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INSTRUMENTAL DEVELOPMENTS IN HIGH-RESOLUTION NEUTRON MEASUREMENTS*

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Instrumentelle Entwicklungen auf dem Gebiet hochauflösender Neutronenmessungen

Zusammenfassung

Die neueren instrumentellen Entwicklungen auf dem Gebiet hochauflösender Messungen werden mit Hinblick auf Flugzeitexperimente diskutiert, die an Neutronanlagen mit kontinuierlichem Energiespektrum ausgeführt werden. Diese Diskussion beschränkt sich vor allem auf den Energiebereich oberhalb von etwa 100 keV, in welchem in den letzten Jahren die größten Fortschritte gemacht wurden. Die Darstellung beginnt mit einigen Beispielen von Untersuchungen, für die eine hohe Energieauflösung von entscheidender Bedeutung ist. Die wichtigsten Voraussetzungen, welche für hochauflösende Messungen erforderlich sind, werden aufgezeigt. Danach werden die entsprechenden instrumentellen Entwicklungen im einzelnen diskutiert. Es wird auch auf Weiterentwicklungen eingegangen, die z. Zt. in verschiedenen Laboratorien im Gange sind.

Abstract

Instrumental developments in high-resolution neutron measurements are discussed from the viewpoint of time-of-flight experiments with broad spectrum neutron sources. Discussions are mainly restricted to the energy range above ~ 100 keV, where most rapid progress has been made in recent years. The presentation begins with a few typical examples of neutron investigations for which high-resolution measurements are important. Experimental conditions necessary to perform high-resolution measurements are briefly summarized. The relevant instrumental developments are then discussed in detail, and further improvements currently under active development are outlined.

INSTRUMENTAL DEVELOPMENTS IN HIGH-RESOLUTION NEUTRON MEASUREMENTS

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1. Introduction

There have been tremendous advances in high-resolution neutron measurements during the last three decades of development, but there is still a growing demand for more and even better resolved measurements, particularly in the energy range above ~ 100 keV. Concerning high-resolution measurements for nuclear power technology, and in particular fast breeder development, two outstanding examples for the need of highly resolved data are related to safety and shielding aspects. Concerning the first aspect the detailed energy dependence of various neutron cross sections is required to a resolution much finer than that necessary for the energy groups entering the basic reactor calculations. The knowledge of the fine resonance structure of the major fissile, fertile and structural materials is necessary, because of its importance in safety considerations based on the Doppler temperature coefficient of reactivity. Regarding the second aspect resonance-potential interference windows in the total neutron cross sections must be known accurately (i.e. measured with high energy resolution) because of their large influence on the overall shielding properties of the commonly used materials such as iron or SiO_2.

In fundamental neutron research the need for high-resolution measurements is even more stringent. High-resolution measurements often provide an important tool for sensitive tests of nuclear models. Three typical examples of this kind are experimental studies of level statistics, of neutron-induced subthreshold fission, and of isospin mixing in low lying isobaric analog states. Concerning level statistics high-resolution neutron measurements have already provided valuable information [1,2], but the present knowledge in this field is still very spotty, and improved high-resolution measurements are needed for more significant tests of modern statistical theories, e.g. the various models developed to describe level spacings. Measurements of high-resolution fission cross sections have provided first important experimental evidence for the existence of a double-humped fission barrier [3,4], but higher resolutions are needed for future investigations in this field, for instance for more detailed studies of the thorium anomaly [5]. Certainly the highest energy resolutions are presently needed for the study of isospin mixing by means of isospin-forbidden neutron scattering in self-conjugate even-even nuclei. T = 3/2 resonances in A = 4 n + 1, T_z = +1/2 nuclei are extremely narrow, because of the isospin-forbidden neutron decay. This is illustrated in Fig. 1 which shows the first T = 3/2 resonance in the ^{16}O+n system. Its resonance energy in the laboratory system occurs at 7.373 MeV, and a width of 2.5 keV has been measured with the KfK fast neutron facility [6]. Resonance energy and resonance width shown in this example are typical for most of the low lying isobaric analog states in light A=4n+1, T_z=+1/2 nuclei. Therefore, energy resolutions of the order of 10^{-4} are usually needed for this type of investigation. Energy resolutions of this order at neutron energies around 10 MeV are presently only achievable with a few pulsed white neutron source facilities.

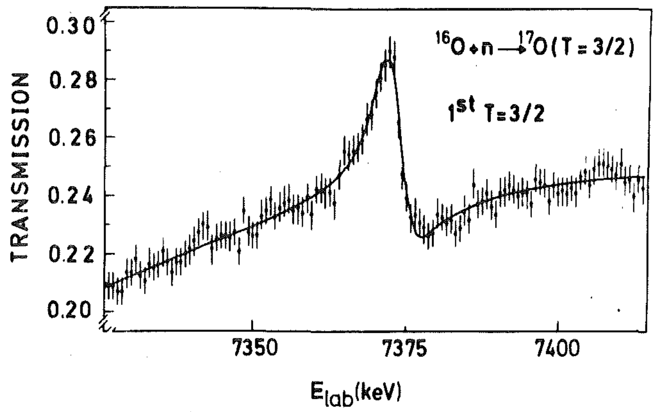

Fig. 1: Resonance excursion of the first T = 3/2 resonance in ^{17}O. The neutron transmission was measured at the KfK fast neutron facility with a spectrometer resolution of 0.005 ns/m providing an energy resolution of 3.8 x 10^{-4} [6].

In this paper the discussion of instrumental developments in high-resolution measurements is restricted to time-of-flight measurements with pulsed white neutron sources above ~ 100 keV, because most rapid progress has recently been made in this field. Of course, exellent energy resolutions can also be achieved in measurements with monoenergetic neutron sources, but instrumental techniques were already highly developed in the early 1960's and had already at that time come close to the utmost possible technical limit. This is ultimately determined by the minimum energy spread of particle beams provided from electrostatic accelerators (presently long-term energy stabilities of the order of $\Delta E/E \approx 1 \times 10^{-3}$ are typical). As shown in Fig. 2 Fossan, Walter, Wilson and Barschall [7] measured already in 1961 the total neutron cross section of oxygen in the MeV region with an energy resolution of $\sim 3 \times 10^{-3}$. This energy resolution has not essentially been exceeded with other monoenergetic sources since that time.

In Section 2 the basic factors determining the energy resolution in a time-of-flight measurement are briefly summarized. The develoments in pulsed neutron sources are described in Section 3.1. The relevant improvements in fast detectors are given in Section 3.2. In Section 3.3 recent developments in data acquisition systems are discussed.

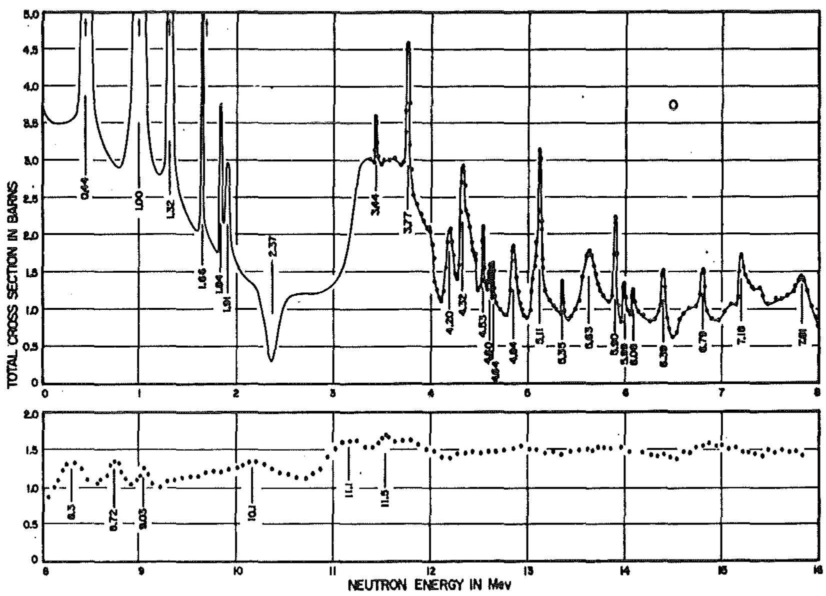

Fig. 2: The total neutron cross section of oxygen from Ref. 7. The neutron energy spread is about 20 keV up to 7 MeV and above this energy about 45 keV.

2. General Considerations

In time-of-flight experiments the fractional energy resolution $\Delta E_n/E_n$ in a non-relativistic approximation is determined by the expression:

$$\Delta E_n/E_n = \text{const} \times \frac{\Delta t}{L} \times E_n^{1/2} \qquad (1)$$

where Δt is the total instrumental time uncertainty introduced by the time-of-flight measurement, L is the flight path length and E_n is the neutron energy.

In addition, the total instrumental time uncertainty in general results from a summation in quadrature of the following five components:

1. The time duration of the neutron pulse.
2. The jitter of the detector response.
3. The time spread related with the effective length of the source.
4. The time spread introduced by the effective length of the detector, and
5. The Doppler broadening.

From these only the first two are energy independent, but fortunately these are usually the most important components. The relative importance of the different components contributing to the total instrumental resolution function is illustrated in Fig. 3 which shows the situation for a very high-resolution measurement with the KfK fast neutron facility. The effective total resolution function R and the various individual components refer to a neutron energy of 7.4 MeV. It can be seen that even for this facility, employing a 0.8 ns accelerator pulse, the important component is the neutron pulse duration (combined in curve γ with the detector resolution function). The source and the detector thickness contribution (T) and the Doppler broadening contribution (D) are comparatively small.

The above description shows immediately that for a given neutron energy high-resolution measurements require short neutron pulses (in conjunction with suitably fast detectors) or long flight paths, or both. Long flight paths require however, high instantaneous source strengths, because the intensity decreases rapidly with distance from the source (for an isotropic source as the inverse of the square of the flight path length). In addition, for longer flight paths a slower pulse repetition rate is usually necessary to avoid overlap of neutrons from successive accelerator pulses.

For very high-resolution measurements with pulsed white sources also the extension of the source and the detector in the direction of the flight path might become important. Therefore, in principle, neutron sources with

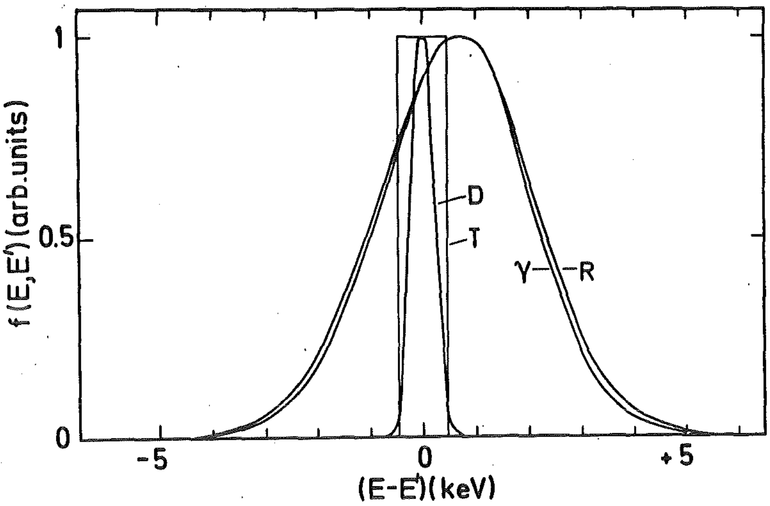

Fig. 3: Total effective energy resolution function at E_n = 7.4 MeV for the KfK high-resolution transmission measurement on O [6]. γ is the combined contribution from neutron pulse duration and detector response. D represents the Doppler broadening contribution and T the combined source and detector thickness contribution. The slight displacement between the two sets of curves reflects the difference between centtroid and adopted nominal reference channel.

inherently small dimensions are most favourable. This applies for instance for the KfK cyclotron source where the effective source length is smaller than 1 mm [6]. For neutron sources employing electron linear accelerators the corresponding value is typically a few cm, due to the electron-photon cascade employed for neutron production. Concerning the choice of detectors, thin systems are most preferable, but usually thinner detectors have correspondly lower efficiencies, which might require shorter flight paths, and thus eventually spoil the net improvement in energy resolution. A reasonable compromise is often a detector of large diameter and small thickness which increases the average count rate in a measurement due to the larger effective beam area.

It appears also from eq. (1) that for a given minimum Δt/L value of a certain neutron facility the energy resolution decreases with energy as $E_n^{1/2}$. Thus, as long as the neutron pulse length is the dominating factor in a time-of flight measurement, improved accelerators providing shorter pulses and higher instantaneous intensities are required, if correspondingly high resolutions ought to be achieved in measurements at higher neutron energies.

3. Instrumental Developments

From the above general considerations it appears that high-resolution measurements with pulsed white neutron sources depend strongly on suitable equipment in three major fields: First of all, suitably pulsed neutron facilities are required which can provide extremely short and intense neutron pulses. In addition, advanced reaction product detectors having fast time response and high detection efficiency are necessary. Finally, advanced time analyzers and data acquisition systems must be available which allow for high-speed, narrow time-channel, broad-spectrum data conversion and accumulation. In the following the instrumental developments in these three fields are discussed in some detail.

3.1 Neutron Facilities

Although the principle types of accelerators used presently for short pulse neutron production had already been developed in the early 1960's, their optimum use for high-resolution neutron work has only been realized subsequently in recent years. In the field of electron linear accelerators many of the machines of the first generation of the travelling-wave type have been upgraded or replaced recently. Shorter pulses and increased peak currents were mainly obtained by using improved electron guns for beam injection. Changing from S-band to L-band radiofrequency supplies provided increased stored energy enhancement with present enhancement factors of up to 20 for ns pulses. Increasing the electron energy to typically ~ 100 MeV brought another considerable improvement in short-pulse neutron intensity.

For medium-energy cyclotrons average internal beam currents have increased considerably in the last two decades. AVF cyclotrons presently provide by an order of magnitude higher beam currents than those achieved with the early machines of this type [8]. Much of the progress is due to intense developments in ion source and target technology, but also computer-controlled operation has largely contributed to recent improvements in short-pulse, high-current operations. Presently these machines are operated routinely with average internal beam currents of a few hundred μA, but also beam currents of up to ~ 1mA have been achieved for some machines [9].

For high energy proton linear accelerators such as LAMPF, running with long macrostructure pulses of 500 μs, suitable pulse techniques have been developed to isolate single microstructure pulses. At LAMPF the Weapons Neutron Research (WNR) Facility is now operated for fast neutron work providing 0.5 ns wide pulses at a repetion rate of 120 pps, although still with comparatively low average proton beam current ($\lesssim$ 150 nA). All of these developments in accelerator technology have improved short pulse neutron intensities in the last decade by at least an order of magnitude.

The short-pulse characteristics of some accelerator-based pulsed white neutron sources are listed in Table I. With the exception of the Proton Storage Ring (PSR),

TABLE I: Short Pulse Characteristics of Some Pulsed White Neutron Sources

Facility/Location	Type of particle	Pulse duration (ns)	Peak current (A)	Beam energy (MeV)	Maxim. prf (kHz)	Neutrons per sec (peak)	Max. flight path length (m)	Best nomin. resolut. (ns/m)	Ref.
GELINA, Geel	e	4	10	120	0.9	4.5×10^{18}	400	0.01	10
HELIOS, Harwell	e	5	6	94	2.0	2.2×10^{18}	400	0.013	11
ORELA, Oak Ridge	e	3	15	140	1.0	4×10^{18}	200	0.015	12
JAERI Linac	e	10	6	120	0.33	1.4×10^{18}	200	0.05	13
Kurchatov Linac	e	50	1.5	60	0.9	2.9×10^{17}	300	0.16	14
LLL Linac	e	5	10	115	1.44	2.3×10^{18}	250	0.02	15
NBS "Above Ground" Linac	e	5	4	120	0.72	$\sim 1 \times 10^{18}$	200	0.025	16
RPI Linac	e	10	1	80	0.72	1.6×10^{17}	250	0.025	17
ANL Linac	e	0.03	200	20	0.8	8×10^{18}	10	0.003	18
KfK Cyclotron	d	0.8	1.5	50	20-200	2.2×10^{18}	200	0.004	6
WNR, Los Alamos	p	0.5	0.17	800	< 6.0	4.5×10^{18}	80	0.006	19
WNR with PSR	p	1.0	16	800	0.72	1.2×10^{20}	300	0.003	19

a planned extension to WNR,the data for all other facilities represent present operation characteristics. The most important specifications for high-resolution measurements are the pulse duration, the neutron intensity in the pulse, and the best nominal spectrometer resolution. The latter is determined as the ratio of the shortest accelerators pulse length to the longest existing flight path. It can be seen that most of the existing neutron facilities have best nominal resolutions of the order of 0.01 ns/m. This corresponds, if we neglect time uncertainties other than the neutron pulse duration, to a fractional energy resolution of $\sim 1 \times 10^{-4}$ for 100 keV and of $\sim 1 \times 10^{-3}$ for 10 MeV neutrons. In terms of nominal spectrometer resolutions the ANL linac, the WNR and the KfK cyclotron have the best performance of the existing neutron facilities. But also most of the modern high-energy high-current electron linacs have very good specifications. Even the Kurchatov linac with a best nominal resolution value of "only" 0.16 ns/m can, in principle, be used for high-resolution measurements with an accuracy of $\sim 10^{-3}$ at 100 keV.

Although useful for a rough estimate of the maximum attainable energy resolution, the best nominal spectrometer resolution must be used with some care to judge the overall quality of a certain time-of-flight spectrometer installation, or to compare different facilities with each other. (For the latter purpose the criteria proposed by Rae and Good [20] are most suited). Recalling that the total instrumental time uncertainty in a realistic measurement is composed of several factors, sources like the ANL linac with its shortest pulse widths of 30 ps are to date too much favoured by the best nominal resolution criterion. For this source, presently only limited use can be made of the extremely short neutron pulse duration, because the time response of available particle detectors is even in the best case an order of magnitude larger than the neutron burst width, and thus spoils the energy resolution in any realistic measurement. In addition, existing flight paths must not necessarily be due to the optimum capability of an existing neutron facility. For example, some of the existing neutron facilities provide sufficient intensity to perform transmission measurements over a distance of up to 1000 m, but evacuated flight paths of this length do not exist. Inversely, fast neutron reactions having small cross sections such as (n,x) reactions on heavy nuclei or neutron capture reactions above $\sim$1 MeV can usually not be measured at the longest available flight paths because of intensity problems. Nevertheless, presently achieved spectrometer resolutions are in many cases close to the given best nominal values. This is immediately obvious for the electron linac facilities providing minimum pulse durations of a few nanoseconds. In this case neutron pulse durations dominate the total instrumental time uncertainty since presently available fast detectors have typical time responses of the order of ∼1 ns which is small compared to neutron pulse duration. But also for facilities such as the KfK source or the WNR with neutron pulse lengths below one nanosecond measured spectrometer resolutions are close to the values given in Table I, if carefully selected detectors were used. A typical high-resolution measurement with a modern high current electron accelerator is shown in Fig. 4. This example was taken from Jungmann et al.[21] who performed high-resolution neutron total cross section and differential scattering cross section measurements at the 400 m station of the Geel facility. The differential elastic scattering cross sections were measured with a fast NE 110 proton recoil detector, 2.5 cm thick, and 5 cm in diameter. In this measurement the experimentally determined spectrometer resolution of 0.013 ns/m is in good agreement with the best nominal value given in Table I. Another example is the high-resolution neutron total cross section measurement of light nuclei with the KfK cyclotron spectrometer. The data obtained for oxygen in the range from 4.5 - 8.0 MeV are shown in Fig. 5. This measurement was performed at the 190 m flight path employing a 1.2 cm thick, 5 cm diameter NE 102A detector. Careful design

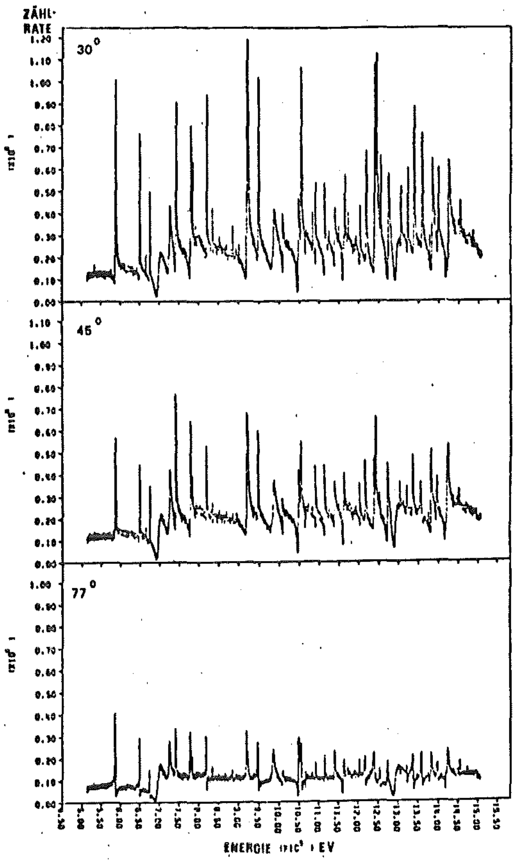

Fig. 4: Differential elastic scattering cross sections for sulphur measured at the Geel linac with a spectrometer resolution of 0.013 ns/m [21]. Data shown between 0.5 and 1.5 MeV represent only a section of the whole set measured in the range 0.1 to 19 MeV.

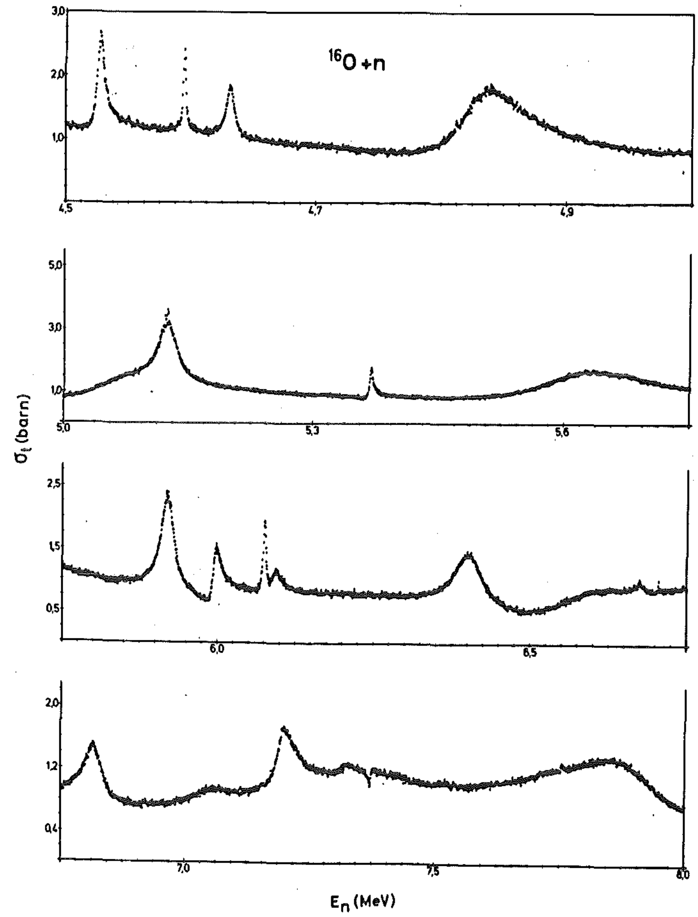

Fig. 5: Total neutron cross section of oxygen measured at the KfK cyclotron with a spectrometer resolution of 0.005 ns/m [6]. High resolution data were measured over the extended energy range from 3 to 30 MeV.

of the neutron detector and constant fraction timing gave a total detector time spread of 290 ps over a large dynamic range (~ 1 : 15). From auxiliary measurements a total spectrometer resolution of 0.005 ns/m was determined which is also in reasonable accordance with the best nominal resolution of 0.004 ns/m calculated for this facility. We can therefore, in principle, use the values in column 9 of Table I as a reasonable measure for presently attainable spectrometer resolutions, except for the ANL linac with its extremely short (picosecond) pulse structure.

Turning to further improvements in short and intense neutron pulse production, there is presently active work on a few different developments. In the field of electron linear accelerators current work concentrates on pulse compression systems in order to provide higher short-pulse peak currents. In addition, the possible use of the induction linac as another extremely powerful alternative to the existing travelling wave machines has repeatedly been studied [22,23], and accelerator development is proceeding independently. But it is not very likely that new induction linacs will be built in the next future to drive fast neutron sources because of budgetary reasons, except for the IBR II injection linac which is, however, dedicated for slow neutron work. The most advanced development is certainly the Los Alamos Proton Storage Ring (PSR) whose completion is scheduled for 1985. In addition, the development of suitable methods for the separation of single micropulses in klystron-driven linacs (realized to date for the low energy ANL linac) has in principle opened the possibility for the production of extremely narrow and very intense neutron bursts, also with high energy machines.

Concerning pulse compression methods work is presently under way at the ORELA and the GELINA neutron facilities. For ORELA a buncher is presently under construction which is expected to compress a 15 ns wide pulse into a 3 ns pulse with essentially no loss in beam power [24]. A schematic drawing of the buncher used in a study of the final design parameters is shown in Fig. 6. The buncher has six decelerating and three accelerating gaps and the voltage applied to the gaps varies such that a decelerating gap reduces the kinetic energy of the electrons in front of the pulse relative to the energy in the back. Conversely, an accelerating gap increases the kinetic energy of the electrons at the end relative to those at the beginning of the pulse. The gaps have been designed for a maximum voltage of 50 kV which is needed for final operation. Because of the large space-charge effects, the buncher includes a longitudinal magnetic field of several kilogauss to prevent the beam from spreading out radially. In a test of the buncher

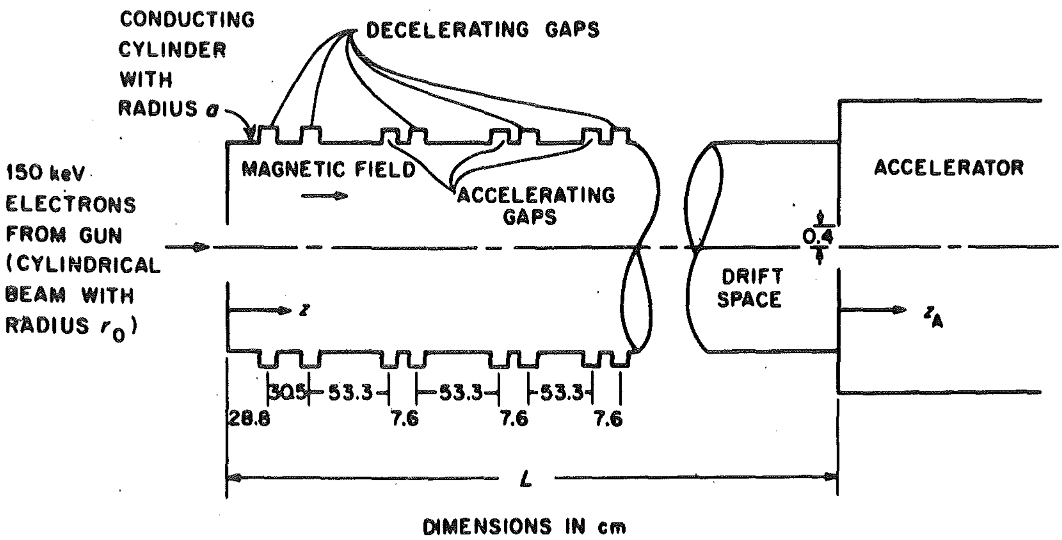

Fig. 6: Schematic diagram of the ORELA prebuncher used in a study for short pulse compression. The ultimate goal is to compress a 15 ns long pulse into a 3 ns pulse with essentially no loss in beam power [24].

with one third of the design voltage a 17 ns pulse was compressed to about 8 ns with only 7% beam loss.

For use with the Geel linac (GELINA) a system for bunching after accelerations has been studied [10] and was ordered for delivery in early 1982 [25]. From the manufacturer a pulse-compression factor of three has been guaranteed for a not yet specified initial pulse length between ~10-15ns. The operation principle is illustrated in Fig. 7. A "macropulse" from the S-band linac consisting of a train of R.F. microstructure pulses, each ~ 50 ps wide and separated by 330 ps in time, is incident on the buncher. For short "macropulses" of the order of ~ 10 ns the energy stored in the cavities is continuously transfered to the electron beam. Since each of the micropulses takes a certain fraction of the stored energy, the average electron energy of the micropulses decreases monotonically from the beginning to the end of a "macropulse". If such a pulse is injected after acceleration into a 360^{o} bending magnet, the electrons from the first micropulse move on trajectories with larger diameter than those from the successive pulses. Since the highly relativistic electrons have practically equal velocities, the macroburst is compressed in time when it leaves the magnet after a full turn. The reduction in pulse length depends on the difference between the minimum and the maximum trajectory length in the magnetic field.

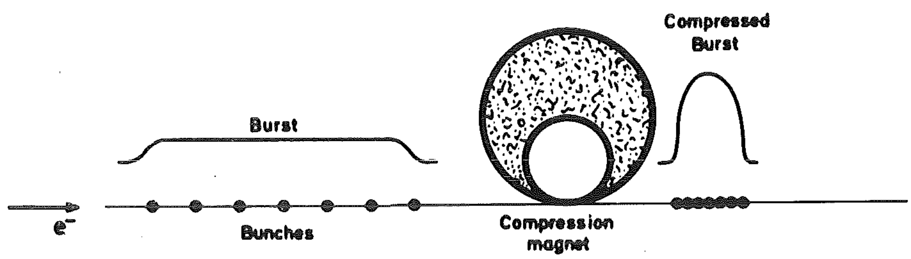

Fig. 7: Principle of a pulse compression system studied for use with the GELINA fast neutron source. The 360^{o} bending magnet is expected to provide bunching after acceleration with a pulse compression factor of three [25].

The Proton Storage Ring (PSR) is a planned extension to the WNR facility. It will initially store 100 μA of H^- beam from the LAMPF accelerator, and could eventually store 400 μA without any redesign of the ring and the associated hardware. For short pulse operation ejection of 1 ns wide pulses at repetition rates up to 720 Hz is expected. This mode of operation is illustrated in Fig. 8. The ring is decahedral in shape and has a beam circulation time of 360 ns. At the entrance of the ring a suitable stripper foil is used to produce a beam of positive ions. The R.F. bunching cavity is operated at ∿ 640 MHz.

A fast kicker magnet requiring at least 60 ns between each group of pulses circulating in the ring ejects the pulses back into the main WNR beam line. The ring is filled 120 times per second. About the last 72 μs of each macropulse from the accelerator is structured so that one of every twelve micropulses is injected into the ring which then forms six supermicropulses that are extracted from the ring at regular intervals between macropulses. The expected specifications for the extended WNR source plus PSR are given in the last line of Table I.

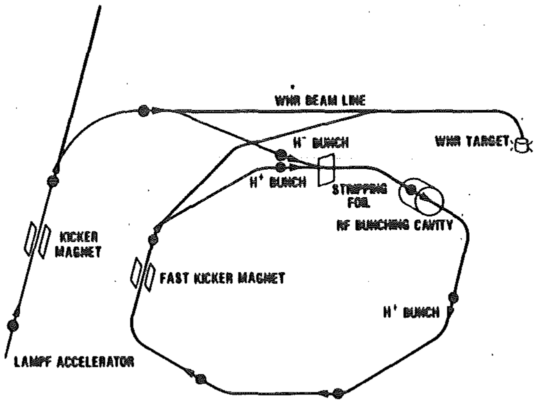

Fig. 8: Schematic drawing of the Proton Storage Ring (PSR), a planned extension to the WNR facility [19]. In the short pulse mode of operation 1 ns pulses with 7.2×10^{13} protons/second will be produced at repetition rates of up to 720 Hz.

The necessary developments for the separation of single R.F. micropulses from klystron-driven electron linear accelerators have been performed in the accelerator laboratory of Edgerton, Germeshausen and Grier by Norris and Hanst [26]. A system based on this work was installed at the ANL linac. A schematic drawing of the layout of the linac is shown in Fig. 9. Basically, the Argonne linac is a two-section L-band travelling wave accelerator. The original bunching system consists of two travelling wave prebunchers (PB), and a tapered prebuncher. In normal operation mode the accelerator provided a beam of 20 MeV electrons with a peak pulse current of 20 A at 10 ns pulse duration. To achieve the picosecond beam bunch, a subharmonic (SH) buncher was added with the original components being axially repositioned. Using an injection time of 2.5 ns, a 100 keV mean electron energy from the gun and the 6th subharmonic index for the subharmonic buncher, allowed to produce a single pulse of 30 ps duration with a charge of 8 nC (200 A) at pulse repetition rates up to 800 Hz. The charge in this mode is thus equivalent to that existing in one conventional "fine structure" pulse.

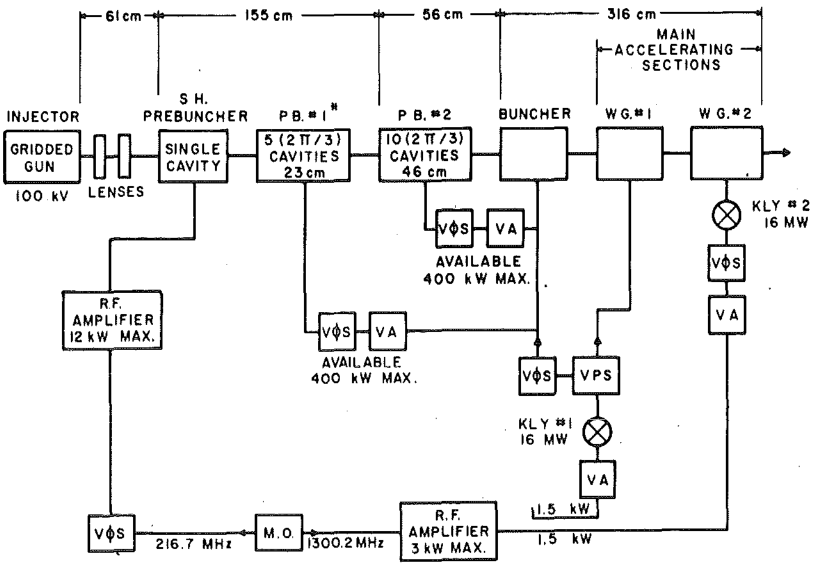

Fig. 9: Dimensional layout of the ANL electron linac. To achieve 30 ps beam bunches a subharmonic (SH) prebuncher was added with the original components being axially repositioned.

3.2 Detectors

The investigation of fast neutron-induced reactions involves three principal types of detectors: Fast neutron detectors are necessary for the study of neutron total and neutron scattering reactions, while fast γ-ray detectors are required for investigations of radiative neutron capture and neutron-induced γ-ray producing processes. In addition, suitable charged-particle and fission-fragment detectors are needed for measurements of neutron-induced charged-particle production and fission reactions. In high-resolution work employing the time-of-flight method the two closely related essentials for the operation of a detector are fast time response and high detection efficiency. In the following the recent achievements in this field are briefly summarized.

3.2.1 Neutron detectors. Although considerable effort has been devoted to fast neutron detector development, no essentially new detectors and methods have been explored during the last years. Work in this field has rather concentrated on the most effective use of existing detector types including the precise determination of detection efficiencies over a wide range of energies. An excellent survey of fast neutron detector developments before 1976 has been given by Zeitnitz [27], and this review still describes to a large extent the present state-of-the-art. In the range above ∿ 100 keV the most commonly used neutron detectors for high-resolution work are solid or liquid hydrocarbon scintillation detectors. Their overall time response and absolute detection efficiency depends on the scintillator size, the detection threshold and the required dynamic range. In recent years a lot of work has been devoted to the measurement and calculation of precise detection efficiencies and time responses [28, 29, 30]. Main emphasis was on neutron energies below ∿ 20 MeV. Presently available Monte Carlo codes provide sufficiently good efficiency predictions with accuracies of typically 5 - 10 %, but accuracies of ≲ 3 % have also been quoted in some instances [29]. Other measurements and code developments were also extended to neutron energies up to several hundreds of MeV [31, 32]. Time responses of standard detectors having a few inch diameter and similar thickness are typically of the order of 1 ns, if suitable time-walk compensation methods (zero-crossing, constant fraction etc.) are used. Below 50 MeV incident neutron energy detection efficiencies of such counters range between ∿ 5 and 30 % depending on the threshold and the neutron energy. With specially designed detectors subnanosecond time resolutions have also been achieved. This applies e.g. for the KfK detector mentioned in Section 3.1 [6] for which a total time response of 290 ps (FWHM) was measured. The good time response was, however, obtained at the expense of a considerably reduced detection efficiency due to the small size of the scintillator. A neutron detector with subnanosecond time resolution <u>and</u> high efficiency was recently designed by Evers et al. [33]. Using a 5 l NE 213 liquid scintillator these authors obtained a time resolution of 650 ps for neutron energies higher than 22 MeV.

3.2.2 <u>Gamma-ray detectors</u>. Recent developments in the field of fast gamma-ray detectors for time-of-flight measurements have been discussed in some detail by Lynn [34]. Especially for use in high-resolution capture cross section work the desirable features in addition to fast time response and high sensivity are 1) an efficiency for the detection of a capture event which is independent of the particular γ-ray cascade, 2) a low sensivity to scattered neutrons and 3) low background and ease of shielding. Detectors combining these characteristics in a useful manner are non-hydrogeneous total energy detectors and detectors of the Moxon-Rae type [35,36,37], which have therefore been increasingly used in recent years for fast capture studies. Both types of detectors have fast time responses, and detector resolutions of ∿ 1-2 ns have been achieved in the past. Their detection efficiencies are, however, rather low (for Moxon Rae detectors typically a few tenths of a percent per MeV total gamma energy [37] and for non hydrogeneous scintillators such as C_6F_6 or C_6D_6 usually 5-10% [35,36]).

Time-of-flight measurements of γ-spectra from resonance neutron capture and from neutron-induced (n, x γ) processes are often performed employing GeLi detectors. Large coaxial crystals of several tens of cm^3 typically provide detector resolutions of $\sim$ 1-2 ns for γ-energies above 1 MeV if constant fraction timing is employed. The achievable time resolutions increase, however rapidly with decreasing γ-energy to several nanoseconds in the 100 keV range. This increase is partly due to the energy-dependent time shift observed in the time- energy distributions of such detectors. In the past various methods have been developped to reduce the time broadening due to the time shift by on-line or off-line corrections on an event-by-event basis using the pulse height information. By this method time resolutions below 1 MeV could be significantly decreased, e.g. [38].

3.2.3 <u>Charged-particle and fission-fragment detectors</u>. The most important detectors for high-resolution charged particle work are thin plastic scintillators and solid state detectors the latter of which provide also good energy resolution. The most suitable fast counters for fission fragment detection are gas scintillation counters and surface barrier detectors. All of these provide 100 % detection efficiency except for low energy absorption effects in samples or insensitive detector surfaces (if any). Their overall time responses over sufficiently large dynamic ranges are all typically of the order of 1 ns. For silicon solid state and surface barrier detectors suitable techniques have also been developed to reduce the effective time resolutions by almost an order of magnitude. This is possible because the intrinsic timing uncertainties (resulting from the variation of plasma times with energy and mass of the projectiles) are extremely small [39] and reduce to less than 100 ps for cooled detectors. The large overall time resolution is therefore dominated by the variation of the rise time delay with pulse amplitude and can be avoided by suitable rise time corrections. A typical example for the variation in rise time delays is shown in Fig.10 illustrating the size of this effect for a large silicon surface barrier detector. It can be seen that the corrections needed to cover a dynamic range of $\sim$1:10 are of the order of 1 ns. Employing 6 cm^2 surface barrier detectors (cooled to liquid nitrogen temperature) and off-line rise time corrections Patin et al. [40] obtained an overall time resolution of 150 ps in detecting the entire spectrum of fission fragments from the ^{233}U(d,pf) reaction. The same technique provided also time resolutions of 300 ps for proton detection over the range 6 to 13 MeV using a 300 μm thick dE/dx detector.

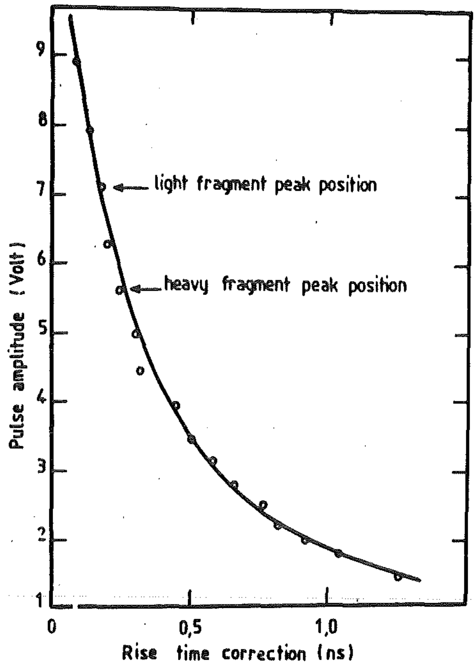

Fig. 10: Example of the time shift occurring on the discriminator pulse as a function of the pulse height for a 6 cm^2 silicon surface barrier fission detector [40].

3.3 Data Acquisition Systems

Modern unmoderated pulsed white sources typically provide broad continous energy spectra with sufficient intensity in the range from ∿100 keV to 20 MeV, or more. If the corresponding time spectra from such sources (spread over a flight path distance of 400 m) ought to be covered in 1 ns time intervals about 10^5 time channels are needed for data recording. Time resolutions of 1 ns over the required range of 100 μs cannot any more be achieved with standard time-to-pulse height converters. This requires advanced time-of-flight encoders which employ direct time-to-digital conversion. Furthermore, the mentioned number of channels needed in well resolved measurements with pulsed white sources usually increases by another order of magnitude due to the large number of experiments performed simultaneously at different flight paths. This requires also rather large, fast on-line computer complexes.

3.3.1 Time-of-flight encoders. Electronic developments in recent years have provided several advanced systems which largely suite the present requirements in time resolution and time range. At the new Harwell source, HELIOS, CAMAC-based time-of-flight encoders of 64 K channels are available, and memory increment units are used when channel widths in the range 20 to 1 ns are required [41]. Almost all of the experiments at the Oak Ridge linac source, ORELA, involve commercially produced TDC-100 time digitizers [42] providing even larger channel numbers and narrower minimum channel widths [42]. Another commercially available time digitizer with similar specification is the TDC-4202 model [43] which is also widely used. The main time digitizer employed for high-resolution neutron experiments with the KfK cyclotron source is a LABEN-UC-KB unit providing up to 256 K channels of 250 ps minimum channel width [6]. The operation principle of this unit [44] is based on a continuously running clock, and time readings are made by sampling a suitable set of oscillators tuned by a highly stabilized master clock generator. Time readings for fractions of the time period of the highest oscillator frequency ($\sim$ 250 MHz) are accomplished by a particular digital interpolation system. This digitizer allows also a large number of stop events to be accepted during a single time-of-flight cycle. At KfK a highly improved new time-of-flight encoder is presently under development which is partly based on the above mentioned operation principle, but involves a completely different digital interpolation method. In its final form the new digitizer is expected to provide up to 1024 K time channels with a minimum channel width of 20 ps. A prototype of such an analyzer has been built and was recently successfully tested [45].

3.3.2 On-line computer complexes. Large fast on-line computer complexes have been installed at most of the neutron sources used for high-resolution measurements. The corresponding data acquisition systems presently provide typically a few millions of channels for storage during data accumulation and allow for average event rates of up to several tenthousands of events/s [41]. A typical example of an advanced system is the data accumulation and analysis system used with the ORELA neutron source [12]. In Fig. 11 a schematic diagram of the entire computer complex is shown. The data acquisition computer complex comprises three SEL-810B on-line computers which are 16 bit, 32 K word units with a cycle time of < 1 μs. Each of these computers has four input ports which permit the reception of data from four experiments simultaneously. Input rates totalling 5×10^3 events/sec are permissable provided no average individual rate exceeds 1.8×10^3 events/sec. Each of the three computers is equipped with an extremely fast head-per-track disk. The total storage capability of these three units is 2×10^6 channels. A fourth SEL 810B computer is used as a peripheral equipement controller (PEC). This computer drives a line

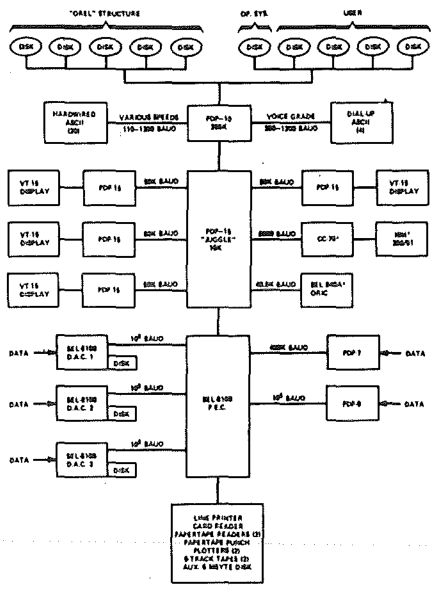

Fig. 11: The ORELA data acquisition and analysis system [12]. The data acquisition computer complex comprises three SEL-810B machines. A fourth SEL-810B computer is used as a peripheral equipement controller (PEC).

printer, a card reader, two plotters, two magnetic tape drives, a paper tape reader and a paper tape punch. In addition, the PEC computer provides a high-speed link via a PDP-15 computer to the remainder of the data acquisition system. Finally, a PDP-10 time-sharing computer with 240 K, 36 bit words of main memory and with 250 Mbytes of magnetic disc storage serves as the main data storage and analysis computer.

4. Summary

Since a long time neutron physics has been, to a large extent, a spectroscopic science, and as such many important steps in the knowledge of neutron-induced reactions have followed an improvement in the resolution capabilities of its instruments. In the past there have been tremendous advances in instrumental developments for high-resolution neutron work, particularly in the time-of-flight field, but further improvements are still needed to answer many open questions both in basic neutron physics and in nuclear technology. Concerning the present status the situation can be summarized as follows:

1. Instrumental developments in intense pulsed neutron sources, in fast and high-sensitivity detectors and in appropriate data acquisition systems have largely extented the resolution capabilities for neutron measurements. Presently measurements with energy resolutions of up to

$1:10^5$ can be performed in the high keV region and experiments with resolutions of the order of $1:10^4$ are possible in the 10-MeV range.

2. There is still considerable potential for further improvements of existing time-of-flight instruments and techniques, and a lot of active work is presently underway for its exploitation.

3. Recent developments in accelerator technology and timing electronics demonstrated that short pulse production and time readings in the 20 - 30 ps range are, in principle, technically possible. This gives rise to the hope, that considerably higher resolutions than those presently achievable might be obtained in future measurements. In the moment the chief hindrance to the exploitation of an extreme picosecond time-of-flight technique comes from detector limitations. But, there are already detector systems capable of subnanosecond time responses as low as 150 ps, and it is possible that optical picosecond techniques employed in laser studies could also stimulate important future developments in this field.

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