EXPERIMENTAL NEUTRON SPECTROSCOPY – PRESENT STATE AND DEVELOPMENT PROSPECTS

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1. Introduction

By analogy with classical optical techniques, neutron spectroscopy can be divided into emission and absorption spectroscopy. The former would represent the study of such phenomena as the neutrons emitted in nuclear reactions or scattered from a sample placed in an intense neutron flux; the latter would most simply describe the study of neutron total cross sections by the transmission method, but might be extended to include all cross-section work. In the same way neutron-diffraction studies are directly analogous to classical techniques with x rays. Thus neutron spectroscopy includes the study of a wide range of phenomena both in nuclei and in bulk matter. The only common feature is the measurement of the wavelength or energy of the neutrons involved.

The technique used for the measurement of neutron energy depends greatly on the energy range of interest. Most neutron spectroscopy at low energies ($\lesssim 1$ eV) utilizes neutron diffraction (Bragg condition) either as a monochromator or analyzer. At high energies ($\gtrsim 1$ MeV) the observation of the energies of charged reaction products [e.g., ^{3}He(n, p)T] or knock-on elastic collisions with protons can be used to infer the energies of fast neutrons. The only technique, however, which offers a precise determination of neutron energies over the entire range of interest (certainly from 10^{-2}–10^8 eV) is that of time of flight where the neutrons are produced or released in short pulses and their flight timed over a measured distance. Given sufficient intensity, the precision of these measurements can always be arbitrarily increased by increasing the distance (flight path) over which the timing is accomplished, and, furthermore, the use of multichannel time analyzers permits measurements to be made at thousands of different energies simultaneously.

Time does not permit us here to describe even superficially the whole range of techniques mentioned above. The subject has been dealt with in the literature [1], so we shall restrict our talk to the time-of-flight techniques, which certainly has the widest range of applications. In addition, since the use of the time-of-flight technique in the study of bulk matter is well covered elsewhere in this conference, we shall also restrict our talk to its use in the nuclear physics field, which also happens to be my own field of specialization.

2. Time-of-flight Spectrometers

Time-of-flight spectrometers utilize normally a pulsed source which provides neutrons over a wide band of energies. The basic principle of the method is that the time interval between the emission of the pulse of neutrons and the arrival of individual neutrons at a distant detector is a measure of the neutron velocity, and so energy. By connecting the output of the detector to a multichannel time sorter, the distribution in velocity of the neutrons from the source is obtained directly. Let us suppose that the neutron pulse has duration Δt, that measurements are made over a flight path of length l, and that the delay t between the start of the neutron pulse and its detection can be determined exactly. Let us further assume that the physical dimensions of the pulsed source and detector introduces an uncertainty Δl into the flight path length. Then we can write the energy resolution $\Delta E/E$ as

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$$\frac{\Delta E}{E} = \frac{2\Delta v}{v} = \frac{2\sqrt{(\Delta l)^2 + (v\Delta t)^2}}{l},$$

Δl and Δt being assumed to have independent Gaussian distributions, and v being, as before, the neutron velocity. We observe at once that in the high-energy limit, where $(v\Delta t)^2 \gg (\Delta l)^2$, this expression becomes

$$\frac{\Delta E}{E} = 2v\frac{\Delta t}{l},$$

where $\Delta t/l$ is the nominal resolution in microseconds or nanoseconds per meter.

It is also clear that in the low-energy limit the resolution is given by $\Delta E/E = 2\Delta l$ which is independent of the neutron's velocity and of the pulse length provided the latter satisfies the inequality $(v\Delta t)^2 \ll (\Delta l)^2$. Hence, to achieve good resolution at low neutron energies (say $E_n < 100$ eV) the important factors are a long flight path and short detector, while at high energies, say $E_n > 10$ keV, the most important factor apart from the flight path length is the shortness of the pulse Δt. The timing uncertainty in the moderation process in the case of pulsed accelerators can be shown to be roughly equivalent to an irreducible length uncertainty Δl of the order of a few centimeters. This fact must be borne in mind in calculating resolution widths.

The pulsed neutron sources used in time-of-flight spectroscopy can be mechanical devices for the low-energy end of the range, and indeed much of the earlier work on neutron cross sections was done with mechanically chopped beams from high-flux reactors. Fast neutron choppers with pulse durations ~1 μsec still provide very competitive fluxes with reasonable resolution in the energy range below, say, 100 eV, as is well illustrated by the recent work on the γ-ray spectra from resonance neutron capture carried out by Chrien and his collaborators at Brookhaven [2]. A unique form of mechanically pulsed system is the IBR-30 Pulsed Reactor here in Dubna. In its purely mechanically pulsed mode of operation, the pulse length (~90 μsec) is well suited to providing an extremely intense pulsed source of thermal neutrons for the study of bulk matter. In this field, it is at the moment without serious competitors, providing as it does $\sim 10^{13}$ thermal neutrons per pulse. The pulse length is, however, too long to be suitable for use in nuclear physics applications, and for this work the system is both mechanically and electronically pulsed. Used in this way, its pulse length is ~3 μsec and its regime of applicability is similar to that of the choppers. The absolute fluxes obtained on the end of a flight path, however, exceed those of the choppers by one or two orders of magnitude, so that longer flight paths can be used to maintain competitive resolution to higher energies. At still higher energies we enter the domain of the pulsed accelerators whose burst length can be made much shorter than that of any mechanical system. Almost any pulsed accelerator capable of initiating a neutron-producing reaction can be used for neutron time-of-flight measurements providing the neutron intensity is sufficiently high. The pulsed Van de Graaf accelerator has been extensively used in the study of nuclear reactions initiated by charged particles. Here the spectrum of fast neutrons emitted from (p, n), (d, n), and other similar reactions has thrown much light on the subject of isobaric analogue states. Another application is the production of short pulses of monoenergetic neutrons (pulse duration ~1 nsec) which are then used as a pulsed source for nuclear inelastic scattering studies. Where a white spectrum moderated neutron source is required for neutron time-of-flight spectroscopy over a wide neutron energy range, however, the pulsed Van de Graff cannot compete in intensity with cyclotrons and electron linear accelerators. The 400 MeV synchrocyclotron at Columbia University (20 nsec burst) has been used intensively as a pulsed neutron source utilizing the spallation reaction induced by energetic protons in a lead target, and the Harwell 150 MeV synchrocyclotron (4 nsec burst) has also been used for this work. The machine which has been most exploited in the field of time-of-flight spectroscopy is, however, the electron linac, because of its relatively low cost and flexibility. These machines which utilize the (γ, n) and (γ, f) reaction in heavy targets can, in principle, provide, at the turn of a switch, pulse lengths varying from tens of microseconds for low-energy work down to a few nanoseconds for faster neutrons. The performance of these machines can in turn be improved at the low-energy end of their range by the use of a fast fission "Booster," such as is used on the Harwell Electron Linac. The Booster gives an increase of an order of magnitude in neutron yield at the cost of restricting the burst width to values $\gtrsim 100$ nsec. Some leading parameters of a number of pulsed neutron sources are given in Table 1. In general the total number of neutrons emitted in the pulse is the quantity of interest for thermal neutron work. At higher energies the intrinsic time spread of the source, due to the effect of the moderator, decreases as $1/E^{1/2}$, having a value ~50 nsec at 1 keV. Even at neutron energies $\gtrsim 100$ keV, where the moderator ceases to be

TABLE 1. Characteristics of Pulsed Accelerator Neutron Spectrometers

Spectrometer installation	Accelerator	Particle accelerated	Target	Energy, MeV	Pulse current, mA	Pulse duration, nsec	max. prf.	Neutr. prod. rate in pulse (neutr./sec · 10^{17})	Neutrons per pulse	Best nominal resol. (nsec/m)
Karlsruhe	90-in isochronous cyclotron	Deuterons	U	50	3000	1	160 000	6	$6 \cdot 10^{8}$	0,005
Harwell	110-in synchrocyclotron	Protons	W	150	3000	4	800	300	$1{,}2 \cdot 10^{11}$	0,04
Oak Ridge	Electron linear accelerator	Electrons	Ta	140	15 000	2,3—24	1000	40	$\approx 10^{11}$	0,03
Harwell	Electron linear accelerator	Electrons	^{235}U booster	40	650	100—1700	500	≈ 10	$1{,}7 \cdot 10^{12}$	0,3
IBR-30 Dubna	Electron linear accelerator	Electrons	Mechanically pulsed booster	44	180	1800	100	100	$1{,}5 \cdot 10^{13}$ (assuming 100 pps)	≈ 2
LIU-30 proposed for Dubna	Linear induction electron accelerator	Electrons	(U)	30	25 000	500	500	240	$1{,}2 \cdot 10^{13}$	

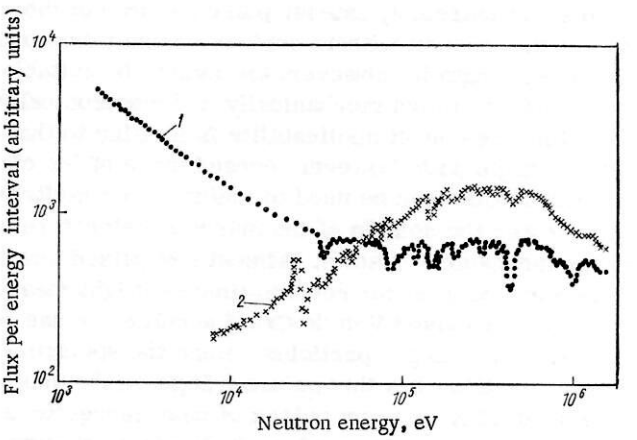

Fig. 1. Booster leakage spectra. 1) With water and boron; 2) without water and boron. Both curves are normalized using electron input to booster.

important (see Fig. 1), the finite size of the neutron target introduces a similar time uncertainty. Under these conditions, neutron flux for a given resolution is optimized by setting the accelerator pulse length to about the same value as the moderator time spread, and the important parameter is then the neutron production rate during the pulse. Figure 2 shows the neutron flux available at the end of a flight path for a fixed value of the logarithmic resolution ($\Delta E/E$) as a function of neutron energy for a number of the pulsed sources mentioned. Pulse overlap and variable pulse repetition frequency are taken into account (the latter being optimized within the range permitted for each pulsed source) and the flight path is allowed to increase at higher energies to maintain the resolution at its constant value. The curves shown for the pulsed reactors, operating as boosters, can only serve as rough guides. A 3-μsec pulse is assumed, and it is also assumed that they can be pulsed to the mean power shown and that the total neutron flux through the surface depends linearly on the power and is independent of the configuration. Even so, it is clear that they provide the highest intensities at low neutron energy but are rapidly overhauled by the short pulse accelerators at

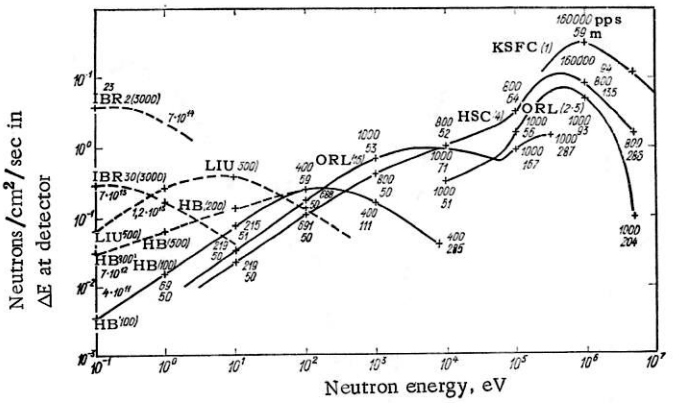

Fig. 2. Comparative fluxes from pulsed neutron sources, $\Delta E/E = 0.88 \cdot 10^{-3}$ (for 50-m flight path at small E). IBR-30) Dubna pulsed reactor in booster mode, run to heat-transfer limit (25 kW); IBR-2) proposed IBR-2 pulsed reactor in booster mode, run to heat-transfer limit (250 kW); LIU) proposed Dubna linear induction electron accelerator; HB) Harwell booster run to heat-transfer limit (25 kW fission power); ORL) Oak Ridge Orela project; HSC) Harwell synchrocyclotron; KSFC) Upgraded Karlsruhe sector focused cyclotron. Associated numbers are machine pulsed lengths in nanoseconds. Numbers on curves are pulse repetition frequency and flight path length (meters).

higher energies because of the very long flight paths necessary to maintain equivalent resolution. There is, however, a class of experiments in nuclear physics where moderate neutron energy resolution is sufficient, and where a very high flux is required to observe weak effects. Such experiments include the observation of weak lines in the measurement of neutron resonance capture γ-ray spectra [2] and the study of the resonance (n, α) reaction [3]. For these experiments, the boosters have a definite advantage as they do also in the normalization of capture and fission cross sections in the low-electron volt region. For the study of detailed resonance structure of lighter nuclei, however, the short pulse machines have a clear advantage, and one which increases with increasing neutron energy.

Although most neutron time-of-flight spectrometers are repetitively pulsed, it would be impossible to conclude even a brief discussion on this subject without mentioning the use of a nuclear explosion as a pulsed neutron source [4]. In this case, naturally, there is only one pulse, but this is so intense that the total neutron yield ($\sim 10^{24}$ neutrons in $\sim$100 nsec) is equivalent to running a modern electron linac pulsed source (with equivalent pulse length) for several centuries. Of course, such a comparison is misleading; individual events in experiments cannot be detected, and currents are measured in detectors rather than individual pulses. Furthermore, the heating and movement of the moderator adversely affect the resolution at low energies, and the problem of carrying out an experiment once only, with no scope for human error, is formidable. Nevertheless, the brief duration of experiments with this method doses permit the measurement of cross sections of very short-lived and highly active materials which could not be measured at all on other pulsed sources; it is in this field, especially in measurements on short-lived transuranic nuclides, that the nuclear explosion source has provided much new and interesting data.

3. Current Nuclear Physics Interest in Neutron Spectroscopy*

The nuclear physics interest in neutron spectroscopy is inextricably mixed with the reactor interest in accurate cross section measurements for reactor-physics calculations. Thus much of the present work

* In this section the author has drawn freely upon his contributions to "Experimental Neutron Resonance Spectroscopy" edited by J. A. Harvey, Academic Press, New York, to be published.

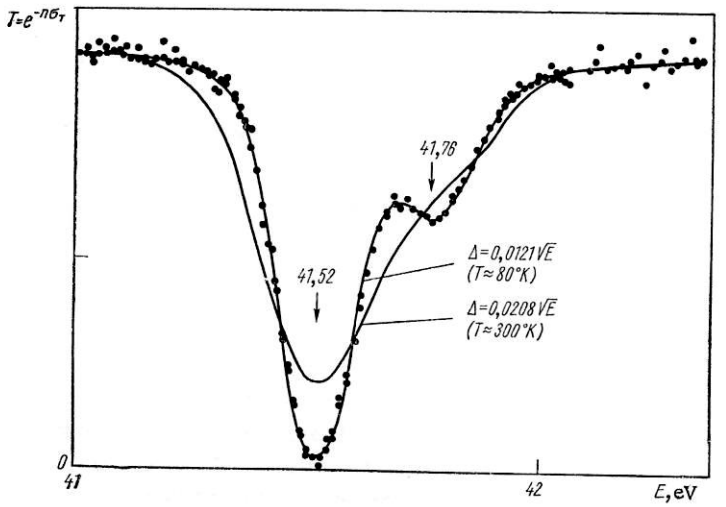

Fig. 3. Effect on observed cross section of cooling target.

in both fields will be found in the proceedings of international conferences such as Nuclear Structure Study with Neutrons (North Holland, 1966), Nuclear Data for Reactors (IAEA Vienna, 1967), Neutron Cross-Sections and Technology (NBS Spec. pub. 299, 1968) and the proceedings of the 1970 Helsinki Conference on Nuclear Reactor Data (IAEA Vienna, to be published).

The reactor interest, as mentioned above, is primarily in the provision of accurate cross-section data for the calculation of overall reactivity, of individual reaction rates, of Doppler temperature coefficients, and so on. This interest has led to much of the technical development in the field of time-of-flight spectroscopy development of pulsed sources, of detectors, of timing and data collection systems, and of elaborate computing codes for data correction and analysis. It has also led to a concentration of effort on the measurement and evaluation of certain "Standard cross sections" such as that of the $^{10}B(n, \alpha)$ reaction, against which most other partial cross sections are measured (see, for example, [5]). All of these developments, largely motivated by the demands of reactor physics, have proved fruitful also in providing information of interest to nuclear physicists. Let us then look at some examples of recent technical developments and the resulting nuclear physics interests.

Cryogenic Techniques. Many examples will be found in the general references quoted earlier of high-resolution resonance and average total cross-section measurements, including the use of separated isotopes which are now available in large-enough quantities to permit the use of neutron beams up to, say, 2 cm in diameter. An interesting development is the use, pioneered at Saclay, of samples cooled to liquid-nitrogen temperatures in order to reduce the Doppler broadening of the resonance structure [6]. For heavy nuclei with high-resolution spectrometers, this effect is more severe than the experimental resolution broadening below a neutron energy of ~1 keV, and minimizing the Doppler effect permits the observation of many additional small resonances in this energy range. Figure 3 shows an example of the effect of cooling the target. A close doublet in ^{239}Pu is seen to be clearly resolved at liquid-nitrogen temperature and not at all resolved at room temperature [7]. Another interesting technique is the use of polarized neutron beams and polarized targets in transmission experiments to determine resonance spins. This has been successfully done for very low-energy neutrons using a cobalt crystal as polarizer and monochromator, in conjunction with a polarized target, at the Naval Research Laboratory, Washington, D. C. [8] and by Sailor's group at Brookhaven [9]. More recently, the difference in the hydrogen cross sections for singlet and triplet scattering interactions has been used as a basis for producing polarized neutrons over an energy range up to tens of kiloelectron volts. Shapiro [10] reported the use of a 44% polarized neutron beam obtained from the Dubna IBR pulsed reactor by transmission of the beam through the dynamically polarized protons in a crystal of LMN ($La_2Mg_3(NO_3)_{12} \cdot 24H_2O$) at a temperature of about 1°K. This polarized neutron beam was then passed through a 40% polarized sample of holmium (15 kOe at 0.3°K) with the neutron polarization vector either parallel or antiparallel to that of the target nucleus. Since this corresponds essentially to the two possible channel spins for the formation of the compound nucleus with s-wave neutrons, and since a given resonance corresponds to a state of definite channel spin, it is clear

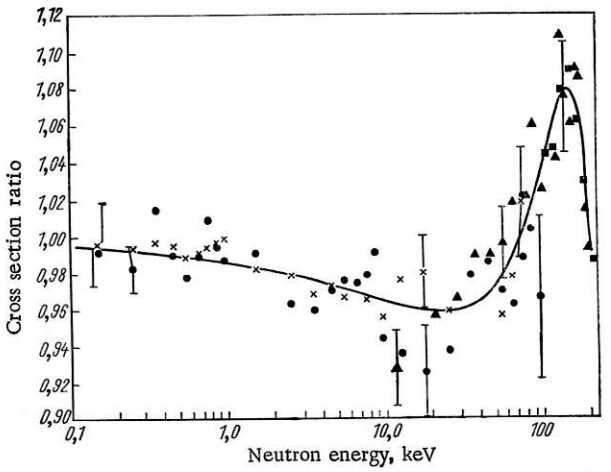

Fig. 4. $^{10}B(n, \alpha)$ cross section relative to $19.30/(E_n)^{1/2}$. Δ) Mooring et al., 1966; ×) ratio $\sigma_{n,'\alpha}(^6Li)/\sigma_{n,\alpha}(^{10}B)$ from [27] combined with data of Uttley and Diment, 1970, $\sigma_{n,T} - \sigma_{nn}(^6Li)$; ●) difference $\sigma_{n,T}(^{10}B)$ [26] $- \sigma_{n,n}(^{10}B)$ [25]; ■) difference $\sigma_{n,T}(^{10}B)$ [26] $- \sigma_{n,n}(^{10}B)$; ——) fitted curve $\sigma_{n,T}(^{10}B)/(19.30/E^{1/2}) = 0.717 - 1.616 \cdot 10^{-2}E^{1/2} - 5.254 \cdot 10^{4}E + \{1.455 \cdot 10^{4}/[(170.3 - E)^2 + 2.243 \cdot 10^{4}]\}$.

that the spins of the resonances are readily determined by this method where they are well resolved. In the case of the Dubna experiments, the spins of 22 s-wave resonances in holmium have been reported [11].

Capture Cross Sections. The measurements of the capture cross sections of fissile nuclei or the ratio α of capture to fission cross section, which is of great importance for reactor applications, has always presented great difficulty where the prompt capture γ rays are detected because of the γ rays and fast neutrons emitted in the competing fission process. One possible method, used successfully by a joint Oak Ridge–RPI team at RPI for ^{235}U [12] is to remove the fission events by an anticoincidence method. Here the fissile sample is placed in an ion chamber or other fission-fragment detector of high efficiency, and the capture cross section is determined from the capture-detector yield in anticoincidence with the fission chamber after suitable corrections have been applied. This technique becomes extremely difficult in the case of more α-active materials such as ^{239}Pu since only a rather small quantity of material may be placed in the fission chamber. A second method was used originally by Hopkins and Diven [13] with a pulsed Van de Graaf accelerator and later by Ryabov et al. [14] with the Dubna pulsed reactor. Here the liquid-scintillator tank used to detect the prompt γ rays from capture is loaded with some material such as gadolinium which itself has a large capture cross section. The fast neutrons from a fission event are slowed down in the scintillator tank surrounding the fissile sample and eventually captured in the gadolinium, giving rise to a second pulse from the detector. This delayed pulse is used to separate fission from capture events.

A third method, also used by the ORNL-RPI team [15] makes use of the difference in the pulse-height response of their large liquid scintillator to capture and fission events occurring in a fissile sample placed at the center of the tank. About 12% of the fission events result in a pulse height which is larger than that produced by ~99% of the capture events, so that a "high bias" placed at a suitable level permits a measure of the fission rate in the sample to be made coincidentally with a count of the total capture plus fission rate. The fission rates can then be subtracted to obtain the capture rates and so the cross section. Another subtraction technique is used at Harwell [16], where pulse shape discrimination is used to permit the detection of knock-on protons in a liquid scintillator which is also used as a Moxon-Rae type of γ-ray detector. Again the knowledge of the fission rate for a given neutron time-of-flight channel permits a subtraction to be made to obtain the capture cross section. All of these techniques are difficult, and serious discrepancies existed between some of the earlier measurements; but the results for ^{239}Pu from the various methods described are now in reasonable agreement, at least up to a neutron energy of 10 keV [17].

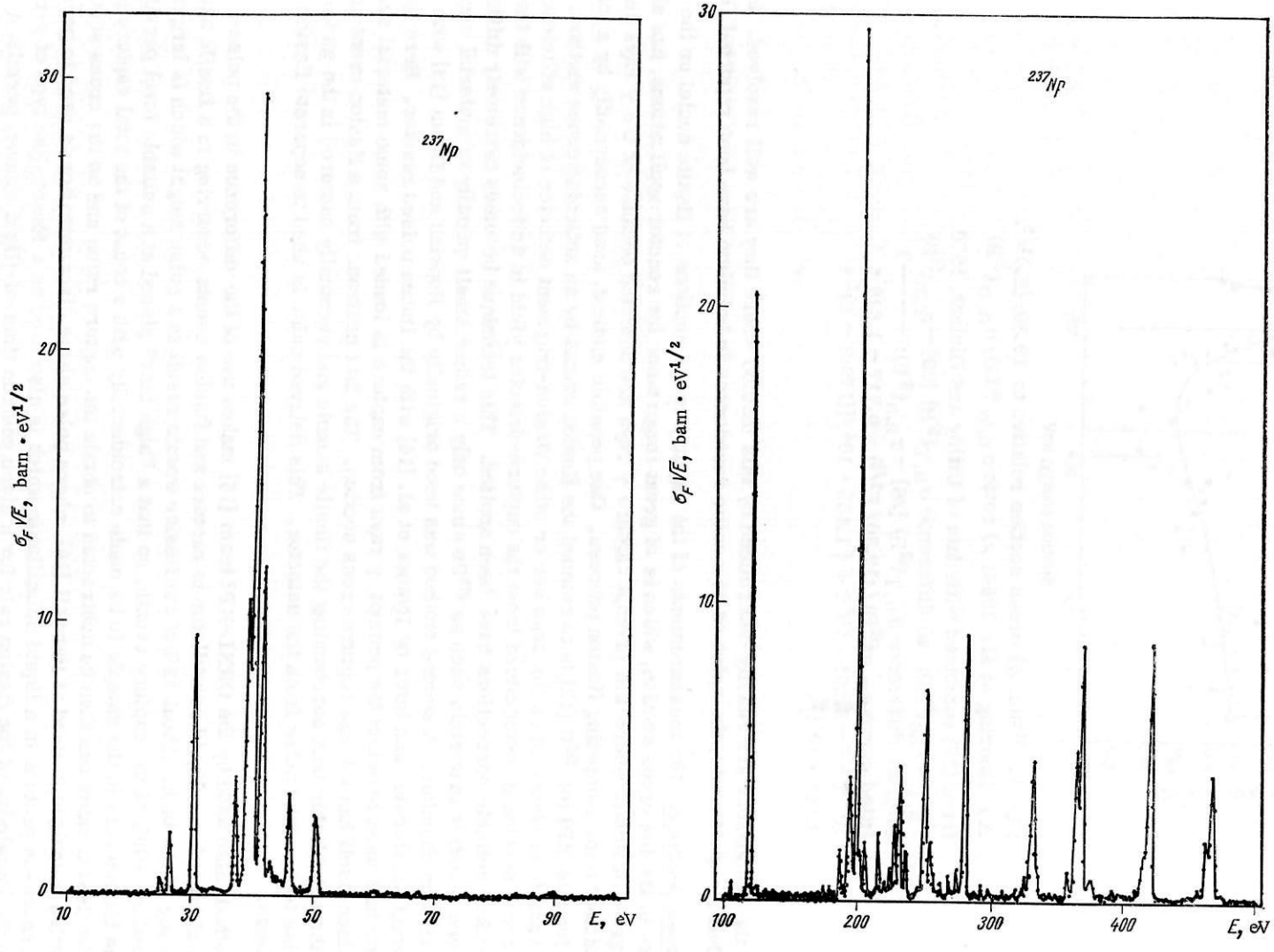

Fig. 5. Fission cross section of ^{237}Np.

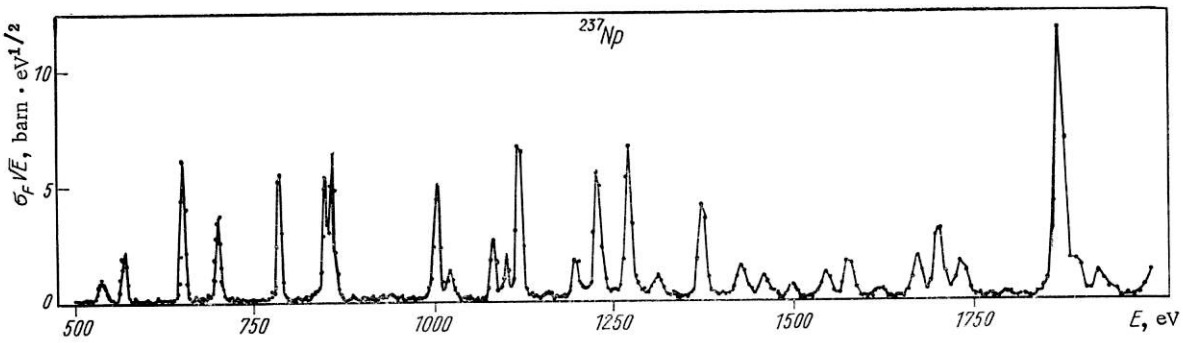

Fig. 6. Fission cross section of ^{237}Np.

Capture Gamma-Ray Spectra. The study of the γ-ray spectra for resonance neutron capture has also received much attention in several laboratories in recent years due to the development of lithium-drifted germanium detectors. These studies permit the determination of partial radiation widths for transitions from the capturing state to the ground and various excited states of the compound nucleus. Interest here centers on whether the Porter-Thomas law (originally introduced to describe the distribution of reduced neutron widths) holds for the distribution of reduced, partial radiation widths. This law implies the validity of the statistical model and the absence of nuclear structure effects in resonances. The published papers from RPI, Saclay, and Harwell appear to confirm this [18-20]. Work done with the Brookhaven high-flux reactor and fast chopper, however, suggests the existence of a nonstatistical behavior in Tm [21], and the existence of intermediate structure in neutron cross sections, particularly the fission cross sections of the heavy nuclei, suggests that structure effects must exist in the capture spectra. The search for such effects continues.

Before leaving the application of pulsed neutron sources to the study of the capture processes, we must mention the observation of the ratio of single counts to coincidence counts for two sodium iodide crystals as a function of neutron time of flight when detecting capture γ rays from a sample placed at the end of a flight path. This ratio is sensitive to the multiplicity of the capture γ-ray cascade, which in turn depends on the spin of the compound nucleus. It therefore provides a powerful tool for the determination of resonance spins and was first used for this purpose by Soceva et al. [22] at Ispra and has been successfully used at the Geel installation to determine the spins of large numbers of resonances [23].

Neutron Scattering. Most of the scattering measurements have been on resonances in heavy nuclei where a scattering measurement can determine unambiguously the resonance spin, and one of the more interesting developments here has been the successful use of the "bright-line" technique at Livermore [24] to measure the resonance scattering from ^{239}Pu and ^{241}Pu.

More recently, scattering measurements at Harwell have been extended to light elements, and a careful measurement of the scattering cross section of ^{10}B up to 100 keV [25] has been combined with precise total cross-section measurements [26] to yield a determination of the absorption cross section of ^{10}B, an important nuclear standard. The deviation of this important cross section from 1/v behavior now seems well established and is shown in Fig. 4, taken from Sowerby et al. [27]. A measurement of the angular asymmetry of neutrons scattered by the weak resonance in ^{56}Fe at 1167 eV has also been used to determine unambiguously the parity of this resonance [28].

Fission. The most important recent application of time-of-flight spectrometers in the field of nuclear structure is, however, surely the study of the so-called subthreshold fission cross sections of isotopes where the excitation energy of the compound nucleus following neutron absorption is close to the fission-barrier energy. The existence of structure other than simple compound nucleus behavior was first pointed out by the Saclay group when they were unable to explain the distribution of fission widths in the resonances in ^{237}Np in terms of accepted statistical behavior [28]. Figures 5 and 6 show the group of resonances close to 40 eV observed in the original study [8], together with higher-energy unresolved groups reported later [7, 29]. The interesting feature of the cross section is that the resonances in which fission is observed are grouped together in clusters between which the fission cross section falls almost to zero. The spacing of the clusters is ~100 times that of the compound-nucleus resonances. The total cross section of ^{237}Np, on the other hand, contains no such structure, showing that it is the fission widths which have large values

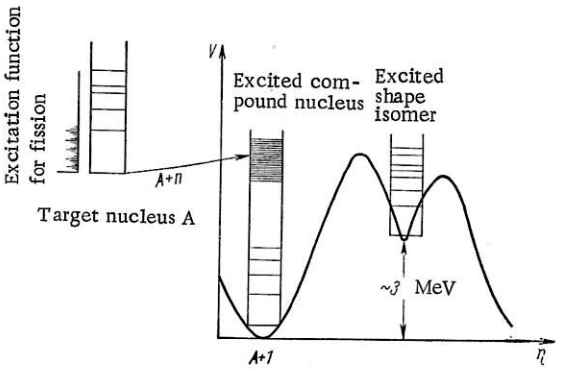

Fig. 7. Effect on near-barrier fission cross section of double-humped potential barrier.

only in certain well-defined energy regions. A similar dramatic effect in the subthreshold fission cross section of ^{240}Pu was observed at Geel [30] and in ^{234}U at Harwell [31], the spacing of the clusters of fission resonances being ~700 eV for ^{240}Pu and 7 keV for ^{234}U. Weigmann [32] at Geel (and independently Lynn, [33]) explained that this structure was associated with the double-humped fission barrier postulated by Strutinsky [34] as the result of shell effects modulating the simple liquid-drop barrier shape. Strutinsky's theory provided an explanation (Bjornholm et al. [35]) of the spontaneously fissioning isomeric states found at Dubna in the odd americium isotopes [36], which have lifetimes of the order of 1 msec and which lie ~3 MeV above the ground state. The clusters of fissioning resonances observed in the fission cross sections of ^{237}Np, ^{240}Pu, and ^{234}U then correspond to those resonances which lie close in energy to complex states built on the isomeric "ground state" in the second minimum in the fission potential barrier (Fig. 7). The discovery of the clustering of strong-fission resonances in the subthreshold region has led to a careful examination of the fission cross sections of the fissile nuclei ^{235}U and ^{239}Pu. Here, no threshold behavior is observed in the total fission cross section, but for one of the channel spins possible with s-wave neutrons the fission barrier does lie above the neutron separation energy for the compound nucleus, and there is a modulation of the fission cross section for this channel spin. The effect has been demonstrated by the use of an autocorrelation analysis due to Egelstaff [38] which was applied at Geel [37] to their high-resolution measurements of the ^{235}U-fission cross section, and at Harwell [39] and Saclay [40] to their measurements on ^{239}Pu. The interpretation of the correlation analysis is not a simple problem, and the extraction of intermediate structure spacings by the experimenters concerned may be open to doubt [41]. The existence of intermediate structure in the fission cross sections is, however, well established, and is shown clearly in Fig. 8, which is a plot of the Harwell data on ^{239}Pu averaged over 33-eV intervals in order to reduce the effect of the fine-structure resonances [42].

The interpretation of the clusters of fissioning resonances has been fully developed by Lynn [33, 43-45] who has also interpreted, in terms of the Strutinsky model, other forms of structure in near-barrier fission, such as the complex behavior of the fission cross section of ^{241}Am observed at Los Alamos in a nuclear-explosion experiment [46] as shown in Fig. 9.

Many aspects of the fission process other than the cross sections have also been studied with pulsed sources. At Columbia University the synchrocyclotron pulsed source has been used to study fission fragment energy and mass distributions and ternary fission as a function of neutron energy [47-49]. Studies of the ratio of binary to ternary fission in the resonances of ^{235}U have also been made at Saclay [50] and Geel [5]. Perhaps the most sophisticated experiments on the fission process made with linac pulsed sources are those in which the angular distributions of the fission fragments are measured for a number of resonances in order to determine the effective value of K, the projection of the compound nucleus spin on the nuclear symmetry axis, for comparison with theoretical models of the barrier structure. Such an experiment carried out at Saclay with apparatus developed at Oak Ridge by Dabbs has recently been reported [51]. In this experiment the anisotropy of the fission fragments is measured in the individual resonances when fission is induced by unpolarized neutrons in aligned ^{235}U nuclei. Alignment is obtained through the interaction of the electric quadrupole moment of the uranium nuclei with the crystal fields when a crystal of $UO_2Rb(NO_3)_3$ is cooled down to 0.6°K. The 220 h of counting time on a flight path of 5 m permitted the

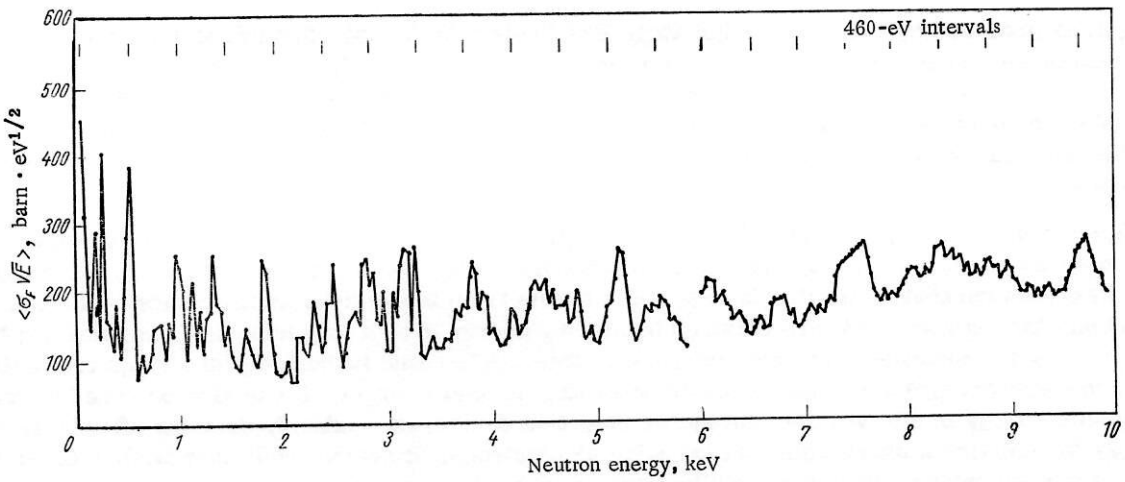

Fig. 8. Fission cross section of ^{239}Pu averaged over 33-eV intervals.

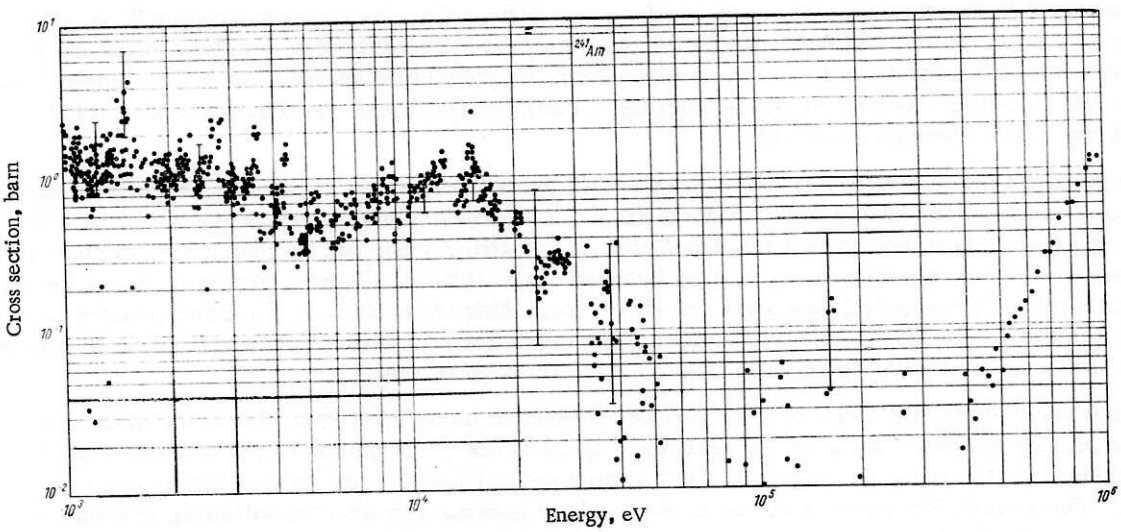

Fig. 9. Fission cross section of ^{241}Am and ^{242m}Am from 10^3 to 10^6 eV.

determination of effective K values for about 30 resonances below 50 eV. Previous work with a crystal spectrometer [52] has been restricted to neutron energies up to a few electron volts. A similar experiment in which a ^{3}He–^{4}He dilution refrigerator is used to cool the $UO_2Rb(NO_3)_3$ crystals to a temperature <0.1°K has recently been completed at Harwell. This cryostat was developed by H. Postma at the Netherlands Reactor Center at Petten and is installed on a 10-m flight path. The greatly reduced temperature accentuates the anisotropies in the angular distributions and simplifies analysis of the results, and the improved resolution (factor of 2) should allow the analysis of an increased number of resonances. The counting time in this experiment was ~500 h [52].

Future Trends in Neutron Time-of-flight Spectroscopy. In looking towards the future of this field, one's first thought is to wonder how much potential for development remains in the pulsed sources themselves. At the low-energy end of the neutron spectrum, where relatively long pulses and high duty cycles are useful, the intensity limit may in the end be set by the rate at which heat can be removed from the neutron-producing target or assembly. In this case, it is worthwhile noting that the production of neutrons by an electron beam is relatively inefficient, several GeV of electron energy being dissipated in the target for each neutron produced. Boosted fission neutron sources are more efficient, the energy dissipation per neutron being several hundreds of MeV, but the most efficient source of all is the spallation reaction involving high-energy charged particles (protons). For 1 GeV protons, for example, a uranium target will have to dissipate only 20-30 MeV per neutron emitted. Thus the ultimate high-intensity pulsed neutron source may well consist of a high-energy, high-current, pulsed proton accelerator with a liquid heavy

metal target, as proposed by Chalk River for their ING Project [53]. Unfortunately this project was abandoned because of its great expense. For low-energy work, and especially for thermal energies, the design of the moderator systems used is very important. Several studies have been made of the advantages of using cooled and poisoned moderators to restrict the effective pulse length for thermal neutrons. Such developments can lead to considerable improvements in time-of-flight resolution without further increase in pulse power [54].

At higher neutron energies where short pulse lengths (a few nanoseconds) are essential, present technology does not permit us yet to approach heat-transfer limits, the maximum available yield being set by the maximum currents available in very short bursts from the various accelerators used. Generally speaking, the highest yields are obtained by storing energy over a longer period and releasing the energy over a few nanoseconds to produce the pulse. This can be done by building up a large circulating current, as in a synchrocyclotron, and suddenly deflecting it onto a target. It can also be done by storing electromagnetic energy in a waveguide, cavity, or induction device, and suddenly draining off a large part of the energy by injecting a short high-current pulse of electrons. It seems likely that further development of very short intense pulses will come about by further sophistication of these techniques, by improvements in electron guns, and so on.

Other technical developments likely to affect the future of neutron spectroscopy will be improvements in efficiency and in energy and time resolution of detectors. The continuing development of ever faster on-line computers with larger memories must also affect the subject profoundly, as more complex experiments involving the simultaneous recording and sorting of distributions which are functions of several parameters, with high resolution, becomes possible.

To point out the directions in which progress in the understanding of physics is likely to arise from these technical developments is much more difficult, but already certain trends are apparent. Many cross sections of great importance to fast reactor design are settling down and becoming established after years or decades when large discrepancies existed between the results of different authors. Accurate measurements and studies of the techniques used are slowly revealing the causes of the discrepancies in earlier work and leading to soundly based sets of data. The existence of sound cross-section data in turn permits a critical evaluation to be made of calculational methods used in reactor physics.

In the nuclear physics field we have already remarked on the dramatic discovery of the intermediate structure in near barrier fission cross sections caused by the phenomenon of shape isomerism. This work will continue until the complex shapes of the fission potential barrier are thoroughly mapped out and understood. The search for doorway states in the study of gamma-ray spectra following resonance neutron capture has yet to disclose any such strong effects, but the indications are there that such effects exist, and surely the introduction of new, more powerful pulsed sources, combined with improved germanium spectrometers and more sophisticated data accumulation systems, must lead to the development of this topic also. Improvements in the intensity of pulsed white spectrum sources must lead to further investigations of weak effects, such as the resonance (n, α) studies at Dubna. These improvements have already led to the point where the study of the (n, n'γ) reaction can give excitation curves for particular decay channels in great detail. A knowledge of the details of this reaction over a series of resonances in lighter nuclei will reveal the presence of correlations between the channels if these exist, and once again probe the limits of applicability of statistical models of nuclear reactions. Certainly too the use of nuclear and neutron polarization techniques is increasing and must lead to more detailed study of the formation and decay of compound nucleus states. In all of these areas, and in many others, the new powerful pulsed sources together with better experimental instrumentation must lead to improved fundamental understanding of nuclear reactions.

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