International Atomic Energy Agency

INDC(CCP)-378
Distr.: L

INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

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(Translated from a Russian original published in
Yadernye Konstanty 1/1992, p. 48-54)

Translated by the IAEA

August 1994

IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

Reproduced by the IAEA in Austria
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94-10591 (C)
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ABSTRACT

The leakage neutron spectra from metallic spheres were measured on the 14 MeV pulsed neutron generator of the Physics and Power Engineering Institute. The experiment was performed by the time-of-flight method. The experimental set-up and the methods of conducting the measurements and treating the results are described. The experimental data are compared with calculations performed with the BLANK program, using ENDF, ENDL, JENDL and BROND evaluated data files.

Measurement of the neutron spectra emitted from the surface of a spherically symmetric sample and comparison of the experimental data with a model calculation, in view of the simple geometrical conditions, provide a means of assessing the accuracy of neutron data investigated in calculations. Such an exercise with a 14 MeV neutron source at the centre of a sphere is particularly important now for materials used in current or projected nuclear fusion devices [1].

We have already conducted similar investigations for spheres of Be, Pb and V [2] and for Fe [3]. In the present work the measurements were extended to such widely used constructional materials as Al, Ti and Ni. In other laboratories, as far as can be derived from the literature, measurements have been performed for Ni - a sphere with a diameter of 32 cm [4] and Al and Ti - spheres with a diameter of 17.9 cm [5].

The leakage neutron spectra were measured by the time-of-flight method on a fast neutron spectrometer using a KG-0.3 pulsed neutron generator [6]. In principle the experimental set-up does not differ from those used by us previously [2, 3]. Therefore we shall dwell here only on modifications made and matters not fully explained in our previous work.

Geometry of the experiment

The scheme of the experimental set-up is shown in Fig. 1. The dimensions of the spheres investigated are given in Table 1. The spheres had a hole through which an ion guide was passed, so that the 14 MeV neutron source was located at the centre of the sphere.

The detector recording the neutron spectra was located in a shield which in the present experiment was reinforced with a 10 cm thick layer of polythene which enabled the background level to be reduced by approximately 40%. The neutron spectra were measured at three angles: 8°, 40° and 75°. The path length was 360-390 cm.

The detector consisted of a paraterphenyl crystal 5 x 5 cm in diameter having increased light output compared with stilbene and a FEhU-143 low-noise photomultiplier. The time resolution of the spectrometer with this detector was 3 ns with a neutron recording threshold of around 50 keV.

In order to monitor the pulsed operation of the accelerator, a monitoring detector was employed consisting of a SPS-156 fast scintillator (∅ 2.5 x 2.5 cm) and a FEhU-87 photomultiplier. The detector had a time resolution of around 0.5 ns and a neutron recording threshold of 3 MeV.

The number of neutrons escaping from the source was determined with a DKP silicon semiconductor alpha-particle detector. The detector was located in the target holder at an angle of 173 degrees to the direction of incidence of deuterons on the tritium target. An iron cone 100 cm long was installed for measuring the background between the sphere and the detector. The readings of an all-wave detector were used for normalizing the measurements.

Target assembly

In our previous experiments [2, 3] the neutron source was a tritium target 2.8 cm in diameter bolted to the target holder (see scheme *a* in the inset in Fig. 3). For this design of target assembly we carried out investigations of the angular dependence of the neutron yield which revealed a ~ 20% depression of the yield at angles close to 90 degrees, entailing a ~ 4% correction in the value for the neutron yield in the full solid angle.

In order to reduce such distortions in the present experiment, we used a target with a diameter of 1.1 cm which was mounted in a thin aluminium dome (see scheme *b* in the inset in Fig. 3).

The calculation of the transmission for this target assembly shows that the maximum depressions at angles of ~ 90° are reduced to 8%, while the correction of the neutron yield in the full solid angle is ~ 2.5%.

A general view of the target assembly is shown in Fig. 1. Figure 3 shows the experimental and theoretical results for the angular dependence of the neutron yield for both the target assemblies employed. Also shown is the angular dependence of the neutron yield for a TiT target, ignoring the effect of the target and the target holder [6]. In addition, these target assemblies are shown schematically in the inset to this figure.

Circuit diagram of the electronic part of the experiment

The leakage neutron spectrum was measured by the time-of-flight method. The circuit diagram of the experiment is shown in Fig. 2. The anode signal of the scintillation detector passes to the BDK discriminator which makes it possible to select the timing of the "start" signal and identify the signal formed during recording of a neutron from the shape of the pulse. The start signal from the monitoring detector is converted analogically.

The logic equipment (BUML) receiving two "start" signals makes it possible to record the time spectra of neutrons from the two detectors with one time-amplitude digital converter (TADC) in different sections of the RAM memory. The "stop" signal was taken from the pick-up electrode and after amplification and discrimination was transmitted to the "stop" input of the TADC. The time interval between the "start" and "stop" signals was measured by the TADC-8. The maximum time interval of the converter is 1800 ns and the differential and integral non-linearities of the conversion coefficient were around 1%.

The amplitude spectrum from the semiconductor silicon detector was recorded with an amplitude-digital converter (ADC). Monitoring of the experiment was performed with an all-wave detector, the signals of which after amplification and shaping were fed to MKS and MOS4 counters. The latter was interlocked to the data processing time of the ADC and TADC. By comparing the readings of the MKS and MOS4 counters, one can determine the dead time of the recording system. On completion of the measurements all the accumulated data were read through CAMAC on the SM-4 computer.

Treatment of the experimental data

After deducting the background and converting the time spectrum to the energy spectrum N(E), the leakage neutron spectrum L(E), normalized to one source neutron, was calculated by the formula

$$L(E) = \frac{N(E)}{\epsilon_D(E) \cdot \Omega_D} \cdot \frac{1}{N_0} \quad , \tag{1}$$

where $\epsilon_D(E)$ is the absolute efficiency of the neutron detector measured with the aid of a californium source by the hydrogen scattering method [2, 3] or by the associated particle method (see below); Ω_D is the solid angle of the detector; and N_0 is the number of neutrons escaping from the target.

The value of N_0 is found by the associated particle method, starting from the number of alpha particles N_α recorded by the semiconductor detector installed in the ion guide:

$$N_0 = \frac{N_\alpha}{\epsilon_\alpha \cdot \Omega_\alpha} \cdot \frac{4\pi}{Y(\theta_\alpha)} \quad , \tag{2}$$

where $Y(\theta_\alpha = 173°) = 4\pi \cdot \sigma(\theta_\alpha)/\sigma = 1.05$ is a coefficient taking into account the isotropy of the angular distribution of alpha particles from the reaction $^3H(d,n)^4He$ [6]. $\epsilon_\alpha \cdot \Omega_\alpha$ is the product of the recording efficiency and the solid angle of the silicon detector. The latter value was measured with the aid of a calibrated ^{238}Pu alpha particle source installed in place of the tritium target.

$$\epsilon_\alpha \cdot \Omega_\alpha = 4\pi \cdot \frac{N_\alpha(P_n)}{A(P_n)} \quad , \tag{3}$$

where $N_\alpha(P_n)$ is the counting rate of alpha particles recorded by the silicon detector; and $A(P_n)$ is the known activity of the alpha source.

Combining formulae (2) and (3), we obtain the final expression for the number of neutrons escaping from the target.

$$N_0 = N_\alpha \cdot \frac{A(P_n)}{N(P_n)} \cdot \frac{1}{Y(\theta_\alpha)} \quad . \tag{4}$$

The method of recording of associated particles also enables us to determine the absolute efficiency of the neutron detector at energies close to 14 MeV.

$$\epsilon_D(E) = 4\pi \cdot \frac{N_D(\theta_D)}{\Omega_D} \cdot \frac{N(P_n)}{A(P_n)} \cdot \frac{Y(\theta_\alpha)}{Y(\theta_D)} \quad , \qquad (5)$$

where $N_D(\theta_D)$ is the number of neutrons recorded by the detector when measuring the neutron yield from the target at an angle of 0°; and $Y(\theta_D)$ is a coefficient taking into account the anisotropy of the neutron yield from the target [6].

Experimental results and discussion

Figures 4-8 show the integral leakage spectra for the investigated spheres and the neutron spectra from the target obtained by averaging the data at angles 8°, 40° and 75° and multiplying by 4π. Table 2 shows a series of parameters characterizing these spectra.

The relative energy resolution of the spectrometer is summed from the following components:

$$\frac{\Delta E}{E} = \left\{ \left(\frac{2\cdot\Delta t}{t}\right)^2 + \left(\frac{2\cdot\Delta L}{L}\right)^2 + \left(\frac{\Delta E_0}{E}\right)^2 + \delta_\epsilon^2 \right\}^{1/2} ,$$

where $\Delta t/t$ and $\Delta L/L$ are the relative time and spatial resolution of the spectrometer, taking into account the dimensions of the spheres and the detector; ΔE_0 = E(8°)-E(70°) = 0.58 MeV is the energy difference of neutrons emitted by the target at angles 8° and 70°; and δ_ϵ are additional factors taking into account the probability of multiple scattering and reduction of energy with elastic scattering, etc.

Analysis of these components for the present experiment shows that the predominant contribution is made as a rule by the time resolution of the spectrometer, which is significantly affected by the duration of the grouped deuteron cluster, in other words the quality of the pulsed operation of the neutron generator. This evidently explains the different energy resolution (see Table 2) occurring in the two experiments performed at different times (the first with aluminium and nickel spheres, and the second with titanium). The difference in the width of the 14 MeV neutron peak in the leakage neutron spectra from the Al sphere and from the source is due to the effect of the variation in energy of the elastically-scattered neutrons. This effect is most significant for the lightest of the elements investigated here, i.e. aluminium.

Table 2 also shows the values of the integral in the energy ranges corresponding to inelastic scattering and to the whole range of the neutron source, with the total area of the neutron spectra from the target normalized to unity. The neutron spectra from the target shown in Figs 4-6 have been normalized to the area of the 14 MeV neutron peak in the leakage neutron spectrum.

The neutron spectrum from the target has a low energy region which evidently corresponds to neutrons interacting inelastically with the constructional materials of the target assembly. The coincidence of the area within these energy ranges with the evaluation of the contribution of inelastic scattering derived from the analysis of the angular dependence of the neutron yield from the target confirms this conclusion.

Figures 4-6 also show the leakage neutron spectra for the investigated spheres calculated according to the unidimensional BLANK program [7], using the ENDF/B4, BROND, JENDL-2 and ENDL-83 evaluated neutron data files. For a correct comparison with experimental data the calculated spectra were averaged over the energy taking into account the spectrometer resolution function.

The ratios of the calculated and experimental spectra integrated in different energy ranges are shown in Table 3. From the data given in Table 3 and in Figs 4-6 it can be seen that, for an aluminium sphere, calculations with the ENDF/B4 and ENDL-83 libraries agree satisfactorily with experiment, whilst the JENDL-2 library gives a slightly too low result in the energy range below 8 MeV.

In similar calculations for a nickel sphere the JENDL-2 library gives a result that agrees well with experiment, whereas the ENDF/B4 library and BROND give a too low evaluation.

For Ti spheres calculations have only been performed hitherto with the ENDF/B4 library which give satisfactory agreement with experiment, though in the 1-3 MeV energy range they give a slightly high evaluation, and in the 3-8 MeV range a slightly low one.

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Table 1

Dimensions of the spheres

Material	Diameter, cm		Wall thickness		Diameter of the hole, cm
	External	Internal	cm	l/λ	
Al	24	9	7.5	0.6	6.4
Ni	24	9	7.5	1.7	6.4
Ti	32.5	30	1.25	0.16	6.2
	34.7	30	2.35	0.31	6.2
	36.5	30	3.25	0.42	6.2

l/λ is the wall thickness of the sphere expressed in units of length of a neutron free path $\lambda = \frac{1}{n \cdot \sigma_t}$, where n is the number of nuclei in 1 cm^3 and σ_t is the total interaction cross-section for 14 MeV neutron energy.

Table 2
Results of the measurements

Sphere	Wall, cm	Resolution, MeV	Energy range, MeV	Integral
Al	7.5	3.5	0.2-8 8-15	0.357±0.018 0.685±0.034
Ni	7.5	2.6	0.2-8 8-15	0.553±0.033 0.381±0.023
Target		2.6	0.4-5 5-15	0.029±0.001 0.971±0.060
Ti	1.25	1.7	0.1-8 8-15	0.153±0.009 1.098±0.065
	2.35	1.7	0.1-8 8-15	0.226±0.014 1.033±0.061
Ti	3.25	1.7	0.1-8 8-15	0.287±0.016 1.024±0.060
Target		1.7	0.2-5	0.028±0.001 0.972±0.060

Table 3

Ratio of calculated to experimental data

Sphere	Library	Energy range, MeV				
		0,2-1	1-3	3-8	8-15	0,2-15
Al	ENDF/B4	1,05±0,06	1,05±0,06	1,06±0,06	0,99±0,06	0,97±0,06
	JENDL-2	–	0,93±0,06	0,87±0,06	1,03±0,06	0,99±0,06
	ENDL-83	–	1,01±0,06	1,03±0,07	0,95±0,06	0,97±0,06
Ni	ENDF/B4	0,75±0,05	0,87±0,05	0,84±0,05	0,91±0,06	0,84±0,05
	JENDL-2	–	1,02±0,06	1,03±0,06	0,90±0,06	0,94±0,06
	BROND	–	0,82±0,05	0,83±0,05	0,76±0,05	0,77±0,05
Ti-1	ENDF/B4	0,96±0,06	1,10±0,08	0,77±0,05	0,96±0,06	0,96±0,06
Ti-2		1,00±0,07	1,13±0,07	0,78±0,05	1,04±0,07	1,03±0,07
Ti-3		1,00±0,07	1,13±0,07	0,76±0,05	1,06±0,07	1,05±0,07

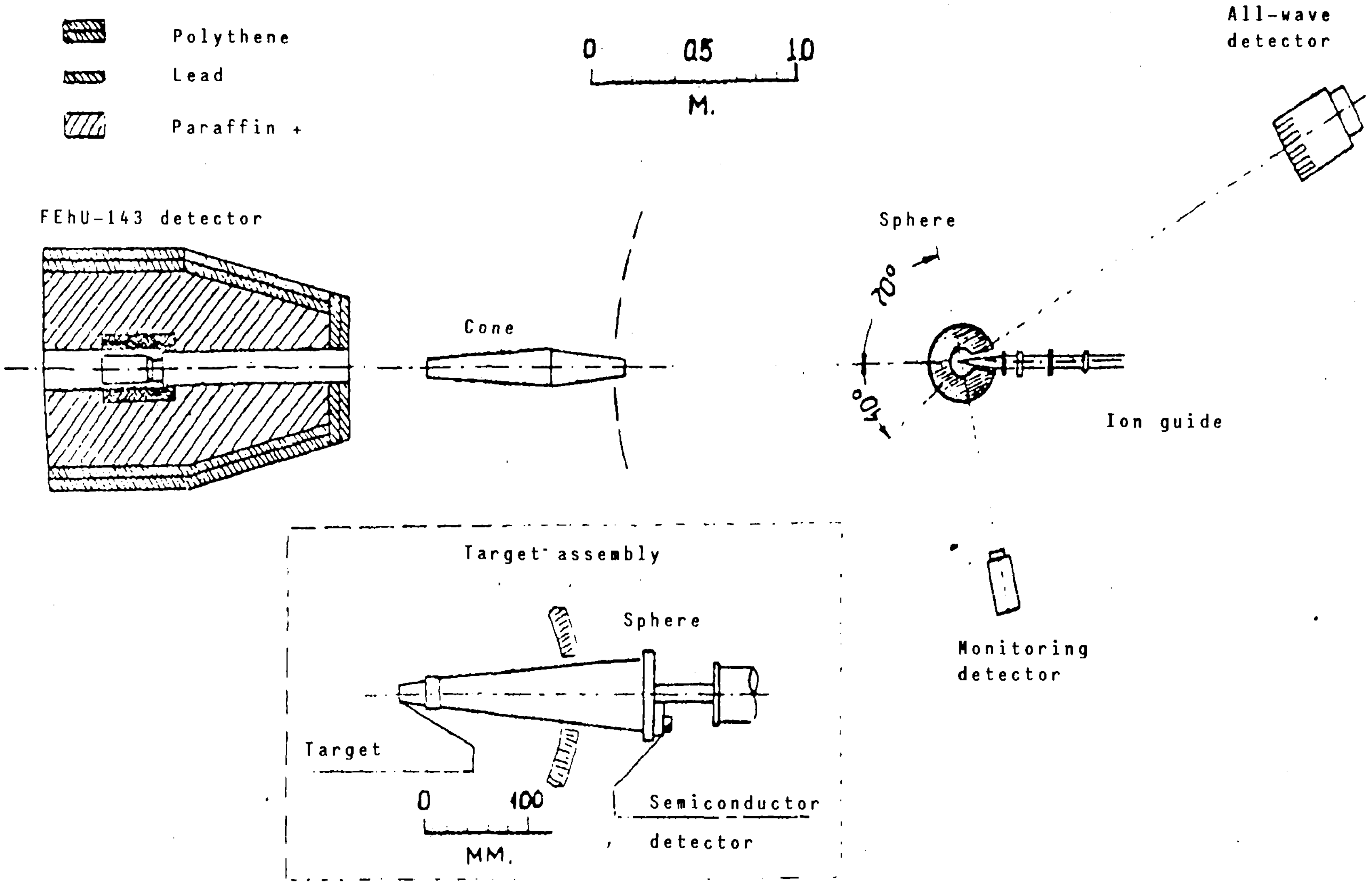

Fig. 1. Geometry of the experiment

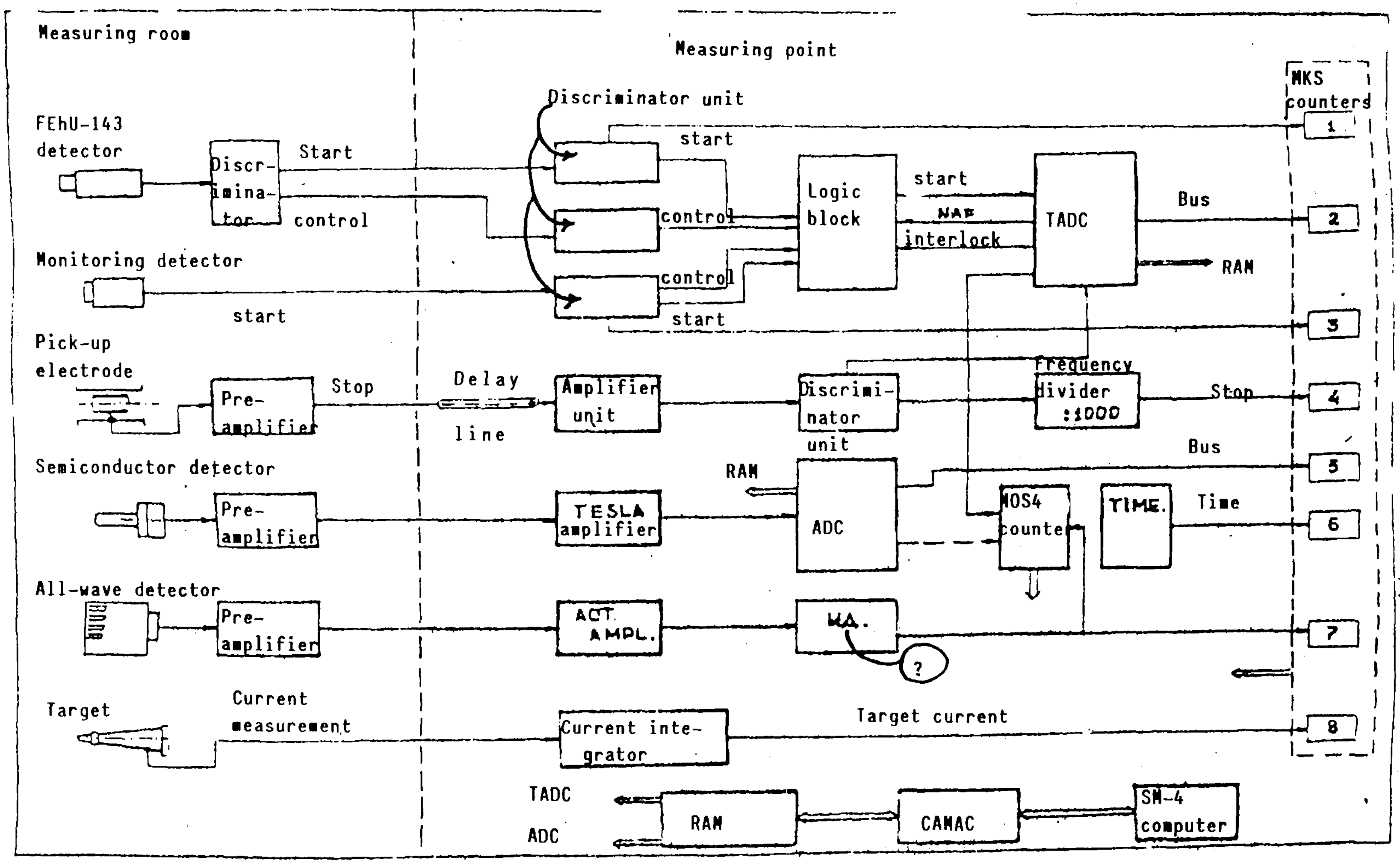

Fig. 2. Circuit diagram of the electronic part of the experiment.

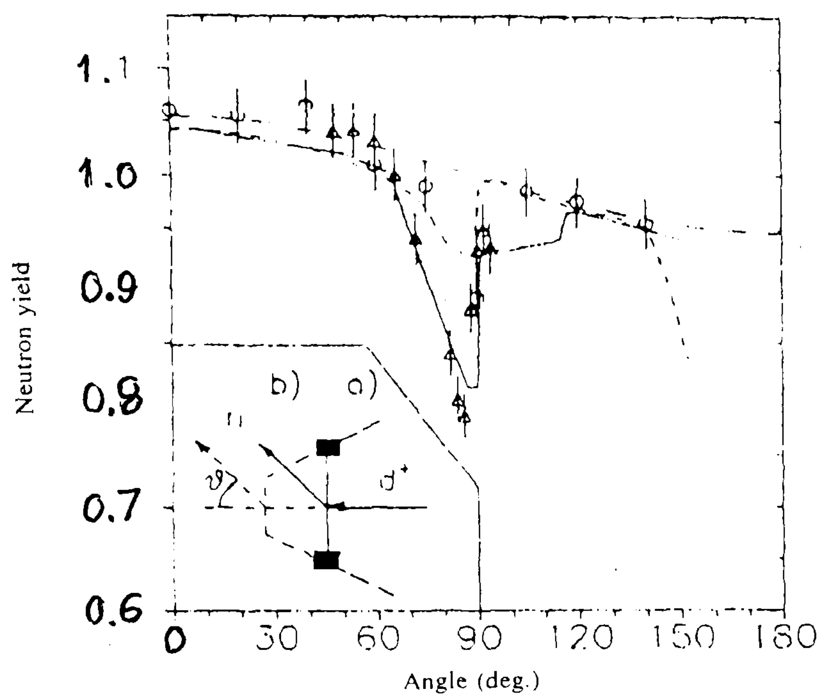

Fig. 3. Angular distributions of the neutron yield from the target assembly. Calculation: _ _ _ = thin target; ________ = scheme *a*; --------- = scheme *b*. Experiment: o = activation measurements from the reaction Al(n,α), Δ = measurements by the time-of -flight method.

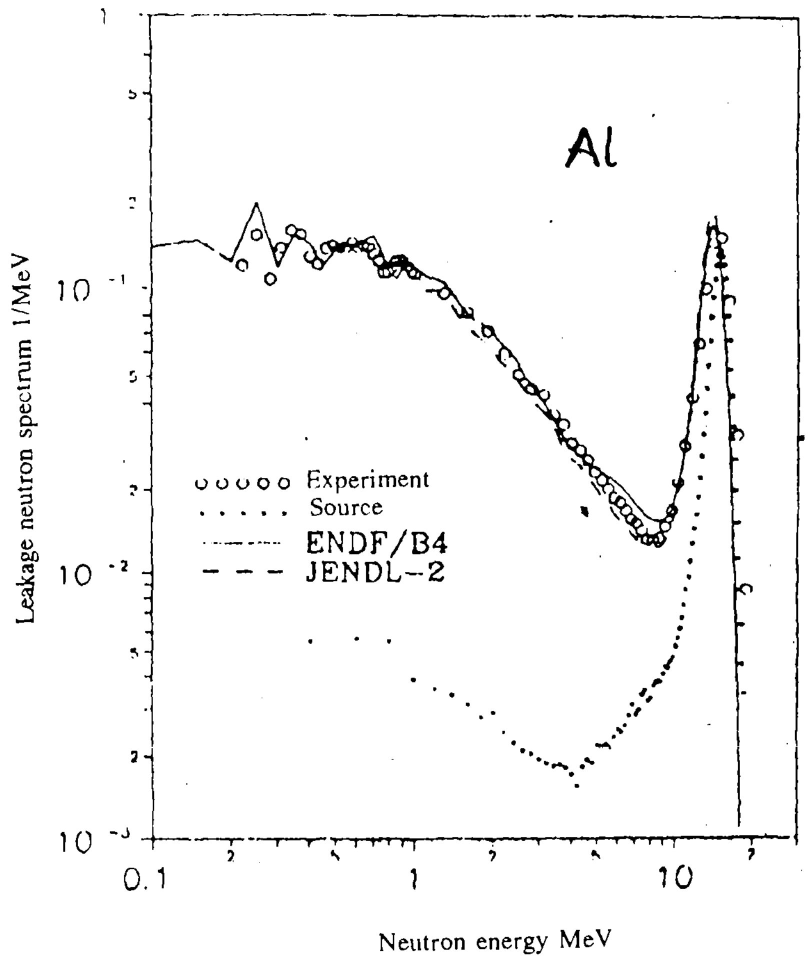

Fig. 4. Integral leakage neutron spectrum from the aluminium sphere.

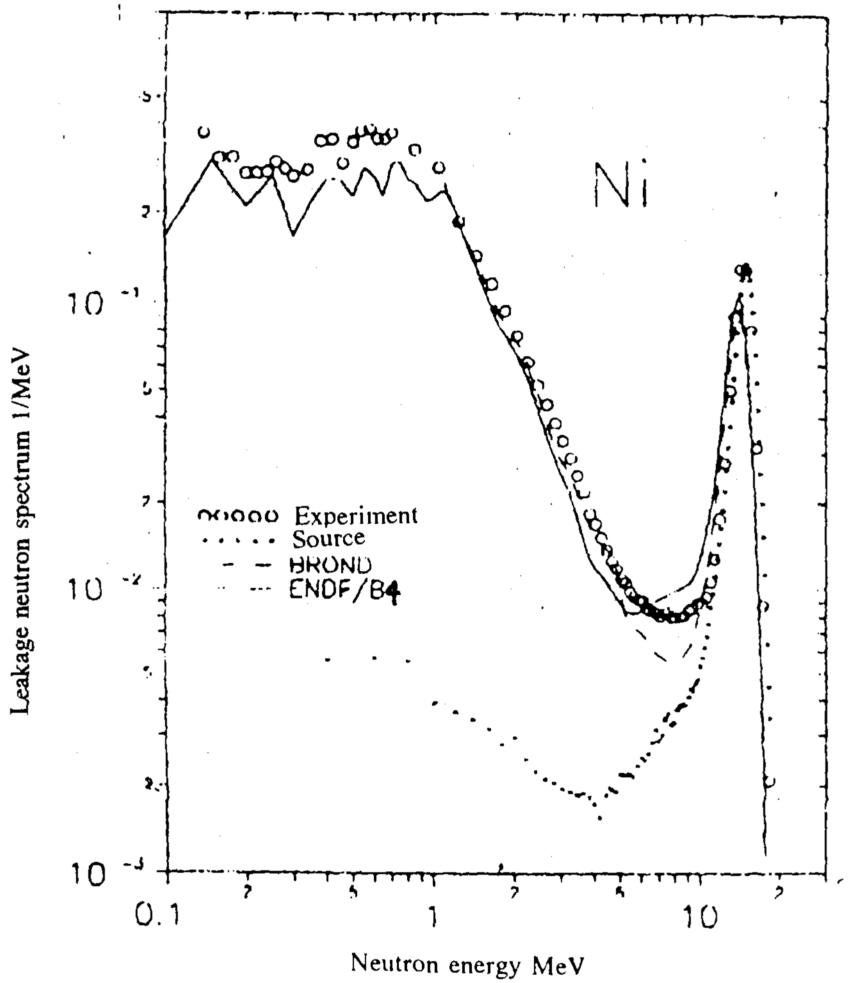

Fig. 5. Integral leakage neutron spectrum from the nickel sphere.

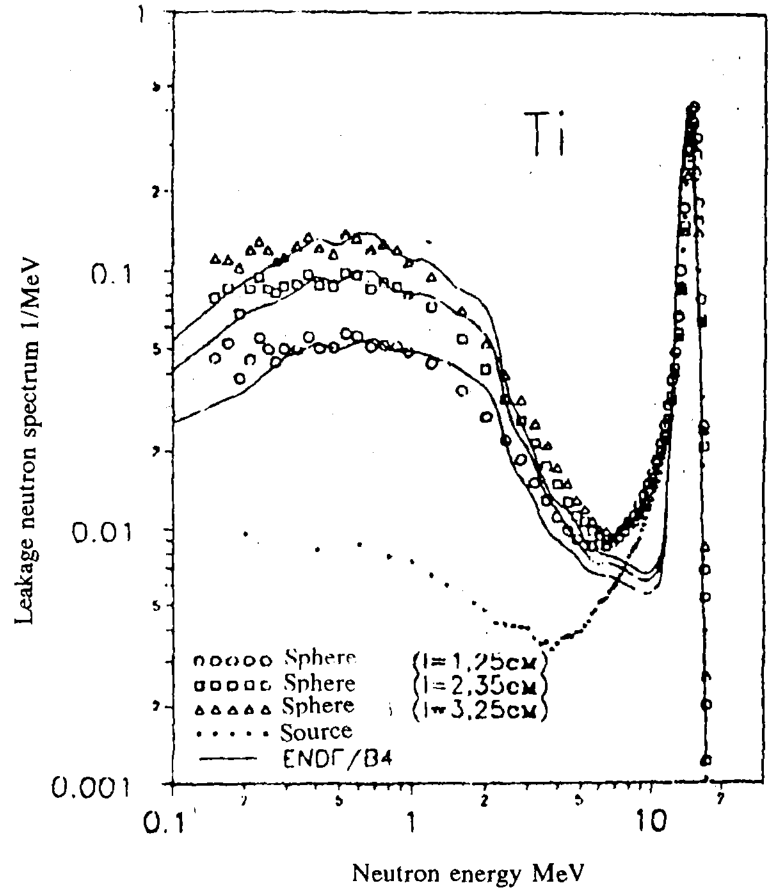

Fig. 6. Integral leakage neutron spectrum from the titanium spheres.

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