Neutron spectrometry based on the moderation time in lead: from "the poor man's spectrometer" (E. Wigner) to record fluxes

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This paper considers the main features of neutron spectrometry based on the moderation time in lead, the construction of the first such spectrometer ("lead cube") under the supervision of F. L. Shapiro, and the results of realization of the scientific program with it. Second-generation neutron moderation-time spectrometers, their research programs, and the experimental results are briefly discussed. The final section is devoted to the development of a new generation of such spectrometers with powerful proton accelerators (meson factories) as pulsed neutron sources. These spectrometers will have record intensities of the fluxes of resonance neutrons at the sample and, despite the serious limitations of this method as regards the energy resolution (~30–50%), will permit original physics studies to be made. Some proposals for such a program are discussed. © *1995 American Institute of Physics.*

SOME HISTORY

At the end of the forties and beginning of the fifties, a series of studies of the density of neutrons in uranium–graphite systems[1] was carried out, on instructions "from above," at the Nuclear Physics Laboratory (at that time, the I. M. Frank Laboratory) of the P. N. Lebedev Physics Institute of the USSR Academy of Sciences. A natural continuation of this work was the study of fundamental problems of the physics of slow neutrons such as the moderation and diffusion of neutrons and the spectrometry of neutrons in various media, in particular in weakly absorbing media. In the course of study of these problems, E. L. Feĭnberg noted an interesting property of the process of elastic moderation of neutrons in a heavy medium, namely, the grouping of the neutron velocities in a comparatively narrow interval of velocities around a mean value that decreases with increasing moderation time. As a result of discussion of this velocity-grouping effect of neutrons undergoing moderation, L. E. Lazareva, E. L. Feĭnberg, and F. L. Shapiro[2] proposed a new and original method of neutron spectrometry—neutron moderation-time spectrometry.

If in a large volume of a moderator that consists of nuclei with $A \gg 1$ a brief burst of fast neutrons is created, the neutrons will, as they are slowed down as a result of elastic collisions with the nuclei of the moderator and in each collision lose on average a fraction $\approx 2/A$ of their energy, become grouped into a quasi-monoenergetic group that with increasing moderation time will be displaced downward in the scale of velocities (energies). If the neutron detector (or a detector of the particles that accompany the capture of a neutron by a nucleus of the investigated sample) is activated during a narrow time interval Δt shifted by the time t relative to the time of the neutron burst, it is then possible to select quasi-monoenergetic neutrons whose mean velocity is related to the moderation time t by

$$t = A\lambda(1/v - 1/v'), \quad (1)$$

where λ is the mean neutron range until scattering, and v'=const is the initial neutron velocity.

The first neutron moderation-time spectrometer (MTS) was constructed under Shapiro's supervision at the P. N. Lebedev Physics Institute and was commissioned at the beginning of 1955. It was a lead cube with side of about 2 meters made of lead that had been specially purified of impurities (total weight $\approx$140 ton) with a vertical channel to the center for the neutron source and several horizontal channels passing through the cube in which the samples and detectors could be placed. The pulsed neutron source was a very simple deuteron accelerator of Cockcroft–Walton type with a zirconium–tritium target and a mean yield of about 10^8 neutrons per second from the $T(d,n)^4He$ reaction. The new spectrometer had a restricted energy resolution (about 30%) but exceeded in luminosity time-of-flight spectrometers having the same neutron-source power by three orders of magnitude. The results of the MTS commissioning were presented by Shapiro in the summer of 1955 at the First Geneva Conference on the Peaceful Uses of Atomic Energy.[3]

The session chairman, E. Wigner, christened the new type of spectrometer a "poor-man's spectrometer." However, as the subsequent development of neutron spectrometry showed, the high luminosity of the MTS and some other original qualities had the consequence that such detectors were also built in countries that were by no means poor, for example, the German Federal Republic, the United States, Japan, and several others.

INVESTIGATIONS WITH THE FIRST MODERATION-TIME SPECTROMETER

The moderator

Experiments performed at the Lebedev Institute with the lead moderator and neutrons with initial energy of order 14 MeV showed that the FWHM of an individual resonance was constant for $E_n \leq 1$ keV and equal to 35%, while at high energies it increased, reaching $\approx$70% at E_n=15 keV. The mean neutron energy (in kilo-electron-volts) was found to be related to the moderation time (in microseconds) by

$$E_n = 183/(t+0.3)^2. \quad (2)$$

Comparison of the theoretical dependence (1) with the experimental result (2) shows that the mean neutron range to scattering, λ, remains constant for the region $E_n < 15$ keV.

Because of the escape of neutrons through the boundary of the moderator and capture of them in the moderator, the neutron density decreases with the moderation time and also as the boundary of the moderator is approached. For a moderator in the form of a cube with edge 2η, the neutron distribution in space and time (for $t > 10$ μs) is given by

$$\rho = \text{const}(t+0.3)^{-\alpha} e^{-t/T} \Pi_i \cos \pi x_i / \eta, \qquad (3)$$

where x_i are the coordinates of the position of measurement of the neutron density in a coordinate system whose origin is at the center of the cube and the axes are parallel to its sides. For the first lead MTS, the values $\alpha = 0.35$ and $T = 890$ μs were obtained.

The working material for an MTS must be chosen in order to achieve the best resolution for minimum γ background and maximum neutron intensity. Therefore, the material must be heavy, have a small neutron capture cross section, and be available in amounts measured in cubic meters. The best material is probably lead, although if the experiment can be performed with poor resolution (for example, measurement of the resonance capture or fission integrals) it is expedient to use graphite, which compared with lead gives a neutron intensity greater by an order of magnitude and a γ background smaller by the same factor. At the same time, we must emphasize the need for special purification of the lead to remove extraneous impurities, which can raise the γ background of the MTS by several times (this was evidently the reason for the failure of the MTS at Karlsruhe at the beginning of the sixties[4]).

The fullest account of the results of the study of properties of an MTS based on lead (and also iron and graphite), details of the method of measurement, and the main results of the investigations were presented in Shapiro's Doctoral Dissertation and the Candidate's Dissertations of A. I. Isakov, Yu. P. Popov, and A. A. Bergman, which were published in the Tr. Fiz. Inst. Akad. Nauk SSSR (Proceedings of the P. N. Lebedev Physics Institute of the USSR Academy of Sciences).[5] However, this publication has already become a rarity, and therefore a brief account here of the main results obtained at that time and a comparison of them with modern data is justified. Elucidation of various theoretical aspects of neutron spectrometry based on the moderation time are considered in the dissertation of Kazarnovskiĭ[6] (see also his paper in this commemorative issue).

The specifics of the method

In contrast to neutron time-of-flight spectrometry, moderation-time spectrometry has some specific features. First, there is the isotropic irradiation of the sample with neutrons. Therefore, it is impossible to perform transmission experiments in a "good" geometry, so that total neutron cross sections cannot be measured. At the same time, the existence of the large mass of lead around the detector and sample greatly reduces the background from γ rays and from stray neutrons in the facility. Neutron scattering in a thin sample has a weaker effect on the results of measurement of the capture cross section than in the case of time-of-flight spectrometry, since in the MTS the scattering does not change the neutron mean free path through the sample and only slightly changes the neutron energy.

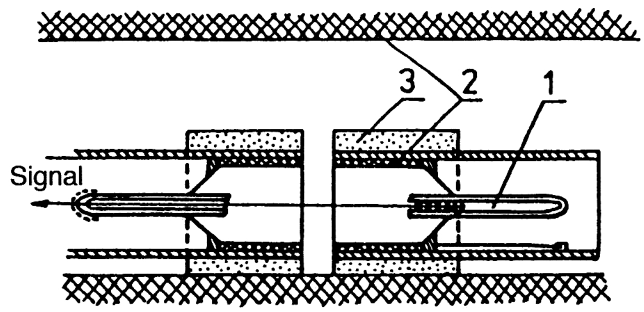

FIG. 1. Arrangement of sample and γ-ray detector in channel of the moderation-time spectrometer. 1) Gas proportional counter; 2) lead wall of counter (γ-ray converter) and, above and below, lead as moderator; 3) sample.

The measurement of cross sections by the detection of reaction products reduces to the measurement at one and the same point of the moderator of the time dependence of the slowing down in the number of counts $I_1(t)$ of the detector of the reaction products and in a reference sample (boron or lithium), $I_B(t)$, for which the cross section satisfies the $1/v$ law, i.e., $\sigma_B E^{1/2} = \text{const}$. For thin samples,

$$I_1(t)/I_B(t) = k\langle \sigma_1 E^{1/2} \rangle \cong k(\sigma_1 E^{1/2})_{\langle E \rangle}, \qquad (4)$$

where the angular brackets denote averaging over the neutron spectrum in the moderator at the time t, and k is a constant determined by the normalization of the complete curve (4) to the known cross section in the thermal region or to the area under the curve of a resonance with known parameters. An estimate of the approximation in the expression (4) shows (see p. 35 in Ref. 4) that in the most unfavorable case with $E_n = 50$ keV the correction is 10% for the working geometry of the first MTS if $\sigma_1 \sim 1/E$ and is smaller than this by a factor 3 for $\sigma_1 = \text{const}$.

Measurements of cross sections

Given isotropic irradiation with neutrons of the sample and detector placed in narrow channels in the moderator, cylindrical geometry of both is optimal. This was the geometry chosen for the detectors of the neutrons (proportional boron, lithium, and He-3 counters), the fission fragments, and some γ-ray detectors (see Fig. 1).

The measurements of the capture cross sections using the MTS covered a wide range of energies—from thermal energies to energies of order 40 keV, i.e., the capture of neutrons with angular momentum $l = 0$ (s neutrons) and $l = 1$ (p neutrons) could be detected. To ensure that the efficiency ε of detection of a neutron capture event through the detection of the decay γ rays was constant in the complete working range of neutron energies, special γ-ray detectors with thick lead walls were developed and used. The wall thickness was taken to be of the order of the range of an electron with the maximum energy, $E_\gamma \sim B_n \sim 10$ MeV, which guaranteed

$\varepsilon_\gamma = \text{const } E_\gamma,$

and then

$\varepsilon = \text{const } B_n,$

where $B_n = \Sigma E_\gamma$ is the neutron binding energy[7] (see Fig. 1). Later, the scintillation form of such a detector became known as a Moxon–Rae detector.[8]

To reduce the load on the electronics from the original burst of neutrons and γ rays in investigations using scintillation γ-ray detectors, blocking of the photomultipliers by sending a pulse synchronous with the neutron burst to the first electrode was successfully used.[9]

Since the energy resolution of an MTS does not exceed 30%, while the luminosity is higher by 3–4 orders of magnitude than in the time-of-flight method, the use of an MTS is promising in the study of nuclei with low level density (parameters of individual weak resonances, behavior of the cross sections between resonances, deviation of the cross sections from the $1/v$ law, and determination of the energy position of "negative" levels), and also in the measurement of cross sections averaged over many resonances. Analysis of these last cross sections makes it possible to obtain the mean resonance parameters for s and p neutrons, which are needed to test various theoretical models. In addition, measurements of the mean cross sections for neutron capture in the region of stellar temperatures, i.e., at energies 10–30 keV, is of undoubted interest for solution of the problems of primordial nucleosynthesis in the universe.

Already the first MTS studies of the interresonance behavior of the cross sections of the (n,α) and (n,p) reactions on light nuclei made it possible to demonstrate the strong aspects of moderation-time spectrometry.[10] The possibility of making high-precision measurements of the ratios of the cross sections of these reactions on the ^{3}He, ^{6}Li, and ^{10}B nuclei in a wide range of energies made it possible to obtain original results. The existence of a constant component in the cross sections of these reactions, i.e., deviation of the behavior of the cross section from the generally accepted $1/v$ law, was established, and the parameters of a more accurate expansion of the cross sections in powers of the velocities than is given by the $1/v$ law were obtained. In the case of the $^3\text{He}(n,p)^3\text{T}$ reaction, the effect of a "negative" resonance—an excited state in the compound nucleus ^{4}He with excitation energy $E=20.5$ MeV and spin and parity $J^\pi=0^+$—was found. This gave rise to "unease" among the theoreticians, since such a level could not be reproduced in the framework of the models of the simplest nuclei that then existed.

As an example of the first measurements of the cross sections of radiative neutron capture, Fig. 2 shows the energy dependence for the cross section of capture by the natural mixture of copper isotopes, normalized by the cross section $\sigma_\gamma = 3.77 \pm 0.03$ b for thermal neutrons. The deviation of the cross section from the $1/v$ law (the solid straight line in Fig. 2) at $E < 150$ eV indicates the presence in one of the copper isotopes of a resonance with energy below the neutron binding energy in the nucleus. Since the thermal cross section of copper is determined to 82% by the ^{63}Cu isotope and to 18%

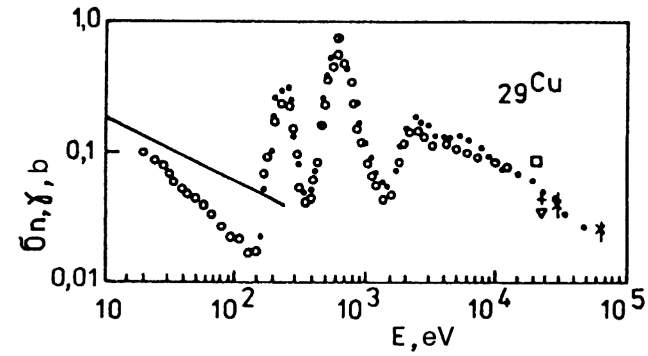

FIG. 2. Energy dependence of the cross section for radiative capture of neutrons by copper nuclei. The black and open circles are the results of measurements for copper samples with effective thickness $n=3.2\cdot10^{22}$ nuclei/cm^2 and $n=6.5\cdot10^{22}$ nuclei/cm^2, respectively. In the region of tens of kilo-electron-volts, the measured averaged cross sections agree well with the data of Gibbons *et al.*[11] (inclined crosses) and Schmitt and Cook[12] (upright cross).

by ^{65}Cu, and the deviation from the $1/v$ law reaches ~70%, the "negative" level (if there is just one) can belong only to the ^{64}Cu compound nucleus. The energy of this level is conveniently determined by linear extrapolation of the expression

$$(\sigma_\gamma \sqrt{E})^{-1/2} = \text{const}(E - E_0),$$

where a preliminary correction for the contribution of the ^{63}Cu isotope to the cross section is introduced.

With increasing atomic number, the level density in nuclei increases (except in the neighborhoods of magic nuclei), and for $A > 70$ the MTS energy resolution becomes insufficient to separate individual resonances in the region of energies above a few tens of electron volts. At the same time, there does appear an interesting possibility of investigating the general features of the dependence of the cross sections averaged over many resonances on the mass number, parity effects, the number of neutrons in the target nucleus, to determine the parameters of the interaction of p neutrons with nuclei, etc. Over a period of several years, the MTS No. 1 was used to measure the cross sections of radiative capture of neutrons by several tens of isotopes, mainly separated, up to thallium.

Analysis of experimental data

Taking the example of the results of measurement of the capture cross section in indium (Fig. 3), we can demonstrate how, by comparing the experimental cross sections in the energy range 1–50 keV with the results of calculations in a statistical theory of the contributions of the cross sections for s and p neutrons, it is possible to determine the corresponding neutron strength functions S_0 and S_1, which play an important role in the choice of the parameters of the optical model of the interaction of neutrons with nuclei.

The upper curves in the figure correspond to the following values of the strength functions for s and p neutrons: for

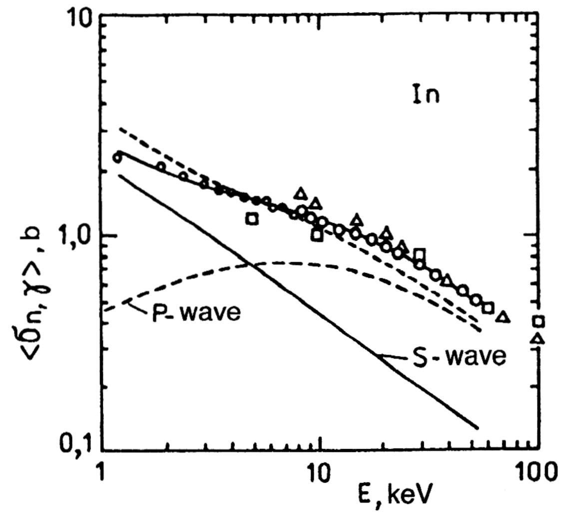

FIG. 3. Cross sections for neutron capture in indium.

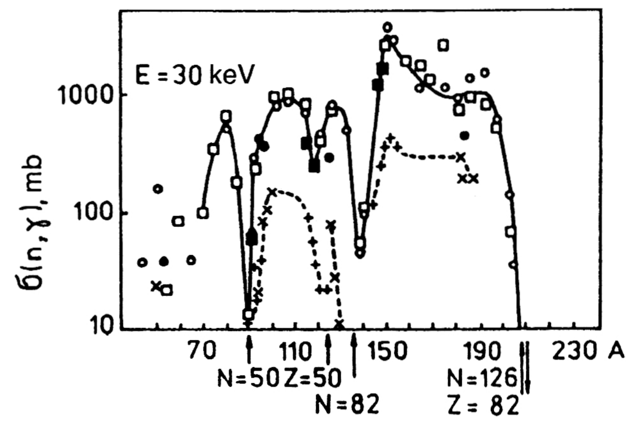

FIG. 4. Dependence of averaged cross sections for capture of neutrons with energy 30 keV on the mass number of the target nucleus.

Target nucleus	e–e	e–o	o–e	
	×	●	○	CB3I
	+	■	□	ORNL

the dashed curves, $S_0=0.5\cdot10^{-4}$ (fixed[11]) and $S_1=(4.1\pm0.5)\cdot10^{-4}$; for the solid curves, $S_0=(0.24\pm0.01)\cdot10^{-4}$ and $S_1=(5.1\pm0.1)\cdot10^{-4}$.

We note that at the present time,[13] the accepted value is $S_0=(0.26\pm0.03)\cdot10^{-4}$.

The lower curves in the figure illustrate the contributions of the s and p neutrons to the total capture cross section.

Such an analysis was also made for about 15 nuclei. The systematics of the values obtained for the strength functions for p neutrons in the region of the $3P$ maximum ($A\sim100$) indicated a possible splitting of it (due to the small values of S_1 for the ^{98}Mo and ^{100}Mo isotopes). Subsequently, direct observation of spin–orbit splitting of the maximum into two components, $P_{1/2}$ and $P_{3/2}$, was obtained in studies of Samosvat.[14]

According to modern ideas, the nucleosynthesis of the elements (isotopes) heavier than iron occurs in stars by the capture of neutrons produced by the burning of lighter elements. These so-called slow and rapid capture processes (s and r processes) take place at stellar temperatures corresponding to Maxwellian distributions of the neutron energies with mean values ~10–30 keV. To test modern theoretical scenarios of the production of elements in the universe, it is necessary to know the cross sections of radiative capture of neutrons in these energy ranges for practically all isotopes. During the last two decades, special attention has been devoted to measurements (and also theoretical or phenomenological estimates) of the averaged cross sections for capture at $E_n=30$ keV. These cross sections were given individually in the handbook of Ref. 13. A main contribution to these data was made by measurements of the neutrons from the ^{7}Li(p,n) reaction near the reaction threshold (see, for example, Refs. 11 and 15) using quasi-monochromatic beams of iron-filtered neutrons from a reactor[16] (these cross sections, measured at 24 keV, were then extrapolated to energies 30 keV), and there were also MTS measurements.[17]

One of the first analyses of the results of measurements of the averaged cross sections of radiative capture of neutrons at $E_n=30$ keV indicated a number of features in the dependence of the cross sections on the mass number (or the number of neutrons) in the target nucleus. The cross sections for even–even target nuclei were regularly found to be smaller by a factor 4–5 than the cross sections for other nuclei. At the same time, the cross sections of odd–even nuclei lay on a common curve with the cross sections of the even–odd nuclei (see Fig. 4). The cross sections clearly "feel" the nuclei that are magic with respect to the neutron number (the shells) and their neighborhoods, decreasing by 1–2 orders of magnitude compared with the cross sections between the shells. The proton shells are manifested somewhat more weakly.

An analysis of the averaged cross sections at neutron energy 30 keV was made on more extensive experimental material in Refs. 18 and 19. This analysis confirmed the features noted above and made it possible to trace several new systematic dependences that may be of interest for estimates of the averaged cross sections, for example, in the case of rare or radioactive isotopes. Thus, for even–even isotopes of a given element it is characteristically found that there is a smooth decrease of the cross section with increasing number of neutrons. However, near magic values of the neutron number N, this dependence is distorted by a more rapid decrease of the cross sections as the magic N is approached. Such dependences of the averaged cross sections (on a logarithmic scale) on the neutron binding energy B_n are shown in Fig. 5.

At the same time, if $\langle\sigma_{n,\gamma}\rangle$ is plotted as a function of the product αU, where α is a parameter proportional to the density of the single-particle states, and U is the excitation energy of the nucleus, then for the neodymium isotopes too the cross sections lie on one straight line. Unfortunately, it is difficult to use dependences of the type $\langle\sigma_{n,\gamma}\rangle=f(\alpha U)$ to estimate unknown capture cross sections, since the value of α for them is, as a rule, unknown and cannot be well estimated using known values for neighboring nuclei.

An analysis of a more extended set of experimental data made recently[20] made it possible to establish more accurately the phenomenological dependences of the mean cross sec-

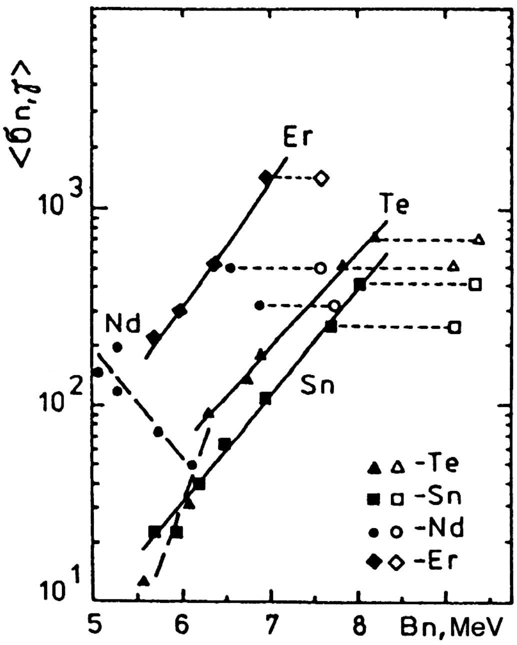

FIG. 5. Dependence of the averaged capture cross sections at E_n=30 keV on the neutron binding energy. The horizontal lines (thin dashes) give the displacements of the points after the introduction of a correction for the pairing energy (Δ≈1.5 MeV) for even–odd target nuclei. The solid continuous lines connect isotopes of one element.

tions at 30 keV and to obtain new estimates of $\langle\sigma_{n,\gamma}\rangle$ for uninvestigated nuclei outside the "stability valley." In Table I, we give the estimated values of the mean cross sections of Ref. 20 for analysis of the *s* process in nucleosynthesis.

SECOND GENERATION OF NEUTRON SPECTROMETERS BASED ON THE MODERATION TIME IN LEAD

The main feature of the second-generation moderation-time spectrometers was the use of more powerful pulsed sources of fast neutrons: linear electron accelerators (RINS at the Rensselaer Polytechnic Institute, USA; the Fakel facility at the I. V. Kurchatov Institute of Atomic Energy, USSR; KULS, at the Kyoto University Research Reactor Institute, KURRI, Japan). This made it possible to raise by two or three orders of magnitude the neutron fluxes on the investigated samples compared with the fluxes in the first moderation-time spectrometer constructed under the supervision of Shapiro. This, in its turn, made it possible to turn to new investigations, in particular to measurements of the cross sections of below-barrier fission on isotopes of transuranium elements, which are sometimes available only in microgram amounts.

TABLE I. Some results of estimates of the cross sections of radiative capture at 30 keV of interest for calculations of the *s* process in nucleosynthesis.

Isotope	$\langle\sigma(n,\gamma)\rangle$, mb	Remarks
^{77}Se	572(120)	Stable nucleus
^{79}Se	333(68)	Unstable nucleus, branch point of the *s* process
^{151}Nd	660	(same)
^{151}Sm	1200	(same)
^{181}Hf	350(80)	(same)
^{182}Hf	82(18)	(same)

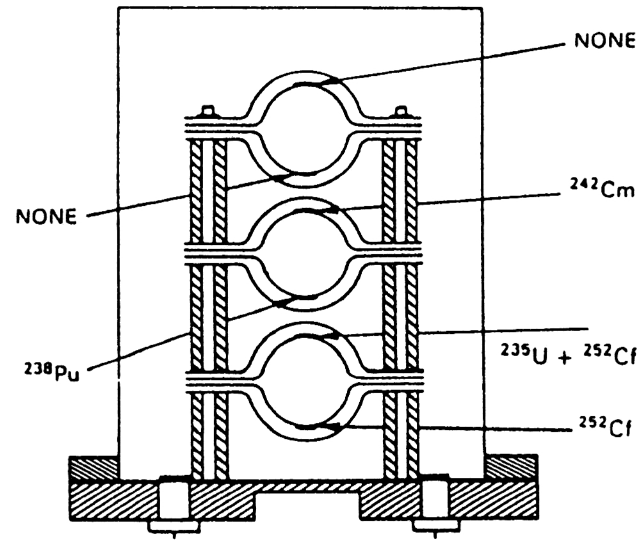

FIG. 6. Arrangement of the fast fission chambers used in the RINS.

The Rensselaer intense-neutron spectrometer

The first of the second-generation moderation-time spectrometers was the RINS (Rensselaer Intense Neutron Spectrometer) of weight 75 tons constructed at the Rensselaer Polytechnic Institute in the middle of the seventies. The neutron source was a linear electron accelerator. As can be judged from the publications, the main program of RINS investigations became the measurement of fission cross sections. Below-barrier fission in the ^{238}U(n,f) reaction was first demonstrated here.[21] In recent years, the measurements of the cross sections have mainly been of the below-barrier fission of a large number of transuranium isotopes. The high intensity of the resonance neutrons in the sample and the original fast-response hemispherical ionization detectors of the fission fragments made it possible to investigate below-barrier fission with microgram samples possessing high α activity. Only the high neutron fluxes at the RINS made it possible to measure the cross section for fission of ^{242}Cm, which possesses a high probability of spontaneous fission (~9 fission events per second in 1 mg of sample) and a specific activity of $\sim 10^8$ α decays per second in 1 mg of sample.

Figure 6 shows schematically the assembly of six fission chambers, in which simultaneously: a) the cross sections of below-barrier fission on ^{238}Pu (12 μg) and ^{242}Cm (1.15 μg) samples were measured; b) the neutron flux was monitored by means of ^{235}U; c) the efficiency of fission-fragment detection was accurately determined by means of a sample of spontaneously fissioning ^{252}Cf; d) the background in an empty chamber (upper hemispheres) was determined.

Figure 7 shows the results of measurements of the ^{238}Pu fission cross section (histogram) in a comparison with a calculated curve obtained on the basis of estimated ENDF/B-V

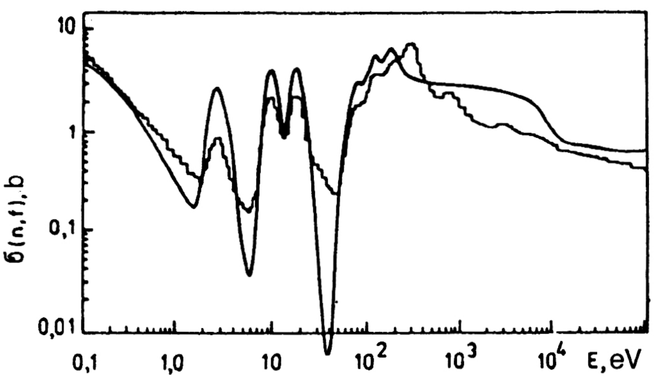

FIG. 7. Cross section for ^{238}Pu fission measured using the RINS moderation-time spectrometer (histogram) and the attempt to describe it by means of the ENDF/B-V bibliographic data.

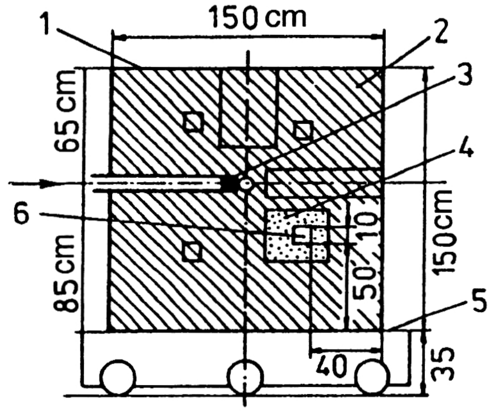

FIG. 8. Schematic arrangement of the KULS moderation-time spectrometer: 1) sheet cadmium; 2) lead moderator; 3) tantalum target of electron accelarator; 4) bismuth inserts; 5) platform on wheels; 6) cavity for sample and detector.

data with a correction for the RINS energy resolution.[22] Comparison of the two curves in the region of energies below 50 eV suggests that even modern calculations by the Monte Carlo method[23] are not capable of reproducing completely all the processes of neutron moderation in large lead blocks. The calculations made in the fifties[5] were also unable to describe completely the shape of the MTS resonance. Usually, the discrepancies are explained qualitatively by the presence in the lead of light-element impurities, but quantitative reproduction of the experimental profile of the resonance could not be obtained. In this connection, it appears dangerous to use the difference between the experimental and calculated curves of the capture cross sections (especially for thick samples) to "discover" new resonances.[24]

The discrepancy between the experimental histogram and the calculated curve in Fig. 7 in the region in which the resonances are averaged indicates incompleteness of the ENDF/B-V data, and the authors of Ref. 22 are correct in recommending that there should be a reestimation of the ENDF/B-V data on the basis of the ^{238}Pu fission cross section in the region of neutron energies below 100 keV.

The authors attribute the observation of the broad maxima in the fission cross sections of ^{238}Pu, ^{242}Cm, and other Cm isotopes investigated at the RINS and in the region of energies above several hundred electron volts to the presence of clusters of several resonances due to below-barrier fission through the second well of the double-humped fission barrier ("interference" with levels in the second well). Essentially, the curve of the cross sections of below-barrier fission measured with the MTS reproduces the envelope of several resonances that "interfere" with an individual level in the second well. This enabled the authors to estimate for the even Cm isotopes the density of states in the second well and the difference between the energies of the bottoms of the first and second wells. It was found that the data for ^{242}Cm, ^{244}Cm, ^{246}Cm agree well with the general systematics, in particular in the fact that the second well lies 2–3 MeV above the first. However, the characteristics of ^{248}Cm distinguish it significantly from the other three even isotopes of curium.

The moderation-time spectrometer of the I. V. Kurchatov Institute of Atomic Energy

This was a lead prism with weight ~60 tons and lead of purity 99.98%. The pulsed neutron source was the linear electron accelerator Fakel. The tungsten target of the electron beam was designed to give a power up to 10 kW. For this, water cooling (~250 cm^3 of water within the spectrometer) was foreseen. However, after calculations of the possible effect of the water on the neutron spectrum in the spectrometer, the idea of using water had to be abandoned.

The main direction of investigations with this spectrometer was also measurement of fission cross sections on microgram samples of transuranium isotopes. For example, Ref. 25 gives the mean fission cross sections of ^{241}Pu, ^{242m}Am, ^{245}Cm in the range of energies from 4.6 eV to 21.5 keV and compares them with estimated cross sections of various bibliographic neutron data (BNAB-78, ENDF/B-V, ENDL-76, JENDL-1). Altogether, fission cross sections were measured for ten nuclei, including ^{236}Pu for the first time. Unfortunately, not all the experimental data obtained with this MTS were published in readily accessible journals.

KULS: The moderation-time spectrometer at the University of Kyoto

Some characteristics of second-generation moderation-time spectrometers can be identified in the example of KULS.[26] The first MTS in Japan was built at the end of the sixties at the University of Tokyo,[27] and then in 1991 the lead was transferred to the University of Kyoto. There, in the Kyoto University Research Reactor Institute (KURRI), the lead was purified to a purity of 99.9%, and the blocks were polished and a cube was constructed on a mobile trolley. The cube had sides of 1.5 m and was covered with 0.5-mm sheet cadmium (to reduce the background from stray neutrons in the building). The general form of the spectrometer is shown in Fig. 8.

The total weight of the lead is 38 tons. The trolley can be moved to the linear electron accelerator (electron energy 46 MeV, current pulse 2 A, pulse duration 33 ns, neutron yield

$\sim 10^{11}$ neutron/s). The tantalum target of the accelerator is cooled by compressed air, and this restricts the power of the electron beam on the target to a level $\leqslant 1$ kW. Replacement of the cooling air by water is regarded as dangerous in connection with distortion of the spectrum of the moderated neutrons by scattering by hydrogen.

One of the measuring channels of the KULS is lined with bismuth (10–15 cm thickness) to shield the sample and the detector from hard γ rays after the capture of neutrons in the lead ($E_\gamma \sim 7$ MeV). This is important not so much for measurement of the capture cross sections as for suppression of the not easily controlled background from photofission on hard γ rays in the study of below-barrier fission, which takes place with small cross sections.

It is interesting to note that for KULS the constants in the expression (2) are very different for the lead and bismuth cavities: 156±2 and 190±2 keV·μs. Qualitatively, this is understandable, since the neutron range until scattering in the bismuth is $\lambda = 3.85$ cm and in the lead $\lambda = 2.68$ cm, and the constant in the expression (1) for a purely bismuth moderation-time spectrometer should be changed by 40% compared with a lead one. The change in the constant by ~20% for the small bismuth insertion in KULS of weight ~440 kg (this is of the order of 1% of the total weight of the moderator) demonstrates the important role of moderation in the immediate vicinity of the sample (or detector). It would be interesting to investigate in more detail the effect of the bismuth on the shape of the resonance curve, since the difference between the rates of neutron moderation inside and outside the bismuth must distort the instantaneous spectrum of the neutrons compared with the case of a homogeneous moderator.

One would like to know how the γ background changed inside the bismuth lining. This may be important for estimating the possibilities of the second-generation MTS for measurements of the cross sections of radiative capture of neutrons by radioactive nuclei (to meet the requirements of nuclear astrophysics and the transmutation of radioactive wastes from nuclear power plants). It is interesting to consider the possibility of developing an optimized method for measuring capture cross sections using small amounts of radioactive nuclei, for example, a cylindrical insert with walls of thickness ~5 cm and made of doubly magic ^{208}Pb (~5 kg of the isotope), a detector placed outside the moderator, etc.

New methodological possibilities in studying the resolution of moderation-time spectrometers at short moderation times (in the region of neutron energies of several kiloelectron-volts) are opened up in connection with the proposal[28] to use analysis of the shape of γ line of a Ge spectrometer after capture of neutrons in the region of the averaged capture cross sections. The natural profile of the γ line measured in the region of thermal neutrons will be appreciably distorted at energies $E_n \geqslant 2$ keV by the energy spread of the neutrons absorbed at the given moderation time. Figure 9 shows schematically a three-dimensional picture that illustrates this experiment. Along the axes are plotted the moderation time (t_3), the number of detected γ rays of the chosen primary γ transition of radiative capture (N_γ), and the energy of the γ rays (E_γ).

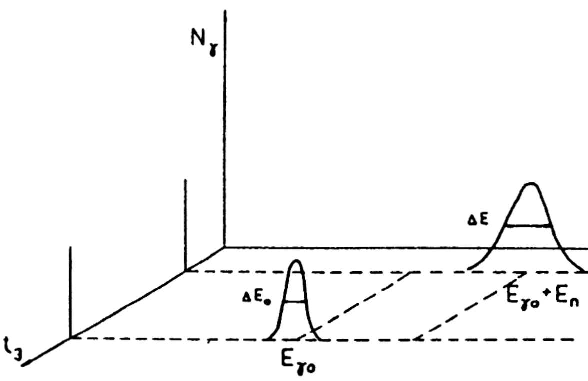

FIG. 9. Three-dimensional spectrum illustrating the change in the shape of a γ line measured at thermal energy ($E_{\gamma 0}$) and at the neutron energy E_n.

PROSPECTS FOR INVESTIGATIONS USING THIRD-GENERATION MODERATION-TIME SPECTROMETERS

The third generation of moderation-time spectrometers is associated with the use of high-flux proton accelerators to energy ~1 GeV (meson factories) as neutron sources. The first such proposal was apparently made by Yu. Ya. Stavisskiĭ in a lecture at the Fourth All-Union Seminar on the Program of Experimental Investigations at the Meson Factory of the Institute of Nuclear Research of the USSR Academy of Sciences (1985).[29] At the following Fifth Seminar (1987), we proposed for discussion a program of scientific investigations using the future MTS.[30]

At the end of the eighties, a group of well-known American physicists from Los Alamos, the Rensselaer Polytechnic Institute, and Livermore made a number of comparative measurements of fission cross sections using RINS (moderation-time spectroscopy) and LANSCE (time-of-flight neutron spectrometer at the Meson Factory at Los Alamos) and demonstrated the good prospects for using an MTS in meson factories.[31] They proposed the development of an MTS on the basis of the beam of the proton storage ring of the Los Alamos Meson Factory. Unfortunately, the MTS project at Los Alamos exists as yet only on paper. Evaluation of methodological aspects of third-generation moderation-time spectrometers has begun using the proton beam of the Moscow Meson Factory and a small MTS model (PITON) (collaboration between the Institute of Nuclear Research and the Laboratory of Neutron Physics of the JINR).[32]

According to the estimates of Stavisskiĭ,[29] use of the total intensity of the bunched protons after the storage ring of the Moscow Meson Factory will give a gain in luminosity compared with the first-generation moderation-time spectrometers by a factor of $\sim 5 \cdot 10^8$. However, the heat release in the lead will then reach ~300 kW, and this will require a rather complicated system of liquid-metal cooling. A version with a beam having a power of order 3 kW (gain $\sim 10^7$) does not create basic problems with cooling. At the same time, it must be borne in mind that for 1 kW of power released in the target the yield of neutrons for a proton beam is almost two orders of magnitude greater than in the case of an electron beam.

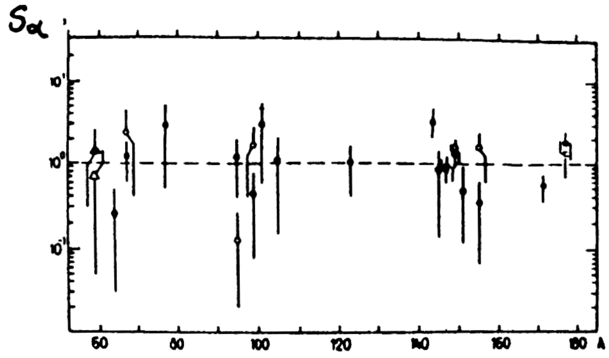

FIG. 10. Dependence of the α-particle strength function S_α (in relative units) on the mass number.

As the intensity of the neutron beam in the moderator is increased, so is the γ background from capture of neutrons in the lead and impurities. The overcoming of this problem naturally requires special technical developments, but, in addition, it is evident that this will restrict the range of possible experiments using the third-generation spectrometers. Nevertheless, there is no doubt concerning the investigation of fission processes: with samples containing up to $\sim 10^{11}$ nuclei, in the case of deep below-barrier fission, etc. In particular, the estimates of Moore *et al.*[31] suggest that it will be possible to study ^{235}U fission from an isomer state using resonance neutrons.

It also appears to be promising to look for previously unobserved reactions of the type $(n, {}^8Be)$ and more complicated reactions (extremely asymmetric fission). This has become topical and encouraging after the discovery of a new type of natural radioactivity with emission of heavy nuclei such as ^{14}C (Ref. 33).

Although not simple, the problem of investigating the (n,α) reaction on resonance neutrons using a third-generation MTS appears realistic. Extensive investigations of this reaction (in other words, α decay of compound states) were made in the sixties and seventies at Dubna. One of the initiators of these studies was Fedor L'vovich Shapiro. The main results of the investigations were summarized in the review of Ref. 34. However, the existing experimental possibilities for further study of the (n,α) reaction are practically exhausted. Because of the Coulomb barrier, the cross sections of the (n,α) reaction are orders of magnitude lower than for the (n,γ) reaction, and therefore moderation-time spectrometers of the new generation are needed.

Figure 10 gives the relative values of the α-particle strength functions for a large number of nuclei, which were mainly investigated at Dubna. The apparent constancy of the S_α values may indicate that to within the existing experimental accuracy (which is determined by the small number of resonances over which the experimental data were averaged) one can say that in the region of intermediate and heavy nuclei a nucleus is black for α particles, i.e., the giant α-cluster levels are much more strongly fragmented over the compound states of the nucleus than what occurs for the single-particle states (see the analogous dependence of the neutron strength functions on the mass number[13]). However, this qualitative conclusion can be verified quantitatively if the accuracy with which the values of S_α are measured is raised significantly. Such a possibility is opened up by the measurement of the cross sections of the (n,α) reaction averaged over many resonances for a large number of intermediate and heavy nuclei using moderation-time spectrometers in meson factories. Analysis of the energy dependence of $\langle\sigma(n,\alpha)\rangle$ in the same way as was done for radiative capture (see Fig. 3) with simultaneous pulse-height analysis of the α particles will make it possible to improve by a factor of several times the accuracy in the determination of S_α and to determine the partial strength functions for α decay to individual excited states of the daughter nucleus. This last possibility is important for elucidating the dependence of the average characteristics of α decay of compound nuclei on the nature of the final states. According to the conclusions of limiting statistical theory, there should be no such dependence, but it is predicted qualitatively by Solov'ev's quasiparticle–phonon model,[35] and some experimental data also indicate such a possibility (see Ref. 34).

The moderation-time spectrometers of the new generation will make it possible to investigate the role of interference effects in the α-decay channels of compound nuclei. It was assumed *a priori* that such effects are unimportant for nuclei for which the widths of the neutron resonances are several orders of magnitude smaller than the spacings between the interfering levels. However, it is evident that only interference effects can explain the discrepancy between the results of measurements of the partial cross sections (only for α transitions to the ground state) of the (n,α_0) reaction in the region of thermal neutrons on the ^{67}Zn and ^{145}Nd nuclei with the results of calculation of such cross sections on the basis of the parameters of known resonances.[36] The calculations gave a value of the thermal cross section that was an order of magnitude greater than the upper bounds of the results of the measurements made in the two laboratories.

CONCLUSIONS

In these April days of 1995, when these lines are being written, my teacher, Fedor L'vovich Shapiro, who left a strong trace in neutron physics, would have become 80 years old. He left us already 22 years ago. However, even today many of his ideas live on and are being realized and developed. I have attempted here to trace the 40-year history of the development of one of these ideas, to which Fedor L'vovich devoted about ten years and with which my scientific work began.

The "primitive" neutron spectrometer constructed under the guidance of Shapiro and consisting of a lead cube and the simplest Cockcroft–Walton deuteron accelerator was, of course, a natural target for Wigner's taunt of a "poor man's spectrometer." However, at that time, at the first Geneva Conference on the Peaceful Uses of Atomic Energy, Fedor L'vovich reported, in practice, only the commissioning of the spectrometer and its main characteristics, and the great possibilities of moderation-time spectrometers and the original results were demonstrated and evaluated later. Today, many specialists in the field of neutron physics impatiently await the third generation of moderation-time spectrometers and the record fluxes of resonance neutrons that it will bring.

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