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AN INTENSE PULSED NEUTRON SOURCE FOR ARGONNE NATIONAL LABORATORY*

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Summary

A pulsed neutron source has been designed for materials research in slow neutron scattering and radiation effects. The facility is based in its first phase on the ZGS 500 MeV Injector Booster Accelerator, which will produce 5×10^{12} protons per pulse and be modified for 60 Hz operation. In its second phase a high intensity synchrotron will provide 5×10^{13} protons per pulse at 60 Hz at 600-800 MeV.

Neutrons are produced by spallation in two targets. A ^{238}U target surrounded by three hydrogeneous moderators provides 12 neutron beams for slow neutron spectrometers. Peak thermal neutron fluxes of 1.5×10^{15} and 10^{16} n/cm^2 sec will be available in Phases I and II, respectively. Such pulsed beams will provide new capabilities for neutron scattering research, especially in the use of neutrons with energies up to 1 eV, which is beyond the capacity of the most advanced research reactors.

A separate tungsten target for radiation effects studies provides fast neutrons (around 1 MeV) in 10 irradiation thimbles, with time-average fluxes around 3×10^{13} and 3×10^{14} n/cm^2 sec in Phases I and II, respectively. The associated γ-ray flux is extremely low.

Introduction

Slow neutrons are a powerful probe for studies of condensed matter. These deal with <u>atomic configurations</u> in crystals, liquids, glasses and molecules; and <u>atomic motions</u> in condensed matter, such as in phonons, molecular vibrations and atomic diffusion. Fast neutron radiation damage phenomena (induced by neutrons of energy above 100 KeV) are important in many areas. After a general description of the means for applying a pulsed source to these studies, and a brief overview of current sources of neutrons, the proposed Intense Pulsed Neutron Source will be described.

Since this talk is addressed to high-energy physicists, the energy scale of concern in "thermal" neutron spectroscopy should be made clear--neutrons having mean energy around kT = 0.025 eV are used. This is some 10 decades lower than the energy range best known to those involved in physics with accelerators. Figure 1 illustrates the scale of energies involved.

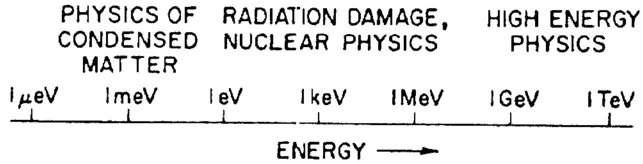

Fig. 1 Scale of energies in materials research, nuclear and high energy physics.

*Based on work performed under the auspices of the USAEC.

Slow Neutron Spectroscopy

Several properties of neutrons make them useful probes for condensed matter study.[1] (1) Since neutrons penetrate most materials to a depth of about a centimeter or so, the bulk of a sample is viewed, in contrast to the case with electrons and x-ray diffraction. This also makes it possible to "see" through rather thick sample containers, such as the walls of cryostats and high-pressure cells.

(2) Because of the point-like nuclear interaction, the nuclear scattering amplitude is constant with respect to momentum transfer. In the case of radiation scattered by the atomic electrons (x-rays, electrons, neutron magnetic scattering), the scattering amplitude decreases for large momentum transfer.

(3) The neutron magnetic moment makes possible magnetic scattering in which neutrons are scattered by fluctuations in local magnetic field intensity. This also enables the production of spin-polarized neutron beams.

(4) The spin-dependent nuclear interaction gives rise also to both coherent and incoherent scattering--in the former, interference effects involving pairs of scatterers is observed; in the latter, the effect of scattering by individual atoms is observed. Since the nuclear scattering varies significantly and irregularly among nuclei, isotopic substitution is frequently used to emphasize or vary the scattering from desired elements.

(5) The relationship between energy, wavelength and velocity makes thermal neutrons convenient for condensed matter studies. Thus for energies of neutrons most prolifically produced by common sources, $E \sim kT \sim 0.025$ eV, the wavelength is $\lambda = 1.8$ Å and the velocity is v = 2200 m/sec. Thus the scattering is sensitive to the atomic ordering in condensed matter, where interatomic distances are on the order of 2 Å. By inelastic scattering, it is possible to determine frequencies of atomic vibrations, wherein the energy transferred to excite one quantum is typically ~ 0.001 to 0.1 eV, with only modest fractional energy resolution, $\Delta E/E \sim 0.01$. Neutron speeds are such that the time of flight across a typical flight path several meters long is several milliseconds. Interest actually extends to use of neutrons up to an energy of 1 eV or more.

Radiation Damage

The effects of fast neutron ($E \gtrsim 100$ KeV) radiation damage in materials is of concern in both fission and fusion reactors. Changes in material properties result from irradiation, and must be understood to make possible efficient design; indeed, the feasibility of some fusion reactor concepts rests in part on radiation resistance of first-wall materials. Fast reactors and low energy accelerators (producing 14 MeV neutrons through the D-T reaction) are now used in neutron radiation damage studies. In the case of the reactor irradiation facilities, such as EBR-II (ANL's Experimental Breeder Reactor) and FFTF (the Fast Flux Test Facility now under construction) fluxes of order

10^{14} n_f/cm^2-sec are available, but are accompanied by high fluxes of gamma radiation, and in an environment otherwise difficult to control. Since for many measurements, the temperature of specimens and instruments must be carefully controlled (sometimes at cryogenic temperatures) gamma ray heating is a difficult problem. In a properly designed spallation neutron source, the ratio of gamma flux to neutron flux can be much reduced (of order tenfold) below that in fission reactor test facilities. This is an important factor in making possible a large class of radiation damage measurements.

Existing Neutron Sources

It is useful to consider existing neutron sources, what these provide in terms of neutron flux and spectrum, their costs, limitations, and prospects for enhanced performance. Most commonly, the sources of neutrons for condensed matter research have been high-flux reactors.[2] These provide a steady thermal-neutron flux at the point from which neutron beams are extracted, as shown in Table I.

Table I

Thermal Neutron Fluxes at High Flux Reactors

Reactor	Location	Thermal Neutron Flux ϕ_{Th}, neutrons/cm^2-sec	Date
HFR	ILL-Grenoble	1.5×10^{15}	1972
HFIR	Oak Ridge	1.0×10^{15}	1967
HFBR	Brookhaven	7.0×10^{14}	1965

These reactors represent the most advanced existing. Brugger[3] has examined the development of neutron sources and their applications.

There is a prime need for neutron sources with higher fluxes than those now existing to provide facilities for experiments involving very small or highly absorbing samples, processes with low cross sections or measurements at ultra-high resolution, that are not feasible with present facilities. There is also a need for much higher epithermal neutron (E_n = 0.1 to 5 eV) fluxes than are now available. Unfortunately, the available thermal neutron flux from reactors has recently leveled off at about 10^{15} n_{Th}/cm^2sec due to several factors:

(a) Heat fluxes between fuel and coolant are near engineering limits. (b) Reactor power is 50 to 100 MW, implying fuel costs of about \$5 M per year. Technology is taxed to provide higher neutron flux at feasible operating cost. (c) The construction cost to provide another such reactor is now anticipated to be at least \$100 M (HFR at Grenoble is reported to have cost ~ \$65 M).

Thus the prospect for high flux reactors providing significantly higher neutron fluxes is not great, although novel departures[4] from current technology may make advances possible in steady state reactors. In order to provide thermal neutron fluxes of 10^{16} n_{Th}/cm^2 sec and higher fluxes of epithermal fluxes, new types of neutron source will probably be required.

New Sources of Neutrons

Since conventional steady state reactors have reached a stage of development where it is difficult to improve their performance, we are looking toward a new generation of sources, in which many of the limitations on reactor development are relieved. These are pulsed sources. To use a steady-state reactor in spectroscopy, some form of energy analysis is needed, in which typically 99% of the neutrons exiting from a beam port are thrown away. A pulsed source operates only "when needed"--the beam is already pulsed, ready for energy analysis by time-of-flight. Since times of flight are of the order of milliseconds, pulses must be of the order of tens of microseconds length to provide appropriate energy resolution. The pulsed mode of operation much relieves the heat transfer requirements, enabling fluxes which are momentarily higher than in reactors. Time-of-flight methods of neutron spectroscopy have proved their worth at steady state reactors, although for certain classes of measurements, such as phonon dispersion curves, steady-state methods are more common.

Table II shows features of several neutron producing mechanisms, based on charged-particle reactions.

Table II

Neutron Production Processes

Process	Energy Deposited	Neutrons Produced
Fission	~ 200 MeV/neutron	1 per fission
$(\bar{e},\gamma),(\gamma,n)$	~ 3000 MeV/neutron	10^{-2} per electron
Spallation	~ 50 MeV/neutron	(800 MeV protons on U^{238}) 30 n/proton
D,T fusion	~ 17 MeV/neutron	1 neutron/fusion

It can be seen that spallation is both prolific and fairly efficient, requiring relatively little energy deposition in the source.

Neutron production varies as a function of proton energy and target material, as shown in Fig. 2.[5] The yield increases rather linearly with incident proton energy, above about 200 MeV, and increases with increasing target mass number. In nuclei having a low fission threshold energy such as U^{238}, a significant contribution comes from fissions. Thus protons of several hundred MeV and heavy-element targets, are desirable. Proton energies greater than about 1 GeV are not advantageous because of their longer range and consequent extended neutron source distribution. While the neutron yield from solid U^{238} targets has been determined to be 30 n/p at 800 MeV,[6] in a practical source, some reduction on this figure is anticipated for engineering reasons.

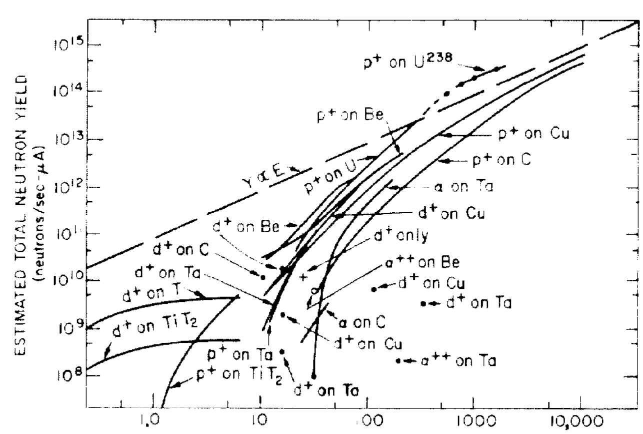

Fig. 2 Neutron yields in charged particle reactions.[5]

Figure 3 shows the energy spectrum emerging from spallation neutron sources.[7] About 90% of the neutrons emerge in an evaporation spectrum (similar to that of fission neutrons) of average energy ~ 3 MeV. About 10% result from the nuclear cascade, in a distribution extending upward to the incident proton energy. These high energy neutrons make necessary a very heavy shield, as much as 5 meters thick.

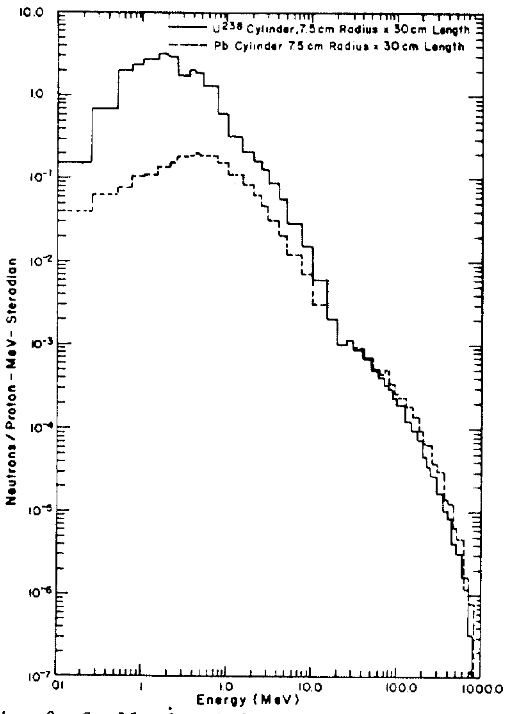

Fig. 3 Spallation-induced neutron spectrum.[7]

Besides accelerator-based pulsed neutron sources repetitively-pulsed fast reactors are potentially very useful. These operate either by being periodically forced supercritical by short reactivity insertion, or operated slightly subcritical as fission multipliers of neutrons generated by an accelerator.

Table III compares several of the most intense pulsed neutron sources. ORELA is the Oak Ridge Electron Linear Accelerator, using (γ,n) production. The Nevis Synchrocyclotron, IPNS (the facility proposed here for construction at ANL) and WNR (receiving 1% of the LAMPF beam at Los Alamos), are spallation sources. ORELA and Nevis are devised for nuclear physics research. WNR is devised for radiation effects research, and ZING for condensed matter research, for which WNR is also to be used. SORA is the proposed Euratom pulsed reactor fast neutron source which was to have been built for condensed matter research; IBR-II is the Soviet pulsed fast reactor, under construction at Dubna. (In the past decade, the Soviets have gathered experience, operating a series of pulsed fast reactors, IBR-I, IBR-30, and soon IBR-II.)

Table III

Neutron Production at Several Intense Neutron Sources

Faculty	Average Neutron Production Rate	Frequency	Pulse Width of Source
WNR (1% of LAMPF)	10^{15} n/sec	120 hz	5 μsec
Improved Nevis Synchro-cyclotron	2×10^{15}	60	2 nsec-1 μsec
ORELA	10^{14}	to 1000	2 nsec-1 μsec
IPNS	9×10^{16}	60	150 nsec
SORA (1 MW)	3×10^{16}	50	75 μsec
IBR-II (4 MW)	1.2×10^{17}	5 to 50	50 μsec

For reasons that the pulse width is narrower, that there are fewer delayed neutrons, that the required proton accelerator technology is well developed, and that the proton spallation source has advantages over fission and photoproduction for radiation damage studies, the spallation mechanism has been chosen as the basis for Argonne's proposed Intense Pulsed Neutron Source.

In order to use a pulsed source for slow neutron spectroscopy, a moderator is erected close by the source as in Fig. 4a. On the order of 1% of the neutrons which collide initially in the moderator, emerge as a rather isotropic flux of thermal neutrons. Hydrogeneous moderators, such as polyethylene, are used to obtain shortest possible pulses of highest intensity.

We find from several measurements[8] that about 10^{12} fast neutrons/cm^2 pulse are required to produce the design goal represented by a peak thermal neutron flux of 10^{16} n/cm^2-sec. This is made possible by use of a novel, Beryllium reflector around the moderator, which somewhat broadens the pulse at higher energies, although this can be controlled. Three moderators will be provided, optimized for different applications, and providing twelve slow neutron beams.

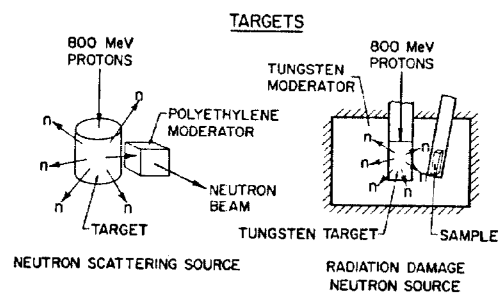

Fig. 4 Schematic diagram of source configurations for (a) neutron scattering and (b) radiation effect studies.

For radiation damage measurements, a tungsten target has been chosen. Irradiation thimbles are arranged in a tungsten reflector, as in Fig. 4b. Tungsten is chosen for the reasons that few gamma rays are associated with the neutron produced, and because it does not rapidly slow down neutrons.

The Accelerator Systems

The facility will become operational in two phases. In its first phase, the ZGS 500 MeV booster accelerator (Booster II) will provide 5×10^{12} protons/pulse at 60 Hz. We have referred to phase I as the ZING Project--ZGS Intense Pulsed Neutron Generator. In its second phase, a new, independent high intensity synchrotron (HIS) will be constructed, to provide 5×10^{13} protons/pulse at 60 Hz, at an energy in the range of 600-800 MeV. We refer to phase II as the IPNS Project--Intense Pulsed Neutron Source.

To provide the design goal of 10^{15} n_{Th}/cm^2-sec, a U^{238} spallation source will be used. Sodium or Pb-Bi eutectic will be used as coolant--the heat dissipation requirements are similar to those in fast reactors. Using a practical target design, we have found that 5×10^{13} protons per pulse, at 600-800 MeV, are required from the synchrotron. The synchrotron design has been worked out by T. K. Khoe and M. Kimura[9] and others--the basic design is now being refined and cost estimates determined.

Basically, the system consists of an H^- ion source, and a linac injector with stripping injection to the synchrotron. Injection at 70 MeV places not too great demands on the H^- source current and on the stripping foil, and allows the required charge of 5×10^{13} protons/pulse to be captured within the calculated space charge limit without requiring an unduly large vacuum chamber.

Provisional basic parameters for the high intensity synchrotron are given in Table IV.

Table IV

Provisional Accelerator Parameters

a.	Pre-accelerator-Cockcroft-Walton	
	H^- current	$\geq$ 25 mA (H^-)
b.	Linear accelerator	
	Energy	70 MeV
	Pulse rate	60 Hz
	Duty factor	5.5%
	Beam current	15 mA (H^-)
c.	Proton synchrotron	
	Maximum kinetic energy	800 MeV
	Intensity	5×10^{13} protons/pulse
	Repetition	60 Hz
	Injection energy	70 MeV
	Number of turns Injected	700
	Average radius	20.37 m
	Number of straight sections	16
	Structure of period	OMOFODOMO
	Bending magnet Peak Field	6 kG

Various instabilities have been examined and found not to limit the accelerator. The required H^- source current, 15 ma, with 70 MeV injection, is about 3 times the current injected into ZGS Booster I. This extrapolation seems to be within reach of the present state of H^- source technology. The stripper foil installed on the periphery of a rotating disk, will be required to withstand approximately 2.5×10^{15} proton transversals per pulse, or 1.5×10^{17} transversals per second. Some development work is anticipated directed towards a better stripping foil material than the 3500 Å polyparaxylylene foils now used in Booster I (50 MeV injection). Carbon foils, such as are now used in electron microscopy, or metal foils, which would have to be somewhat thinner than are now available, appear able to be developed.

Conclusion

The Intense Pulsed Neutron Source will provide unique, new capabilities for neutron scattering research using pulsed thermal and epithermal neutrons, and for radiation damage studies.

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