Be
ϕ_{fast}/ϕ_{th}
ϕ_{th} cm^{-2}s^{-1}
ϕ_{14}/ϕ_{th}
ϕ_{th}
ϕ_{fast}/ϕ_{th}
ϕ_{14}/ϕ_{th}
4
2
10^{-1}
6
4
2
10^{-2}
6
4
2
10^{-3}
6
4
2
10^{-4}
6
4
2
10^{14}
10^{13}
10^{12}
10^{11}
20
40
60
80
100
20
40
60
80
r [cm]

Fig. 9