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NEUTRON SOURCES: Present Practice and Future Potential

by
S. Cierjacks, Kernforschungszentrum Karlsruhe, and
A.B. Smith, Argonne National Laboratory

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ABSTRACT

The present capability and future potential of accelerator-based monoenergetic and white neutron sources are outlined in the context of fundamental and applied neutron-nuclear research. The neutron energy range extends from thermal to 500 MeV, and the time domain from steady-state to pico-second pulsed sources. Accelerator technology is summarized, including the production of intense light-ion, heavy-ion and electron beams. Target capabilities are discussed with attention to neutron-producing efficiency and power-handling capabilities. The status of underlying neutron-producing reactions is summarized. The present and future use of neutron sources in: i) fundamental neutron-nuclear research, ii) nuclear data acquisition, iii) materials damage studies, iv) engineering test, and v) biomedical applications are discussed. Emphasis is given to current status, near-term advances well within current technology, and to long-range projections.

INTRODUCTION

Neutron sources are an essential consideration in a wide range of endeavors, extending from engineering applications to the the most fundamental of research activities. The neutron is at the very heart of the large majority of nuclear applications, and, as the only long-lived non-charged hadron, it is a unique probe for fundamental studies, accessing domains forbidden to other investigations. Nuclear accelerators have become the major tools for production of neutron sources for a very wide range of uses. The primary considerations are the intensity, energy and time characteristics of the source, all of which are accelerator and target governed in one way or another. The broad aspects of the fundamental nuclear reactions underlying all accelerator-based sources have long been known, and their properties remain ordained by nature. The basic accelerator concepts have also long been known; however, their technological application continues to rapidly develop, to a considerable extent driven by other and generally more fundamantal research objectives. This rapid growth continues, inhibited only by the enormity of the materials and costs often involved. The consequence is truly remarkable accelerator-based neutron sources that have greatly refined prior experimental endeavors and made possible entirely new investigations not heretofore conceivable.

Accelerator-based neutron sources generally take two forms: i) "white" sources utilizing time to define the incident energy, and 2) "monoenergetic sources where energy definition is inherent in the neutron production process. There is some overlap in the application of these two types of sources, but they are inherently different, and thus are elementary tools, which, in their optimum usage generally address different types of problems that are frequently forbidden to one another. The following remarks have the objectives of outlining the contemporary status of these two types of accelerator-based neutron sources, illustrating strengths and weaknesses with application examples, and of estimating the future potential.

WHITE SOURCES

Advantages

- Total intensities exceed those of all other sources. There is even potential for cw intensities much higher than that of HFRs.
- High-energy resolution over the entire range from thermal to ~500 MeV. Energy resolutions of up to 0.01% have routinely been experienced in eV-, keV- and MeV-resonance spectroscopy.
- Broad continuous neutron spectra extend over more than 11 decades (1 meV to more than 500 MeV). Often this range can be covered with a single source installation.
- Large facilities allow the access from many concurrent users and the utilization in various concurrent measurements. For many sources even different targets can be served simultaneously for different beam conditions.
- Large data accquisition systems and experimental facilities can be shared by many users.

Limitations

- No control of <u>all</u> canonical variables. Inherent pulsing is needed for primary energy definition.
- Optimum performance for many types of experiments. But preclusion of secondary timing and non-inherent energy definition limits usage in some types of experiments, e.g. activation and n,n'.
- Broad spectrum neutron production does not always give optimum control of background and other experimental perturbations.
- The most efficient sources are rather costly in capital investment and operation.

Source Reactions and Timing

The main types of nuclear reactions which can be used for neutron production are listed in Table I. Also given are the numbers of neutrons per particle or reaction which both represent a measure for the utmost attainable source strengths. In the last column also the type of spectrum is indicated. It can be seen that neutron production for broad continuous spectra is much superior to production of monoenergetic neutrons. (The T(d,n) reaction with 200 keV deuterons is already the most effective one, due to its large cross section of 5 b in the resonance, and large plasma sources based on the DT fusion reaction cannot be realized, except for operating fusion reactors themselves). The specific neutron yields for medium energy electrons or light ions are already more than two orders of magnitude higher than that for the T(d,n) reaction. This factor increases drastically for fission and even more for spallation reactions with ~1 GeV protons.

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Reaction		Yield n/particle or event	Deposited heat MeV/n	Type of spectrum
T(d,n)	(0.2 MeV)	8×10^{-5} n/d	2500	monoenergetic
W(e,n)	(100 MeV)	3.2×10^{-2} n/e	3100	evaporation
Li(d,n)	(40 MeV)	6.7×10^{-2} n/d	600	d break-up + evap.
Fission	(^{235}U(n,f))	~ 1 n/fission*	200	fission
(T,d) fusion		~ 1 n/fusion	3	14 MeV
Pb spallation (1 GeV)		20 n/p	23	evap. + cascade
^{238}U spallation (1 GeV)		40 n/p	50	evap. + cascade

* The yield per fission event is 2.4 but ~ 1.4 neutrons are required to maintain the chain reaction and compensate for parasitic losses.

Table I Specific yields and deposited heat for the main types of neutron-producing source reactions.

In addition to the large increase in specific yield, the heat deposited per particle decreases rapidly, so that target problems for high intensity sources become less restrictive. There is, however, one glaring penalty to be paid for using the more favourable source reactions: These require rather large and expensive accelerators. Concerning neutron spectra, these are typically of the evaporation type, i.e. very similar to the fission spectrum, with some more or less important contributions of direct (high-energy) neutrons. The latter contribution is pretty small for 100 MeV electron sources and most pronounced for 1 GeV spallation sources. All primary neutron spectra can easily be softened on the low energy end by neutron moderation. There is, however, only little possibility to considerably harden the almost pure evaporation spectra from (e,n) reactions. Here the usage of heterogeneous mixtures of a light and a heavy target element can modestly enhance the neutrons yields in the many-MeV range in favourable cases (Boe87).

Another important quantity for white neutron sources is timing, when the source should be used as a neutron spectrometer. In time-of-flight measurements spectral intensity and resolution are anticorrelated, i.e. the better the resolution the smaller the neutron intensity at the detector position and vice-versa. Thus high-resolution measurements require short intense pulses and long flight paths. Moreover, for a given pulse length and a given flight path, the resolution decreases with energy as the square root. Thus, improved accelerators with shorter pulse structure and/or higher intensities are required, if correspondingly high resolutions should be achieved at higher neutron energies.

Electron Linac Sources

Character. For achieving high neutron intensity with electron beams a sufficiently high energy and a heavy element target is required. Neutron production proceeds through conversion of the electron energy into Bremsstrahlung and subsequent neutron production by photonuclear reactions. (For fissile targets like U neutron production is further enhanced by additional photofission). In standard sources a uniform target material is used in the primary impact zone and the surrounding converter region. There are, however, also other concepts for the use of two different target materials, either separated according to the reaction zones (Bow80), or used as a heterogeneous mixture all over the target (Boe87). Modern sources typically employ 50-150 MeV beams In this energy range neutron production is nearly proportional to the electron beam power, and production rates are of the order of 2x10**15 n/s MW for non-fissile and of 4x10**15 n/s MW for fissile heavy target elements. With typical beam powers of 20-200 kW on average and of 5x10**1 to 1x10**4 MW in short pulses, these sources provide average neutron intensities between 1x10**13 and 5x10**14 n/s and peak intensities between 1x10**17 and 6x10**19 n/s in the shortest pulses. Pulse width from these facilities vary from a few ns (or even sub-ns (GELINA)) to a few µs. This allows to use time-of-flight methods with flight paths ranging from a few to several hundred meters.

Accelerator Status. Present sources mainly use travelling wave r.f. electron linacs operating in the S- or L-band range; an exception is the Dubna linear induction accelerator (Ana83). Even though these sources have been used for several decades, their optimum utilization for high-resolution high-energy applications has only recently been fully exploited. Modern machines provide standard pulses variable from a few ns to several µs with peak currents of a few tens of A and ~1 A, respectively. Typical repetition rates vary from about 100 Hz to 1 kHz. Recently, pre- and post-acceleration bunching techniques have been exploited to further improve short-pulse characteristics (Boe87). The first was tried for use with ORELA, the latter was successfully employed at the Geel linac, GELINA. Post-acceleration bunching of the Geel linac presently allows to compress a 10 ns accelerator pulse into a 0.7 ns wide one, practically without any essential beam loss. This rises the peak current in the narrow bursts to more than 100 A. This improvement made the GELINA source (Fig.1) to one of the most outstanding high-resolution facilities. Even though present electron linacs have reached high sophistication, and have, in the past, proven very successful in basic physics and nuclear data work, there are still a few fields in which even better specifications are needed: For the study of highly radioactive targets or samples available only in nano- or micro-gram quantities a drastic increase in intensity, maintaining the short pulse structure, is required. Much higher intensity is also needed for differential measurements in the fusion region (many MeV). Here a factor of 10 (for the range ≤5 MeV) and a factor of 100 (for the range 5 to 20 MeV) would be desirable. Such upgradings are presently not very likely with the existing types of machines. While S-band technology is quite mature, it is, in principle, possible that an order of magnitude increase

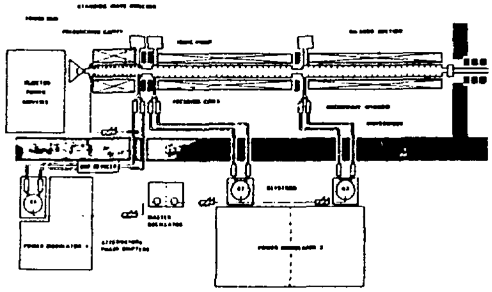

Fig. 1 Geel Electron Linac, GELINA (Boe87).

in intensity can be obtained in L-band technology (Boe87).

Much higher peak currents than presently available with r.f. linacs can, in principle, be achieved with linear induction accelerators (Lei79). An example of this kind is the injection linac (LIU 30) which primarily serves as an injector to the IBR-2 booster target, but can also be used by itself as an extremely powerful white source (Sha79). The design parameters are: 30 MeV electron energy, 250 A peak current, 500 ns pulse width and 50 Hz p.r.f. Linear induction accelerators with an energy of about 100 MeV could, in principle, provide reasonable facilities for white neutron sources, and they might perhaps be built at relatively modest costs, even though detailed cost estimates are not yet available. Such machines are also more versatile than r.f. linacs in that they can accelerate both electrons and light ions. A source concept of this kind has recently been studied at NBS (Joh87). Intense electron beams of 10-12 MeV from small induction linacs, using Ta(e,γ) converters and Be or D (γ,n) radiators have been considered in detail by Bowman (Bow80) as economical small sources for use in standard laboratories. But, a major disadvantage of induction linacs is their large minimum pulse width of 10-100 ns and their small brightness, limiting their use in high-resolution spectroscopy work. An additional disadvantage of the small machines is the absence of neutrons with energies higher than ~4 MeV (needed e.g. in fusion or radiotherapy).

Targets. Beam powers from existing electron linacs are typically of the order of several tens of kW, ranging up to 200 kW for LIU-30. This beam power is usually dissipated in target volumes of a few cm**3, requiring special target designs. For the 14 kW uranium target at GELINA (Boe79) a rotating-target technique together with water cooling is applied. For the 50 kW tantalum target at ORELA (Har70), the tantalum plates are surrounded by a water collar which serves as the cooling system as well as the moderator. The new Harwell source, HELIOS, employs simultanously three largely different targets in the booster, the fast-neutron and the condensed-matter target cells. The high power uranium target employed for the fast-neutron target cell is still watercooled, and is designed to withstand up to 50 kW of electron beam power. The booster target (Rae67) is a much more sophisticated design, and is mercury cooled. For the LIU-30 induction linac the beam power is ~200 kW. This required also liquid metal cooling (in this case a sodium-cooled tantalum target (Ana77)).

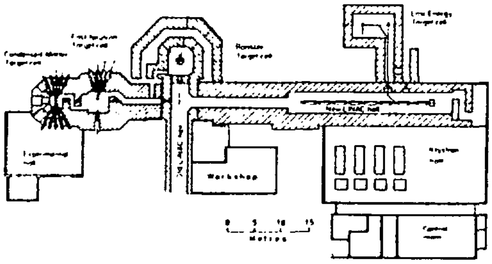

Fig. 2 The Harwell Electron Linac Facility, HELIOS

Neutron Facilities. Presently a large number of electron linac sources are used, e.g. GELINA, HELIOS, ORELA, or the linacs at JAERI, Kurchatov, Livermore, RPI and Sendai (Boe87, Sow87, Har87, Tan87). The neutron emission from electron linac targets is nearly isotropic. This allows the installation of many flight paths all around the target. From these a good fraction can be operated simultaneously (an annual average at GELINA is 5 of 12 installed flight paths). The simultaneous use of flight paths can be even higher at other sources. The new Harwell linac, HELIOS, is unique in that the electron beam is multiplexed into three target cells (Fig.2). The multiplexing is possible on a pulse-to-pulse basis with different beam conditions for each target cell. In this way a pattern of pulses can be scheduled among the set of targets, allowing to operate each of them under optimal beam conditions. The scheduling presently allows variation of the pulse width according to cell operation. Provisions were also made for individual variations of pulse current amplitudes. Most of the presently running linac sources are equiped with large modern computer systems, for simultaneous data aquisition, data handling and on-line evaluation.

Light-Ion Medium-Energy Sources

Character. High-energy neutron production with medium-energy light-ion beams is much more effective than that with electrons. In the range below ~100 MeV (considered here) proton and deuteron beams are most efficient, due to their sufficiently large range in thick targets. Neutron production with ions of less than ~50 MeV is chiefly governed by competition of atomic and nuclear interactions in the target. Bombardment of heavy target elements provides high intensity of evaporation neutrons and of a substantial fraction of high-energy neutrons from direct reactions (~20% above 10 MeV for 100 MeV protons). For deuterons a favourable additional reaction mechanism is the break-up of the projectile by Coulomb and nuclear interactions in the target. This provides a strongly forward-peaked spectrum with a broad maximum centered around about half of the incident deuteron energy. In contrast to the other mechanisms, optimum intensity is achieved with light element targets. For 30-MeV proton and deuteron beams on heavy element targets neutron yields of a few 0.01 neutrons/particle are achieved, and this number increases exponentially with energy up to ~1 n/p at 100 MeV. Typical beam currents of a few 100 µA on average and of a few A in ns or sub-ns pulses are presently realized with modern AVF cyclotron sources. This provides average neutron intensities of ~10**14 n/s and peak intensities of a few 10**18 n/s. With advanced linear accelerators, like that considered for FMIT, cw neutron intensities of a few 10**16 n/s could already be achieved with 35 MeV deuterons incident on light element targets like Li or Be.

Accelerator Status. Medium-energy AVF cyclotrons provide high beam currents of light ions, especially protons and deuterons. These machines are routinely operated for white sources with average beam currents of a few 100 µA (Lon83). The largely increased intensity of these machines over the synchrocyclotrons (used before) is mainly due to their continuous operation. Thus, they provide only a micropulse structure with nano- and sub-nanoseconds widths at pulse repetition rates of typically a few tens of MHz. For this reason, most of the white sources installed at cyclic machines are cw sources which cannot be used for high-resolution neutron work, except for special very high energy measurements where the microstructure with its high p.r.f. is still sufficient. Broad-spectrum cw sources have been extensively used in the past for neutron therapy and radiation damage studies (Lou83). E.g. the AVF cyclotrons at Oak Ridge and at the University of California at Davis have been used for high intensity (&eqv5x10**12 n/s and sr) neutron sources in radiation damage studies. For radiotherapy the facility of the NAC, is another outstanding source for intense high-energy neutron fields. But, AVF cyclotrons can also be used as outstanding high-resolution sources, when suitable pulse compression for the internal beam is provided. This has been demonstrated for the KfK cyclotron (Cie80). Employing a special "deflection bunching" system, allowed to bunch most of the internal beam current into subnanosecond pulses at repetition rates between 20-200 kHz. A correspondingly pulsed 52-MeV deuteron beam with peak currents of up to 1.5 A was achieved. Even though the KfK source had been utilized most effectively since 1966, there has not been any broad adaption of its concept, except for the project at the Kiev cyclotron. (It is, however, not clear, whether the Kiew source has yet come into routine operation) The Kiev isochronous cyclotron has even better specifications than the Karlsruhe machine, because of its higher deuteron energy of 70 MeV. Moreover, internal pulse compression is a factor 3 more efficient, since this cyclotron operates in the first harmonic mode.

Linear accelerators have, in the past, had little application in cw and pulsed white sources. But the situation may change in the future, even though the tendency is more to higher energy machines, operating in the 200-300 MeV region. In this region there are presently a few proposals and studies for advanced sources, e.g. (Ols85). Linear accelerators are inherently pulsed on micro- and macro-pulse scales. Micropulse widths of about 100 ps are typical for such machines. The most advanced study for an intense source involving a 35 MeV linac was the Fusion Materials Irradiation Test Facility (FMIT) in the U.S. (Tre80) which was planned as a cw machine for fusion research. This facility aimed at a cw current of 100 mA, providing a source strength of 4x10**16 n/s. Another more recent proposal is the already mentioned 100 MeV-induction linac studied at NBS which, in addition to electrons, was also considered for acceleration of light-ion beams with peak currents in the few A range. But, as for electron-beam applications, the relatively long minimum pulse width of 10 to 100 ns is a major disadvantage for high-resolution work in the a-few-100-keV and the MeV-range. Furthermore, light-ion peak intensities would be even less than that achieved already with the KfK cyclotron source.

Targets. Heat dissipation in pulsed sources is rather modest at least for the low duty cycle installations such as the KfK cyclotron (~1 kW) or the proposed NBS induction linac source (1.3 kW for the proposed H-beam, and 0.6 kW for the D-[illegible]. This can be easily handled by simple watercool[illegible]. Target aspects are more serious for cw sources, to be operated in the beam-power range of a few MW like FMIT. For facilities operating in this range, the target concepts must involve careful designs, such as rotating targets or liquid-metal systems.

Light-Ion High-Energy (Spallation) Sources

Character. Spallation sources consists basically of an accelerator providing a beam of high energy protons or possibly other light ions on a suitable heavy element target Neutron production proceeds through intranuclear cascade reactions and subsequent evaporation from highly excited residual nuclei. Above about 100 MeV incident particle energy the total number of neutrons/particle increases almost linearly with particle energy and target mass (Bar66). For fissile targets like U neutron production is further enhanced by fast fission. The neutron spectra exhibit a pronounced two component structure with large contributions from the two main types of reaction mechanisms. While the evaporation spectra are almost isotropic, the cascade neutrons are strongly forward peaked (Wac72, Ful72, Mei86, Cie87). Presently, opererating sources typically provide average neutron intensities in the range from a few 10**14 to a few 10**16 n/s and peak intensities of a few 10**17 to a few 10**20 n/s in the primary (unmoderated) pulses.

Accelerator Status. Several kinds of accelerators can be used for producing suitable beams for spallation sources. The Nevis synchrocyclotron (Columbia) was used for a long time with an internal lead target as a pulsed spallation neutron source (Hav 55). Though chiefly built for fundamental meson research, continuous proton beams from the TRIUMF and the PSI (previously SIN) cyclotrons have been used for spallation neutron studies, and to a smaller extent also for high energy neutron work (Fis78). Linear accelerators such as LAMPF or the studied West German machine (SNQ) (Moo74, RSF77, Bau 81) aimed at the production of long macropulses or extremely short single micropulses (≥100 ps) of high energy protons (800 MeV, 1100 MeV) for use with spallation targets. Rapid cycling synchrotrons are being used (Car77, HRS77, IW78) at ANL (IPNS), at KEK (KENS) (Fig.3) and at RL (ISIS) (Fig.4) for producing low-duty cycle intense bursts of 500 to 800 MeV protons for spallation sources. For very high current cw applications in nuclear power, linacs are generally favoured over cyclic machines (Lew77, Myn77, SFT77, Ste78). For all of the presently operating spallation sources there exist already proposals for greatly improved replacement facilities. So, the WNR/PSR, the TKF, the GEMINI and the ASPUN are future replacement concepts for WNR, TNF, KENS and IPNS, respectively. For the TRIUMF Kaon Facility (TKF) project the production of neutron beams is, in fact, not one of the prime motivations for constructing this facility. In the past practically all existing spallation neutron sources were exclusively planned and used for condensed matter neutron research, except for the LAMPF satellite source and MEIN at BNL (Kat86).

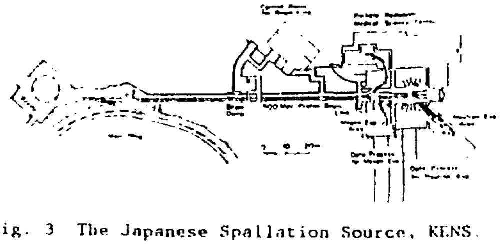

Fig. 3 The Japanese Spallation Source, KENS.

Targets. The essential requirement, dictated by the neutron yield per incident particle for a practical spallation target assignment is, that it involves a heavy element target. The materials most commonly considered as spallation targets are Ta, W, Pb, Bi, Pb-Bi, Th and U-238. Of these U-238 provides the highest total neutron yield per proton and Ta the least. But there are still other considerations which govern the selection of a special target material: These concern e.g. heat produced in a thick target, neutron absorption in the target (thermal and epithermal neutrons), evoluation of volatile materials, radiation damage, dynamic properties of the target (thermal conductivity, melting point), etc.

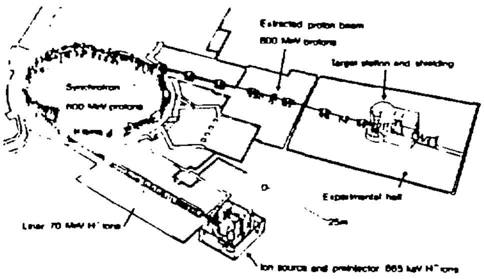

Fig. 4 The Rutherford Spallation Source, ISIS

The pulsed facilities presently in use are operated with low power, and thus can still use water cooling. In the KENS facilty a slab of tungsten forms the target. In the IPNS and the ISIS arrangement the objective was to obtain the maximum possible thermal neutron flux in pulses of ~25 µs duration. For this purpose a U-238 target was chosen which produces more neutrons at the expense of an increasing target power. For the more extreme heat conditions given for the ISIS targets, heavy water cooling and nucleate boiling was chosen. For the production of continuous or high-duty-factor pulsed sources the target must, in general, be immersed in an extended moderator and it becomes important to *minimize the slow neutron absorption in the* target itself. This requirement dictates the adoption of Pb or Pb-Bi eutectic targets. The TNF facility at TRIUMF serves as a beam stop for the 500 MeV proton beam in the meson area and as a neutron source providing modest fluxes for research and isotope production. A melted lead target is used. When the power is further increased in cw systems, the use of a continuously circulating Pb-Bi eutectic becomes very attractive. This concept is foreseen for the new PSI source, (SINQ) (Hof79). The aborted West German Spallation Source, SNQ, which aimed at a 10 mA average current of 1100 MeV protons, considered a large rotating wheel target of 3 m dia (Bau79). Target concepts for future much higher beam-power facilities have also been elaborated (Bar83). Even target concepts for energy application, where beam powers of several hundreds of MW are involved, have been sufficiently studied. This applies e. g. for the Pb-Bi HWR-type target-blanket assembly proposed by the BNL scientists (Gra78).

Hybrid Systems

The total neutron intensity of white sources has been largely increased by neutron multiplication in hybrid systems, involving a white source (typically an electron linac source) coupled to a subcritical fission essembly, i.e with so-called "booster" sources. Such are essentially small reactors existing in the subcritical state of prompt neutrons, in which the power pulse is developed by multiplication of neutrons from the external source. Such systems provide high neutron multiplication factors (up to a few 100), but on the expense of a corresponding large increase in neutron pulse width and a decreasing source brightness. Two early neutron sources making use of such booster targets were the old Harwell linac (Poo58, Poo64) and the Dubna magnetron source (Bun72). The Harwell booster target is still used with the new electron linac, Helios (Lyn80). For the Harwell booster target a multiplication factor of 10 was chosen as a compromise between neutron enhancement and a reasonable relaxation time, resulting in a neutron pulse length of 100 ns. In Dubna the old magnetron source has now been replaced by the IBR-2 facilty. This involves a Pu-239 target and provides a neutron multiplication factor of 100. The neutron pulse duration from this source is typically 1.7 µs (Fig.5). There have been several other booster source concepts and studies aiming at even higher multiplication factors (up to 300) with the corresponding increase in pulse length (Ana69, Egu73, Ger 72). The advantage of a largely increased strength of such sources is, *however, relativated by two important* deficiencies: The largely increased pulse length and the non-negligible background of deleayed neutrons emitted between neutron bursts. While there was great enthusiasm for these hybrid sources two and three decades ago, this approach is not more en vogue, and many of the ambitious previous concepts have never been realized.

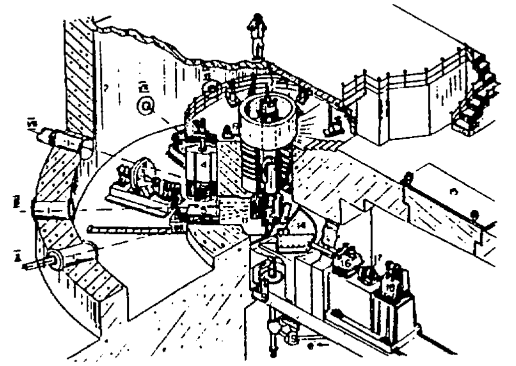

Fig. 5 The Dubna Booster Source (Sha79)

The Future

R.f. electron linacs continue to be very efficient white neutron sources. Though less effective in neutron production yields and spectral range than medium- and high-energy light ion sources they have provided a *wealth of high qualtity results, and* this will remain so in the future. Much progress has been also made in producing extremely short neutron bursts of about 1 ns or even less. Moreover, there have been great advances in producing increased spectral intensities all over the range from 1 meV to more than 20 MeV. While there are still a few possibilities for further improvements, the intrinsic limitations will remain: The lack of spectral intensity in the many-MeV range is governed by the neutron production mechanism, and the limitation in total source strength by the maximum power to be stored in the accelerator cavities. While S-band technology is quite mature, it seems possible that an increase of the total intensity by an order of magnitude can be achieved with present L-band technology. Superconducting S- and L-band linacs could bring, in principle, another order of magnitude in total currents. This is mainly due to the possibility of increasing the pulse repetition frequency substantially. In addition, superconductivity, allows increased storage of electromagnitical energy (Boe87). In this respect the new developments in high-temperature superconductivity allows some optimistic views for the future. But, the techniques for superconductive r.f. linacs are not yet advanced enough to consider this possibility already seriously for a new generation of r.f. linacs for white sources. Linear induction accelerators are presently exploited for much higher instantaneous peak currents than those for r.f. linacs and promise pulsed beams of a few 1000 A. Present technology requires, however, still a trade-off between high beam current or high energy. But, even if both high current and high energy, say 100 MeV, could be achieved, there is still the chief disadvantage of a comparatively long minimum pulse width of 10 to 100 ns. This limits their use strongly to applications in the low-energy range or to uses in fields were energy resolution is not important, such as radiation damage and therapy applications.

Light-ion (mainly proton and deuteron) accelerators for energies below ~100 MeV have also been utilized very successfully for white sources. In the past, mainly medium energy AVF cyclotrons have been involved for cw and pulsed operation. But their average beam currents are limited to a few mA in the internal beams, and even more for extracted beams. "Deflection bunching" techniques have been used e.g. for the high resolution KfK source to obtain sub-ns bursts with peak currents of more than 1 A. The most favourable energy range for this source is, however, above a few 100 keV due to the high intrinsic repetition rates of 20 to 200 kHz. The operation of AVF cyclotrons with a few mA of average beam current has reached maturity, and there is little prospect for further increase in beam intensity, except for low-duty cycle short pulse operations. Medium-energy r.f. linacs promise beam currents of up to 100 mA, and the technology of variable-energy light-ion machines is rapidly advancing. Even machines with superconductive r.f. cavities appear possible for the near future (She88). Such machines are inherently pulsed on a microstructure scale with typical pulse width of ~100 ps. It would be a challenging task to use these microstructure pulses in white-source time-of-flight measurements. Presently the chief hindrance is detector limitation. But there are already special-purpose detector systems, even with high efficiencies, having time responses of a few 100 ps (e.g. Pat77, Cie80), and perhaps advanced sub-ns techniques applied in heavy-ion or in high-energy physics can stimulate further developments.

The advantage of spallation reactions for intense neutron production has been taken in a number of white sources (e.g. IPNS, ISIS, KENS, LANSCE). These sources are all particularly structured for condensed matter research in the thermal and epithermal range, and provide outstanding neutron fluxes. Due to this special application, these sources provide pulse widths in the range from a few ms to a few us. With the exception of the LAMPF accelerator all other machines inherently prohibit the production of extremely short pulses in the 1 ns range at reasonably low repetition rates. At LAMPF, however, the satellite neutron source has excellent short pulse characteristics, providing high intensity in sub-nanosecond bursts. This is already achieved by using only a very small fraction of the totally available negative-ion H beam (Fig.6). All existing spallation sources do not merely exploit the utmost capability owing to the spallation process. But there exist already several proposals for largely improved upgrading or replacement concepts for many of the present sources (e.g. WNR/PSR at LANL, TKF at TRIUMF, IPNS II at ANL and GEMINI at KEK). But even with these new sources the inherent potential of spallation facilities is by far not exhausted. For energy applications (accelerator breeding) machines with still ten times higher beam currents than that of the next generation of sources have been considered already for a long time.

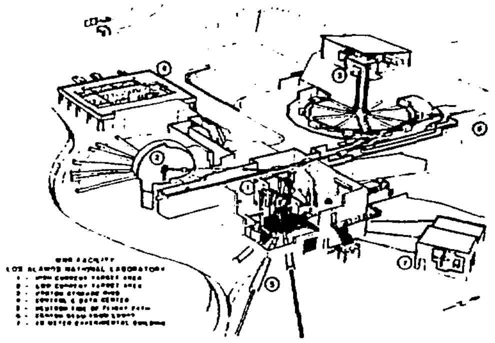

Fig. 6 The Los Alamos WNR Facility (Lis86).

Concerning hybrid ("booster") sources, it is not very likely that they will return to great importance in the future. This is mainly due to the fact, that these are very complex, have certain limitations in pulse length and the disadvantage of an inherent time-average background.

In conclusion, a large number of high-quality white neutron sources have been built and used in the past, and these facilities were perhaps the most prolific sources for excellent new results in fundamental and applied neutron-nuclear research. These sources have still important potential for drastic further improvement, especially those involving the spallation concept. My personal view is, however, that large scale new source projects, dedicated exclusively to our domain of research will be prevented by the present financial limitations. Therefore, main progress must certainly come in the future from modest steps, exhausting all possiblities inherent still in present source concepts and experimental techniques. This is a challenging task for making more efficient use of existing equipment and for employing more inovative techniques and new experimental methods, involving the available highly-scilled manpower.

MONOENERGETIC SOURCES

Advantages

- Control of energy, time, space and momentum. The advantage is well known from the theory of measurements. In important regimes, the monoenergetic source is mandatory.
- Intensities. In optimal energy regions the specific brightness can be superior (Pau55).
- Versatility in steady-state or pulsed modes. The associated facilities are among the most utilitarian found in all science.
- Optimum control of signal/background and experimental perturbations.
- Economy in capital investment and operation.

Limitations

- Optimum in limited energy ranges (≈ 0.1-10, 14-30 MeV).
- $\Delta E/E$ is largely controlled by the target.
- Total intensity not comparable to that of the white source.
- Generally not consistent with concurrent users or concurrent multiple-energy measurements.

The attributes explain why the relatively conventional monoenergetic source has made and continues to make major contributions to basic and applied science.

Electrostatic Ion Acceleration

The principle of mechanically charged electrostatic devices is lost in antiquity. The charging mechanism is commonly an insulating belt (HVEC) or a chain of metallic components (NEC). The terminal voltages are variable to 20+ MV and stable, with maximum currents in the order of $\gtrsim$ 100 μA.

Recently, electronic means have been used to charge electrostatic terminals (RDI). These considerably enhance current capability, but the terminal voltages are restricted to 5-6 MV. The potential for future development of electronically charged devices is good, with 10 MV terminals capable of supporting 100 kW of beam now under consideration.

The voltage stabilities and energy ranges of the above devices are not governing factors in the production of monoenergetic neutrons, and operation can be both steady state and pulsed. The neutron brightness per unit energy is impressive, although the multi-channel capability of the white source is not available.

Many of the productive facilities are pulsed in the nsec regime, making optimum use of the inherent capability to concurrently determine both energy and time. The pulse intensity is now limited by the peak ion-beam intensity rather than the power-handling capabilities of the accelerator and/or target.

Electrostatic accelerators have been increasingly operated in the tandem mode. This approach has the obvious advantage of doubling the accelerator energy. Additional advantages are serviceability of the ion-source and pulsing components, and the availability of essentially unlimited space and power at the source.

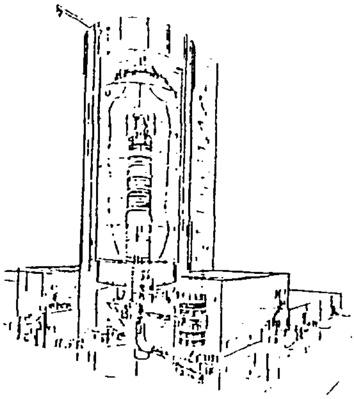

Fig. 1. Large folded tandem accelerator (NEC).

Cockcroft-Walton accelerators (Coc32) arrived with the neutron. They remain very useful devices for the production of ≈ 14 MeV neutrons. Various versions of capacitance and rectification cascades are used, all of which involve considerable stored energy. Voltages are generally limited to less than 1.0 MV, and common operation is in the 200 to 500 keV range. The devices are relatively simple and capable of a few times 10**13 n/sec at 14 MeV (Dav87,Tak86). The intensity limitation is again the target power-handling capability. The prospect of future improvements is relatively modest. Realistic projections suggest intensities in the order of 10**14 n/sec using advanced technologies and rotating-target systems (Dav87).

Cyclic Facilities

Cyclotrons for the production of neutron sources date back more than half a century (Alv38), yet their use has been limited. The devices are complex and costly, but they are capable of relatively intense variable-energy hydrogen-ion beams, good energy control, and they are inherently pulsed. These attributes make them attractive devices, as illustrated by the PTB facility (PTB,Bre80) utilizing a compact commercial unit providing ≈ 100 μA of time-averaged H or D beams up to ≈ 24 MeV, or nsec pulsed beams with an averaged intensity of ≈ 0.5 μA at effective repetition rates. The small size of the accelerators makes possible precise movement of the entire system so as to provide a "source swinger" to vary angular relations, as in neutron-scattering measurements.

At higher energies the cyclotron becomes a preeminent tool for fundamental neutron studies. Measurements have addressed both the primary neutron-source reaction and the secondary processes induced by the neutrons. The latter category is illustrated by the (n,p) studies at the Davis cyclotron (UOC,Bra87). An ≈ 60 MeV neutron beam has an intensity of ≈ 1.5 x 10**5 n/(sec·Mev·cm**2), exceeding the energy differential intensity available at any white source. The fundamental study of neutron emitting reactions has been a source of new understanding; e.g. Gamow-Teller resonances (Goo87), as illustrated by the neutron time-of-flight studies at IUCF (IUCF). With sub-nsec pulses, incident particle energies of 50-200 MeV, a pre-acceleration "stripper loop," a beam swinger, sensitive detectors, and flight paths of ≈ 100 m, truly remarkable (p,n) measurements have been made with ≤ 0.2% energy resolutions. This work is now being extended to polarized-neutron properties (Tad85).

Higher-energy monoenergetic neutrons have been exploited *in biomedical applications*. There is promise for neutron therapy with intense, well-controlled neutron sources (Bro87). These requirements can be reasonably met with specially built, medium-energy, cyclotron facilities. An example is the therapeutic facility at the National Accelerator Center (Jon87). A 60 MeV proton beam is incident on a beryllium target, providing intense neutron fields with energy spreads of ≥ 25% the energy of the incident beam. Collimation is excellent, and an isocentric magnet and collimator provide a well-defined field at the patient. It is premature to estimate the ultimate *effectiveness of such systems. However*, monoenergetic neutron sources may have a potential for effectively addressing one of mankind's more serious ills.

Linear Positive-ion Facilities

Though early-on linear radio-frequency facilities *received attention (Alv46), more recently they* have found little application in the production of monoenergetic neutron sources. That situation may be changing as a consequence of technological development motivated by basic medium-energy (LAMPF) and heavy-ion studies (Bol88). The beams are inherently pulsed on both micro- and macro-time scales, and experimental time resolutions of ≈ 100 psec *have been routinely* demonstrated in heavy-ion measurements. More speculative is the induction linac (Joh87, Bri84). Energies up to ≈ 100 MeV have been proposed, with good ΔE and peak H and D pulsed intensities in the *ampere range. The devices are inherently pulsed*, but at relatively low rates, with burst widths of ≥ 10 nsec. This compara-tively long pulse considerably compromises the potential of the concept in most fast-neutron applications. Compensating factors are the versatility and modular nature of the devices, and the very large overall white-source intensities available with H or D incident on heavy-metal targets (≥ 10**14 n/sec).

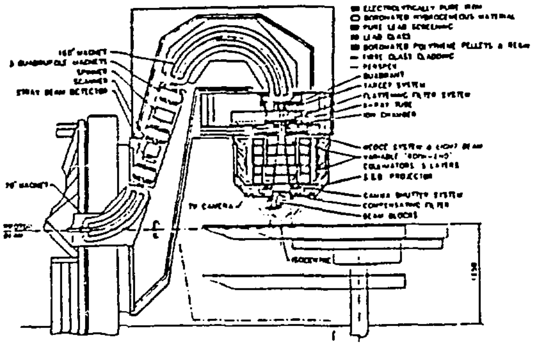

Fig. 2. NAC Neutron Therapy Facility (Jon87,NAC).

Hybrid Facilities

Ion-beam energies have been increased, while retaining good stability, by coupling cyclic and electrostatic or electrostatic single-ended and tandem *machines (Gla75,Jar71). This approach is* not now in vogue, and some such facilities have been taken out of service. This is apparently due to technological advances that have much increased the energies available with single component systems. It seems unlikely that hybrid systems will return to favor, as they are certainly complex, probably more costly, and have not been notable for their intensities.

Source Reactions

The coulomb barrier and the packing-fraction curve conspired to make the reaction of hydrogen beams with light nuclei the major monoenergetic neutron sources.__ These are dominated bv the "big 4."

Reaction	Q-value (MeV)	Breakup Reaction	Breakup Threshold(MeV)	Monoenergetic Range (MeV)
^{2}H(d,n)^{3}He	+3.270	D(d,np)D	4.45	1.65-7.75
^{3}H(d,n)^{4}He	+17.590	T(d,np)T	3.71	11.75-20.5
		T(d,2n)^{3}He	4.92	
^{3}H(p,n)^{3}He	-0.763	T(p,np)D	8.35	0.3-7.6
^{7}Li(p,n)^{7}Be	-1.644	^{7}Li(p,n)^{7}Be*	2.37	0.12-C.6

For all of these basic reactions, breakup or other secondary contributions contaminate portions of the energy range. The characteristics of the "big 4" have been very carefully studied (Dro87), with results as illustrated in Fig. 3.

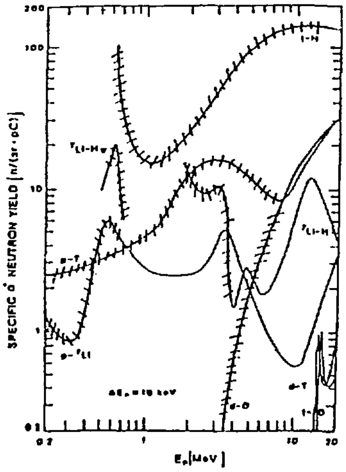

Fig. 3. Yields from the basic monoenergetic source reactions (Dro87). Monoenergetic ranges are "hatched."

The specific brightnesses of these sources is large. At 10 MeV they are several times that of the most powerful electron-linac source and well within an order of magnitude of that of the more optimistic spallation sources operating in the fast-pulsed mode (Boe87). These are impressive values from modest facilities. Signal/background ratios depend upon: the monoenergetic nature of the source, the angular-dependence of the yield, and, of course, on energy and intensity. These are intrinsic properties of the source, independent of the particular experiment. Gas targets have the advantages of: easy control and measurement of target density, even thickness, and convenient determination of backgrounds, and thus are widely used. Geometry and energy control may be a serious concern; e.g., with the Li-7(p,n) reaction. The p→T process generally has the highest yield and the widest monoenergetic range but requires handling tritium. The d→D reaction is less prolific, has a smaller monoenergetic range, and leads to more power dissipation in the target, but it is easy to use and thus has been widely applied. The yield from the d→T reaction is low and, near threshold, nearly isotropic. The advantage is, of course, the high positive Q-value and the low-energy resonance, making the reaction suitable for use with very modest accelerators. Among all the known monoenergetic reactions, the t→H process has by far the highest yield, is intrinsically a monoenergetic source to ≈ 18 MeV, and has a very favorable angular distribution, with the neutron emission confined to the forward cone. The obvious problem is the requirement of a tritium beam, a capability thus far enjoyed at only one major facility (Jar71), though new facilities are planning tritium beams (Dav88). The p→Li-7 reaction has long been used at low energies because of its prolific yield and practical advantages in controlling target thickness. Neutron energy spreads of less than a keV can be realized, but the source is monoenergetic over only a limited energy range. The resulting neutron-energy resolutions are not comparable to those obtained with modern white sources at lower energies. However, as the energy increases into the 10-100 MeV range, the reaction again becomes a very attractive, nearly monoenergetic source as the high yield is largely concentrated in the relatively close-spaced first-two groups, with considerably less secondary neutron-spectrum contamination relative to other sources at these energies (Goo87,Yam87,Bat69). This favorable situation exists to at least several hundred MeV, and the source has been used in some of the most sucessful monoenergetic measurements at higher energies (Bra87,JAERI).

The interactions of heavy ions with nuclei are complicated and only partially understood processes that are of considerable fundamental interest. Neutrons are emitted with only modest intensities (≈ 10**-3 n/ion at 10 MeV/A) (Bl187). Thus, the processes are not attractive from the point of view of neutron sources. That generality does not apply to special cases. The merit of kinematically collimated monoenergetic sources--for example, the Li-7(p,n)Be-7 reaction very near the threshold--is well known (Gno70). The higher-energy inverse reactions--for example, (Li-7)→H and (B-11)→H--greatly enhance the kinematic collimation, with commensurate increases in intensity, and thus offer the potential for very effective sources at selected neutron energies (Dro87). Furthermore, the (B-11)→H reaction accesses the 8-14 MeV energy range, generally "forbidden" to other monoenergetic reactions.

The monoenergetic neutron sources have special properties that make them uniquely suitable for some applications. Many of the reactions provide neutrons with a good degree of polarization in selected angle-energy ranges (Wal74), and have been the basis for most studies of spin-orbit and associated polarization effects. Furthermore, the polarizations can be a concern in certain types of measurements, e.g., ring-geometry experiments. The detection of the associated reaction particle or the residual target activity has been exploited for some of the most precise standard cross section and flux determinations. These monoenergetic neutron sources have been primary tools for precise neutron-standard measurements. Many of the lesser-yield monoenergetic-source reactions are suited for special applications. Examples are: the Sc-45(p,n)Ti-45 source as applied to precise low-energy calibration of biological dosimeters (Coa87), and the low-energy isotropic emission from the V-51(p,n)Cr-51 used for sphere transmission and flux calibrotion measurements.

Pseudo-white Sources

Pseudo-white pulsed-neutron sources available at "monoenergetic" facilities provide effective intensities within broad energy bounds, combining the quantitative determination of backgrounds with the efficiency of multi-channel time detection. The intensities and resolutions are not comparable to a powerful continuum white-source facility, but they can be very cost-effective (Smi87). The reactions used are usually Li-7(d,n) or Be-9(d,n), or composites of the two, with deuteron energies of 8-10 MeV or higher. At deuteron energies of ≈ 8 MeV, the yields are an order of magnitude below those of the large electron-linac (Boe87), but the sources are spatially well-defined, making possible the use of very small samples, and the yields are strongly peaked forward, alleviating background effects. The yields very rapidly increase with incident deuteron energy, and at 20-30 MeV become comparable to the most intense white sources (Yam87). Furthermore, the spectral distribution can be tailored to various measurement requirements by changing the incident particle energy and/or target composition. The consequences are the optimization of the particular experimental configuration, and the ability to provide a variety of standard fields for both microscopic measurements and engineering tests. The effectiveness of pseudo-white sources has been demonstrated by some of the best and widest scope fast-neutron total cross section measurements (Fos71,Poe81) and precise validation of microscopic activation and fission cross sections (Smi87). Many of the most urgent applied needs are for activation information, particularly involving small cross sections and long half-lifes. These pseudo-white fields seem to offer the only hope of successfully addressing this problem area. Combining well-characterized and varied fields with rigorous statistical interpretation, it has been shown that unfolding techniques can provide differential cross-section information in these difficult cases which appear otherwise intractable (Qai87,Smi82). The same type of intense fields are also being used for engineering tests of neutronic performance: e.g., multiplication and energy transfer in beryllium used in fusion blankets (Mic99).

Target Technologies

The intensities of steady-state monoenergetic neutron sources are limited by the power-handling capabilities of the targets, not the intrinsic reactions or the ion accelerator. The well-defined geometries are an advantage in many measurements, but they also mean very high power densities. In practice, the maximum power-handling capability of a good research target, metal film or gaseous, is limited to 100-200 watts. This limitation can be mitigated in special applications by artifices such as: rapid target motion (Dav87), windowless gas cells, liquid metal targets (FMIT), massive coolant flows, etc. However, such approaches have not proven generally practical in research applications as there have always been severe penalties in intensity, target mass and/or complexity, spectral distortions, or other factors. These concerns do not extend to engineering applications where source perturbations are frequently a minor consideration.

The large majority of monoenergetic targets involve the interaction of ion beams with thin metal films, either inherently in the target material or with the container (e.g., the gas-cell window). In addition to the above-cited power limitations, sputtering, migration, and crystalline effects in these films are a concern. These limit the thinness of the target to $\geq$ a fraction of a keV and the power transmission of foil windows to $\approx$ 100 W, and result (together with structural components) in the distortion of the emitted neutron spectra. Artifices in fabrication and use have alleviated some of these problems. For example, the use of gridded support structures will double or triple the power-transmission capability of a gas-cell window (Mea80), and new alloys significantly increase the strength of such windows for a given energy loss, but order-of-magnitude improvements seem very unlikely. The understanding of spectral perturbations, both theorectically (Kor87) and empirically (Mea77), has very much improved, and corrections to the spectra can now be made with a good degree of reliability. Such corrections can have a significant impact upon a diversity of research endeavors.

The inherent secondary-component contamination cannot be removed, but it is now much better understood. For example, the break-up contribution to the widely used d→D reaction is now well defined (Kor87,Cab87), both in intensity and spectral distribution. This new understanding makes possible quantitative corrections that were previously unfeasible, and brings to this convenient source a far more general utility. Concurrently, technological methods have been developed to correct for the d→D break up using the very similar results of d→(He-3) bombardment to closely mock up the break-up contribution (Gri82).

The Future

The well-known and conventional reactions of hydrogen beams with light targets will remain the workhorse monoenergetic neutron sources. While the details of the individual reactions and techniques for their optimization may become better known, the intrinsic limitations will remain. The available steady-state intensities are governed by target power-handling capabilities. Variable-energy positive-ion beams of x 10-100 in intensity are technologically reasonable and relatively economical. Pseudo-white sources at the "monoenergetic" facility have good potential for very significant increases in steady-state neutron intensity, as target power handling is no longer as restrictive. The resulting intense fields promise to be very effective in a variety of research and engineering applications. A promising aspect is the coupling of these intense, variable, and well-controlled fields with quantitative understanding of statistical methods to obtain differential information not otherwise available.

The fast-time-of-flight technique (Cra58) has proven by far the most successful fast neutron spectrometer; and it will probably remain so into the future. The method is uniquely adapted to the monoenergetic source. The quality of the result is dependent upon the peak-pulse intensity, and generally the repetition rate is inversely proportional to intensity; thus, target power limitations are not as governing. There is good growth potential for nsec-pulsed monoenergetic neutron sources. There are intrinsic restrictions on $\Delta E \cdot \Delta t$ (Goo70), and there are technological limitations (e.g., space charge), but contemporary levels of pulsed performance fall far below these limits. Given the tandem accelerator, where essentially unlimited power and space are available for the ion source, very large increases (one or more orders of magnitude) in ion-source intensity can be obtained with acceptable emittance using technologies proven in other contexts. Increases of 20-30 in pulse intensity are routinely achieved by ion bunching, utilizing a sinusoidal voltage. Additional factors of 3-4 have been obtained using harmonic bunchers at heavy-ion facilities (Mil79). The application to the hydrogen beams at the frequencies of interest is a bit more complex but manageable. Thus, at conventional facilities and at relatively modest cost, overall nsec peak-pulse intensity increases of several orders of magnitude are an attractive option that will have a strong impact on measurement capability.

Post-acceleration RF (Lis88) and magnetic (Mob63) bunchers have been used at monoenergetic facilities to obtain sub-nsec bursts. The bunching is applied to a "hard" beam, and the target is restricted to a single position. There are attractive special-purpose uses of sub-nsec bursts, but neutron energy spread, physical dimensions of samples and detectors, overall system time response, and other factors conspire to limit the scope of such applications.

Time-of-flight facilities are in widespead use, in their more advanced form using beam swingers, massively shielded sources, or multiple and long flight paths. The spectroscopic performance is very good, rivaling that of the better charged-particle spectrometers, and addressing a different class of problems accessible only to the neutron probe. However, it remains to unify these components into one integrated system, combining the beam swinger, intense sources, favorable bunching ratios, heavily shielded source, and multiple and well-collimated long flight paths. If such a system were assembled, it would provide a truly "world-class" capability. No speculative technological development is required, and the total costs are relatively modest. The potential of the pulsed monoenergetic sources at higher energies (above ≈ 20 MeV) remains largely unexplored, despite the fact that the available neutron sources in this region are among the brightest in existence (Fin85). This higher-energy area is rich in fundamental understanding, though of less general applied interest.

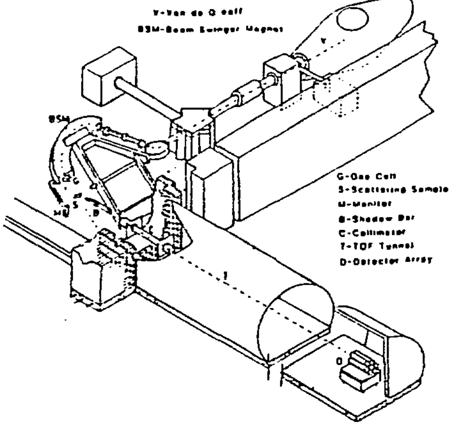

Fig. 4. Ohio University time-of-flight system

Cyclic pre-injection pulse storage has been used to increase peak-pulsed intensities at open-sector cyclotrons. Unfortunately, the application of the method to negative-ion injection or post acceleration storage at the typical electrostatic tandem is apparently confined by phase-space requirements to intensity increases of perhaps 5-8 (Kus88). However, the technology of variable energy positive-ion linacs is rapidly advancing using superconducting RF cavities (She88). Much of the development has been in the context of fundamental heavy-ion research, but similar technologies offer an attractive potential for the production of neutron sources, either as injectors or boosters at conventional tandem electrostatic machines, or as stand-alone devices. Such sources would be inherently pulsed at frequencies in the hundreds of MHz range and have an acceptance resulting in a considerable bunching factor, which can be further enhanced by pre-injection bunching. Energy ranges run from a few MeV to many tens of MeV or more; the accelerator can be made modular, and beam energy stability is very good. At least one of these devices appears to accelerate spatially separated beams, conceptually making possible concurrent use of dual neutron-producing targets. The costs are relatively modest, perhaps a $million (US) for a 10-20 MeV unit, and superconducting power efficiency is very good. The potential of these linear devices is such as to make them attractive stand-alone alternatives to the conventional electrostatic accelerator. A major obstacle to their application as neutron sources seems to be the lack of commercial availability.

The unique features and cost-effectiveness of the monoenergetic neutron sources assure that they will remain a preeminent tool for fundamental and applied fast-neutron measurements, particularly the study of the more complex processes.

References and Definitions

Alv48 MTA, Materials Test Accelerator, L. Alvarez, unpub. (1948)
Alv38 L. Alvarez, Phys. Rev. 54 609 (1938).
Ann83 V. Ananev et al., Dubna Report, OIYaI-13-4392 (1983)
Ann77 V. Ananev et al., Dubna Report, OIYaI-13-4392 (1977).
Ann69 V. Ananev et al., Dubna Report, OIYaI 13-4392 (1969).
Bar83 G. Bartholomew, Neutron Sources for Basic Physics & Applications, Pergamon Press 217ff (1983)
Bar66 G. Bartholomew et al., in AECL Report, AECL 2750 (1966).
Bat69 C. Batty et al., Nucl. Instr. Methods, 68 273 (1969).
Bau81 G. Bauer et al., KFA/KfK Report, Jul-Spez-113/KfK-3175 (1981)
Bil87 M. Bilnov, IAEA-TECDOC-410, 65 (1987).
Boe87 K. Boeckhoff, IAEA-TECDOC 410, 35 (1987).
Boe87 K. Boeckhoff, priv. comm. (1987).
Bol88 L. Bollinger et al., Reports, ANL-ATLAS-series of (1988).
Bow80 C. Bowman, IAEA INDC(NDS)-114/GT, 119 (1980)
Bra87 F. Brady, Can. J. Phys. 65 578 (1987).
Bre80 H. Brede et al., Nucl. Instr. Methods, 169 349 (1980).
Bri84 R. Briggs, Proc. Darmstadt Linear Accel. Conf. (1984)
Bro87 J. Brenese, IAEA-TECDOC-410, 380 (1987)
Dun72 B. Dunin et al., Dubna Report, OIYaI 18-6213 (1972).
Cab87 S. Cabral et al., PTB Progress Report (1985-1987).
Car77 J. Carpenter, Nucl. Instrum. Meth. 145, 91 (1977)
Cie87 S. Cierjacks et al., Phys. Rev. C36, 1976 (1987).
Cie83 S. Cierjacks, Neutron Sources in Basic Physics & Applications, Pergamon Press, 81ff (1983).
Cie80 S. Cierjacks et al., Nucl Instrum Meth 169, 185 (1980).
Cos87 H. Cosack et al., PTB Progress Report (1985 1987).
Coc87 C. Coceva, IAEA-TECDOC-410, 56 (1987).
Coc32 J. Cockcroft and E. Walton, Proc. Roy. Soc. A136 619 (1932)
Cra58 L. Cranberg, Proc Atoms for Peace Conf. (1958)
Dav88 J. Davis, priv. com. (1988).
Dav87 J. Davis, IAEA-TECDOC-410, 303 (1987).
Dro87 M. Drosg, IAEA-TECDOC-410 (1987).
Egu73 T. Eguse et al., EUR Report, EUR 4934e (1973).
Fin85 R. Finlay, AIP Conf. Proc. No. 124 274 (1985).
Fis78 T. Fischer et al., SIN Newsletter 10, 29 (1978)
FMIT FMIT, Fusion Materials Irradiation Test facility
Fos71 D. Foster and D. Glasgow, Phys. Rev. C3 567 (1971)
Ful72 H. Fulwood et al., LA Report, LA-4789 (1972).
Ger72 V. Gerasimov et al., KI Report, IAE-1965, 981 (1972).
Gra78 P. Grand et al., BNL Report, BNL-50838 (1978)
Gla75 D. Glasgow et al. NBS-425 (1975).
Goo70 W. Good, Experimental neutron resonance spectroscopy Academic Press, NY (1970)
Goo87 C Goodman, Can. J. Phys. 65 549 (1987).
Gri82 S Grimes et al., Nucl. Instr. Methods, 203 269 (1982).
Har87 J. Harvey, priv. comm (1987).
Har69 J. Harvey, ORNL Report, ORNL 4230, 125 (1969)
Hav55 W. Havens Jr., Peaceful Uses of Atomic Energy 4, 74 (1955)
Hob77 L. Hobbis et al., RL Report, RL-77 064/C (1977).
Hof79 H. Hoffmann, Int KfK Report unpublished (1979).
HVEC High Voltage Engineering Corp., Burlington, Mass.
Ish78 Y. Ishikawa et al., KEK Report, KEK-78-19 (1978).
IUCF IUCF, Indiana University Cyclotron Facility
JAERI JAERI, Japan Atomic Energy Research Institute.
Jar71 N. Jarmie et al. Phys. Rev. C3 10 (1971).
Joh87 R. Johnson, IAEA-TECDOC-410, 29 (1987).
Jon87 D. Jones et al. Natl. Accelerator Center Ann. Report (1987)
Kal87 C. Kalcoff, priv. comm. (1987).
Kor87 N. Kornilov, IAEA-TECDOC-410, 230 (1987).
Kus88 R. Kuston, priv. com. (1988).
LAMPF LAMPF, Los Alamos Meson Production Facility.
Lan66 A. Langsford et al., Nucl. Struct. Studies with Neutrons, North Holland (1966).
Law47 E. Lawrence et al., Phys. Rev. 71, 449 (1947).
Lei79 J. Leiss, IEEE Trans. Nucl. Sci. NS-26, 3, 3870 (1979).
Lew52 W. Lewis, priv. comm. (1952).
Lis88 H. Liskien, priv. com (1988), also N Olsson and B Trostell, AIP Conf. Proc 124, 401 (1985).
LRL54 LRL Report, LRL-102 (1954).
Lyn80 J. Lynn, Contemp. Phys. 21, 5 (1980)
Man80 F. Mann et al., BNL Report, BNL-NCS-51245, 515 (1980).
Mea80 J. Meadows, *Nucl. Instr. Methods*, 178 439 (1980)
Mea77 J Meadows, Argonne Natl. Lab. Report, ANL/NDM 24 (1977).
Mei86 M. Meier et al., Rad. Effects 96, 487 (1986).
Mic88 B. Micklich et al., priv. com. (1988).
Mil79 W. Milner, IEEE Trans. Nucl. Sci. 26 1445 (1979)
Mob63 R Mobley, Rev. Sci. Instr. 34 256 (1963)
Moo74 M. Moore, in Nucl. Struc. Studies with Neutrons, North Holland (1974).
Myn77 F. Mynatt et al., ORNL Report, ORNL/TM-5700 (1977).
NAC NAC, National Accelerator Center, Faure, South Africa
NEC National Electrostatics Corp., Middleton, Wis.
Nor72 N Norris et al., EGG Report, EGG 1183-2142 (1972)
Ols85 D. Olsen et al., ORNL Report, ORNL/TM 8669 (1985).
Pat77 Y Patin et al., Nucl. Instrum Meth 160, 471 (1977)
Pau55 E. Paul, Proc. Conf. Neutron Time of Flight Methods, NEA Press (1955).
Poo64 M Poole et al., AERE Report, AERE PR/NP7, 47 (1964)

Poo58 W. Poole et al., Peaceful Uses of Atomic Energy 14, 268 (1958)
Pre81 W. [illegible] et al., Nucl. Sci. Eng. 78, 333 (1981)
PTB PTB, Physikalisch Technische Braunschweig
Qai87 S. Qaim, IAEA-TECDOC-410, 53 (1987)
Ray67 E. Rae, Fundamentals in Nuclear Theory, IAEA, 881 (1967)
RDI Radiation Dynamics Inc., Melville, New York.
Rus77 G. Russell et al., LA Report, LA 6020 (1977)
Sch77 S. Schriber et al., AECL Report, AECL-5905 (1977)
Sch88 P. Schmelzbach, priv. comm. (1988)
Sha79 E. Shabalin, Fast Pulsed & Burst Reactors, Pergamon Press, 20455 (1979)
She88 K. Shepard, priv. comm. (1988)
Smi87 A. Smith, IAEA-TECDOC-410, 278 (1987)
Smi87 D. Smith, Proc. 5th ASTM/EURATOM Sym. on Reactor Dosimetry (1987)
Smi82 D. Smith, Argonne Natl. Lab. Report, ANL/NDM-77 (1982)
Sow87 M. Sowerby, priv. comm. (1987)
Ste78 M. Steinberg et al., Atomkernenergie 32, 39 (1978)
Tad85 T. Taddeucci et al., Nucl. Instr. Methods, A241 448 (1985)
Tak86 A. Takahashi et al., Osaka Report C-86-04 (1986)
Tre80 A. Lee Trego, HEDL Report, HEDL-SA 1939 (1980)
UCD Davis, University of California, Davis
Wac72 J. Wachter et al., Phys. Rev. C6, 1496 (1972)
Wal74 R. Walter, Nuclear spectroscopy and reactions, Academic Press, New York (1974)
Yam87 T. Yamamoto, IAEA-TECDOC-410, 253 (1987)