Intense neutron sources

During the past two decades, neutron research has centered around four general types of neutron sources: continuous reactors, electron linear accelerators, other particle accelerators and pulsed fast critical assemblies. Without minimizing the usefulness and accomplishments[1-5] of these more "traditional" source types, modern research will definitely require more intense sources for the future, especially in solid-state physics. This, in brief, was the motive and raison d'être for SINS, the international seminar on intense neutron sources. The seminar, the first of its kind in this new field, was organized by the European-American Nuclear Data Committee and the European-American Committee on Reactor Physics and was sponsored by the US Atomic Energy Commission and the European Nuclear Energy Agency. It was held in Santa Fe, New Mexico on 19–23 Sept. 1966 and was attended by specialists in reactor and accelerator design, nuclear and neutron physics, and solid-state physics.

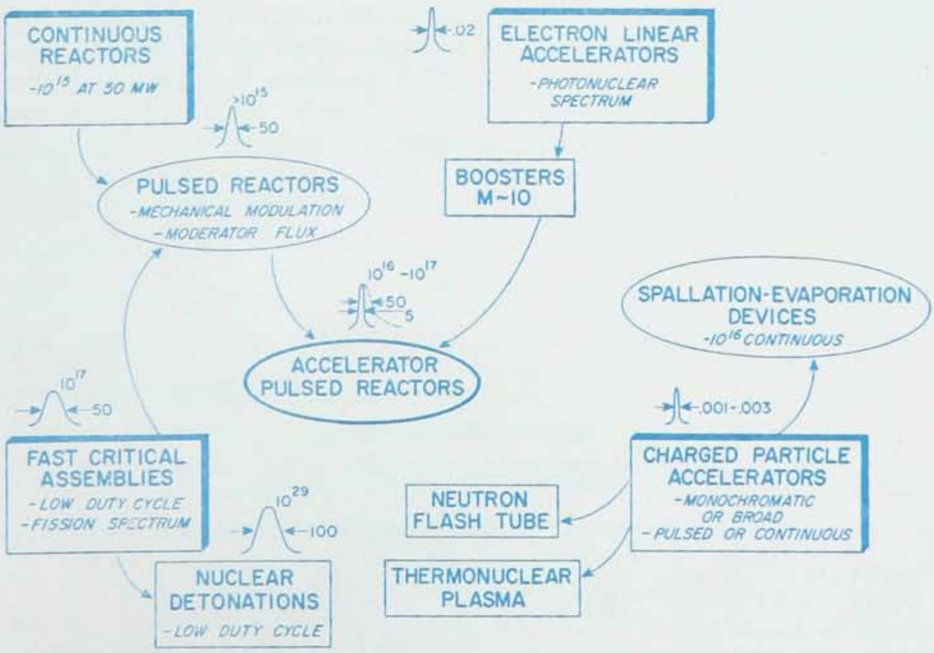
Neutron sources are defined as "intense" if they provide continuous fluxes greater than 10^{15} n/cm^2-sec or its equivalent. In figure 1 the four "traditional" source types are shown in heavy boxes and their general evolution into more recent existing and proposed systems is indicated schematically.

The continuous reactor is now the most common neutron source, and considerable attention was given to it. Not only technological but also economic considerations are fundamental to decisions concerning either proliferation of present high-flux designs and development of still higher-flux systems with correspondingly higher power. The present (MTR, HFBR, HFIR) and proposed (AAAR, UK, Franco-German) high-flux reactors require some \$10–30 million of capital and \$1–5 million in annual operating costs, not including support for experimental programs. The escalating high costs of continuous reactors recently proposed and constructed certainly demand careful consideration of research capability as well as economic and technical merits relative to other competitive systems.

Continuously operating reactors (with suitable monochromators, when desired) are preferable for most nuclear-physics experiments performed with thermal neutrons, but for solid-state studies there are interesting alternatives: the pulsed reactor (mechanically modulated reactivity) and the accelerator-pulsed reactor (accelerator-pulsed injection plus reactivity modulation to shorten the pulses). The notable successes of the IBR pulsed reactor (Dubna, USSR) in many fields of research during the past six years have clearly indicated the great value and potential of such pulsed neutron sources.[1-6] This system, now operating at only 6 kW average power, is also equipped to accommodate an electron injector ("microtron") to obtain 4-microsec pulses at repetition rates up to 50 pulses/sec. In the IBR, reactivity modulation is accomplished with rotating disks containing fissile material.

An interesting pulsed-reactor proposal, SORA, was described by physicists from the EURATOM laboratory at Ispra, Italy. SORA consists of a NaK-cooled pulsed fast reactor with a rapidly rotating beryllium reflector piece that periodically passes near the core, thus producing momentary superprompt critical bursts of neutrons. These neutron bursts are 50 microsec wide and have a repetition rate of 50 pulses/sec. Although the reactor peak power is an impressive 340 MW, the average power in SORA is only 1 MW—an obvious advantage with regard to extended core lifetime. Thus, with a duty cycle of 3×10^{-3}, an equivalent thermal flux more than 10^{15} n/cm^2-sec is readily obtained in hydrogenous moderators as sources for several beam ports. The SORA proposal allows for possible future addition of an electron-accelerator injector that would shorten the pulse from 50 to 5 microsec—a tremendous advantage, since this permits time-of-flight experiments to be extended to higher energies with good resolution.

Accelerators. The high-energy synchrocyclotron (Nevis) and electron linear accelerators are today the best pulsed neutron sources in the energy region from 10 to 500 000 eV and should meet most cross-section requirements in this energy region. In the upper end of this energy region and into the new region, the sector-



TRADITIONAL NEUTRON SOURCES—FIG. 1

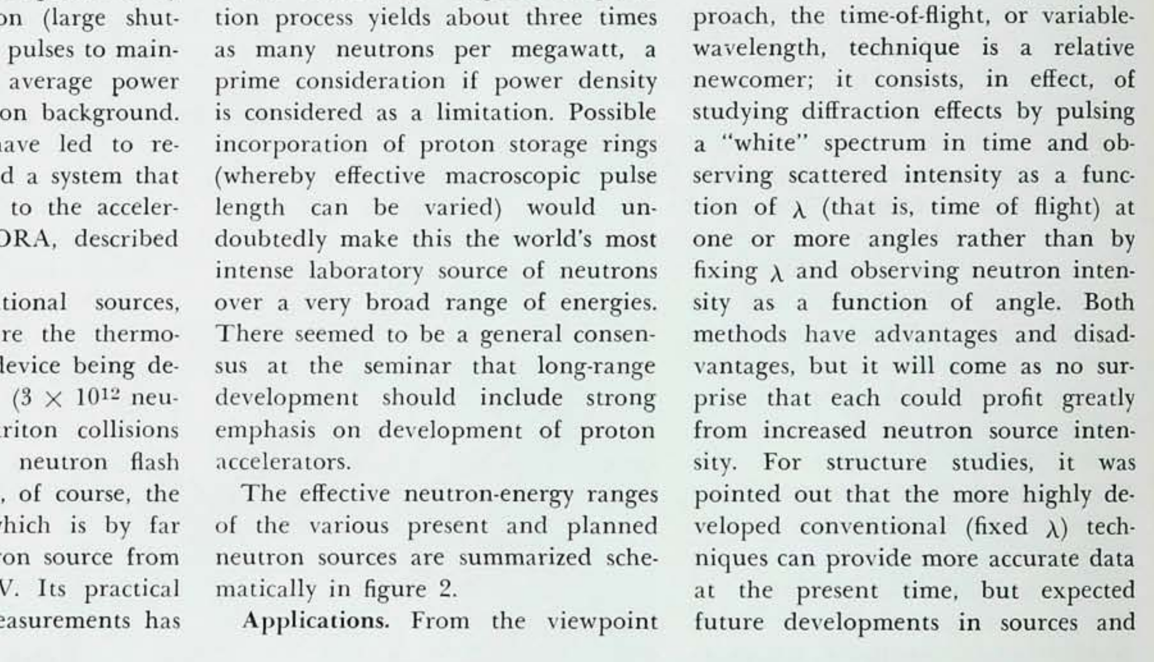
focused cyclotron (Karlsruhe) offers the highest resolution for total cross-section work. The most versatile, and often the most economic, source above about 100 keV is the Van de Graaff accelerator, which can furnish either monochromatic neutrons or broad-band spectra with thick targets and can operate in either the continuous or pulsed mode. Present accelerator-booster combinations (for example, General Atomic, Harwell) provide a factor-of-ten increase in neutron source strength and alter the bremsstrahlung-photofission spectrum to a fission spectrum. New booster designs by General Atomic and Harwell aim at increasing output still further. The desired high peak multiplication during pulses must be compensated by very low multiplication (large shutdown margin) between pulses to maintain the desired low average power and low delayed-neutron background. These requirements have led to reactivity modulation and a system that is indeed very similar to the accelerator-pulsed reactor, SORA, described above (figure 1).

Other less conventional sources, worthy of mention, are the thermonuclear plasma focus device being developed at Los Alamos (3×10^{12} neutrons from deuteron-triton collisions in 0.2 microsec) the neutron flash tube (Karlsruhe)[4], and, of course, the nuclear detonation, which is by far the most intense neutron source from 20 eV to several MeV. Its practical use in cross-section measurements has already been well demonstrated.[1] Three basic limitations were emphasized: only detector current output is available (not individual events and in no case coincidence information), repetition rate is low, and these sources are not generally available.

The most unique and ambitious proposal (cost > \$100 million) for the generation of high continuous thermal flux (10^{16} n/cm^2-sec) is the Chalk River Laboratory's Intense Neutron Generator, ING. This proton linear accelerator will use evaporation and spallation processes from a high-energy (1 GeV), high-current (65-mA) proton beam incident on a liquid lead-bismuth target that must dissipate some 40 MW. Compared to fission sources, the evaporation-spallation process yields about three times as many neutrons per megawatt, a prime consideration if power density is considered as a limitation. Possible incorporation of proton storage rings (whereby effective macroscopic pulse length can be varied) would undoubtedly make this the world's most intense laboratory source of neutrons over a very broad range of energies. There seemed to be a general consensus at the seminar that long-range development should include strong emphasis on development of proton accelerators.

The effective neutron-energy ranges of the various present and planned neutron sources are summarized schematically in figure 2.

Applications. From the viewpoint of experimental applications of intense neutron sources, one dominant theme evident throughout the seminar was the rapidly increasing use of subthermal, thermal and epithermal neutrons as probes for studying both the structure and dynamics of condensed matter. Thermal, or near-thermal, neutrons are naturally suited to this work because their wavelengths are of the same order as interatomic spacings, and energies can be of the same order as characteristic thermal energies of condensed matter. From the extensive background of classical x-ray diffraction technology there has developed a steady-state neutron-beam diffraction technique. In contrast to this "conventional," or fixed wavelength (λ) approach, the time-of-flight, or variable-wavelength, technique is a relative newcomer; it consists, in effect, of studying diffraction effects by pulsing a "white" spectrum in time and observing scattered intensity as a function of λ (that is, time of flight) at one or more angles rather than by fixing λ and observing neutron intensity as a function of angle. Both methods have advantages and disadvantages, but it will come as no surprise that each could profit greatly from increased neutron source intensity. For structure studies, it was pointed out that the more highly developed conventional (fixed λ) techniques can provide more accurate data at the present time, but expected future developments in sources and



EFFECTIVE NEUTRON ENERGY ranges of present and planned neutron sources. —FIG. 2

associated techniques may well tip the scales in favor of the time-of-flight method in many types of experiments. The healthy competitive spirit between advocates of each method was readily apparent at SINS, and one panelist remarked that if nothing else, the rapid improvement and competition from time-of-flight techniques has made the conventional-method people think a lot harder! With the anticipated availability of intense pulsed sources, it will be most interesting to see how these two techniques compare a few years hence. This competition in structure studies will be especially important in the study of biological and organic compounds, a most challenging and important field that is just beginning to receive attention.

Slow neutron scattering. A panel was devoted exclusively to inelastic scattering of thermal or subthermal ("cold") neutrons. This technique is used to determine the dynamics of matter and thus the interatomic forces that underlie dynamics. In this complex field, precision and high resolution are particularly necessary, and presently available sources are barely adequate to study dynamics of even the most basic crystals. Since resolution varies extremely slowly with source strength, at least an order-of-magnitude increase in neutron intensity is needed for these studies. Here again, competition between conventional and time-of-flight techniques is strong, with the present advantage probably going to the more highly developed and more precise conventional techniques. It should be noted that severe engineering problems prevent the use of simple cryogenic moderators with high-flux reactors, but since the heat dissipation is far less, this is more straightforward with pulsed systems.

In the panels devoted to nuclear, neutron and fission physics, the following were cited as fields of research where higher neutron intensities are required:

(a) fundamental neutron-nucleus interactions

(b) studies with polarized neutron beams

(c) capture gamma-ray studies in the thermal and resonance regions

(d) fission studies in individual resonances

(e) investigations of intermediate structure for fast neutron interactions.

In general, it appears that neutron cross sections for reactor design can be adequately measured using presently available and planned sources. Obviously, however, higher-intensity sources at all energies would enable more accurate and rapid measurements to be made and simultaneously would make new fields accessible to measurement, for example, in multiparameter measurements. Needless to say, stronger sources are a necessity in the case of very small or highly radioactive samples.

The development of more intense sources must be accompanied by a commensurate effort to develop better experimental techniques and improved instrumentation in order to take full advantage of available sources. It was repeatedly emphasized that improvements in instrumentation can often bring the equivalent of a many-orders-of-magnitude increase in source intensity—a dramatic case in point is the lithium-drifted germanium detector for high-resolution γ spectroscopy. This does not negate but enhances the need for more intense sources, and also emphasizes the need for a balanced effort in the areas of techniques and source developments.

The seminar provided a stimulating atmosphere and clearly testified to the strong interest and potential in the use of neutrons in many research fields. The enthusiastic support of leading representatives from many laboratories, often in quite different approaches, added considerably to the value of the meeting. The preceding summary can hardly do justice to the 26 manuscripts, four panels and many hours of lively discussions that will be included in the proceedings. The proceedings for SINS will be published by ENEA (38 Blvd. Suchet, Paris 16e) early in 1967. The Los Alamos Scientific Laboratory was the host of the Seminar in Santa Fe and also has the responsibility of editing the proceedings.

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Three meetings on crystals: 1. IUC congress in Moscow

The seventh triennial congress of the International Union of Crystallography drew 3000 crystallographers, 200 from the US, to Moscow last July. 830 contributed papers were classified into 17 subject divisions as follows: theory of structure analysis; theory of diffraction of x rays, neutrons and electrons; symmetry and crystal structure; dynamics of the crystalline state; crystal structures of inorganics; structures of metals and alloys; structures of organics; magnetic structures; coördination compounds; protein structures; breakdown of ideal structures; phase transitions; apparatus and techniques; computing; partly ordered structures; thermal motion; and miscellaneous.

A congress discourse on antisymmetry by A. V. Shubnikov (USSR) was read in the author's absence by a colleague. Five general lectures were interspersed among the other papers. G. N. Ramachandran (U. of