CONF-850110--2

DE85 006185

NEW SPALLATION NEUTRON SOURCES, THEIR PERFORMANCE AND APPLICATIONS

ABSTRACT

Pulsed spallation sources now operating in the world are at the KEK Laboratory in Japan (the KENS source), at Los Alamos National Laboratory (WNR) and at Argonne National Laboratory (IPNS), both the latter being in the U.S. The Intense Pulsed Neutron Source (IPNS) is currently the world's most intense source with a peak neutron flux of 4×10^{14} n $cm^{-2}s^{-1}$ at a repetition rate of 30 Hz, and globally producing $\sim 1.5 \times 10^{15}$ n/sec.

Present pulsed sources are still relatively weak compared to their potential. In 1985 the Rutherford Spallation Neutron Source will come on line, and eventually be ~ 30 more intense than the present IPNS. Later, in 1986 the WNR/PSR option at Los Alamos will make that facility of comparable intensity, while a subcritical fission "booster" at IPNS will keep IPNS competitive.

These new sources will expand the applications of pulsed neutrons but are still based on accelerators built for other scientific purposes, usually nuclear or high-energy physics. Accelerator physicists are now designing machines expressly for spallation neutron research, and the proton currents attainable appear in the milliamps. (IPNS now runs at 0.5 GeV and 14 μA). Such design teams are at the KFA Laboratory Julich, Argonne National Laboratory and KEK. Characteristics, particularly the different time structure of the pulses, of these new sources will be discussed. Such machines will be expensive and require national, if not international, collaboration across a wide spectrum of scientific disciplines. The new opportunities for neutron research will, of course, be dramatic with these new sources.

I. Introduction

Chadwick first produced neutrons by (α,n) interactions of alpha particles from decay of natural radioactive elements, and neutron sources of this kind were the basis of the earliest neutron physics research. Nuclear fission reactors were the next generation of sources, which have become the standard for slow neutron research. Meanwhile, electron accelerators which produce neutrons through bremsstrahlung-photoneutron reactions, and mostly developed as pulsed sources for fast neutron research, have been applied productively for slow neutron research at a number of installations. The most intense electron machine used in this way is HELIOS at Harwell, which produces 10^{14} n/sec globally, and dissipates 45

kW of beam power. However, the bremsstrahlung photoneutron production mechanism is much less efficient than "spallation" induced by ~ 1 GeV protons or other hadrons. Since proton accelerators are becoming available which provide the needed intensity, the focus of future machines will be on proton accelerators and the production of neutrons by spallation. Figure 1 shows a conceptual spallation source.

The first source using a proton accelerator and specifically equipped for neutron scattering from condensed matter systems was a prototype built at Argonne National Laboratory in 1974. Called ZING-P, it had an energy of 200 MeV and a time-averaged current of 0.1 μA. The ASPUN or SNQ projects now advanced by Argonne and KFA, Julich, respectively, have energies of ~ 1600 MeV and projected currents of 4000 μA. These represent an increase in neutron intensity from the early ZING-P source at ANL by a factor of nearly 10^6.

We show in Figure 2 the progress of effective neutron flux from proton spallation sources (normalized to the Intense Pulsed Neutron Source, IPNS, at Argonne as of January 1985) over the period from ZING-P to the (hopefully) operating SNQ and ASPUN type sources, projected for the mid to late 1990's. Figure 2 shows a steady logarithmic increase of a factor of 10 about every 5 years. When one considers the almost nil progress in reactor fluxes over this same period, remembering that the world's highest flux reactor HFIR at Oak Ridge was commissioned in 1966, Figure 2 is an impressive testimony to the development of neutron fluxes from spallation sources. Details of proton spallation sources are given in Table I. To obtain Figure 2 we have simply multiplied the energy and current of the proton sources. This gives one measure of usefulness, but is not by itself enough to assure a steady increase in neutron intensity for scattering experiments. Once the protons are produced they must be "converted" into neutrons; this is done through their interaction in targets of heavy nuclei (lead, tungsten, depleted or enriched uranium). The resulting neutron energy spectrum is far too energetic to be of use in neutron scattering experiments on condensed matter and moderators are required to slow down the neutrons.

The production of neutrons and their preparation for scattering experiments is the subject of this short paper. Areas of special interest are the use of different moderators to tailor the neutron beam for particular experiments (e.g. the production of long wavelength or cold neutrons), and the influence of pulse length from the initial proton pulse, as well as from the various moderators.

We shall conclude with a few examples of scientific areas that will be accessible with these new sources. Predicting ten years ahead is, of course, almost certain to be wrong, especially in such a fast moving field.

II. Accelerators

To produce submicrosecond pulse proton beams the common method is with a synchrotron machine. However, the most advanced rapid cycling synchrotron designs presently completed have a goal of accelerating ~ 6 x 10^{13} protons per pulse (ppp). IPNS runs at 3 x 10^{12} ppp and the Rutherford at full power of 200 μA and 800 MeV will have 2.5 x 10^{13} ppp. Scientists at KEK, Japan, have discussed a synchrotron (GEMINI) that could possibly deliver 500 μA at 800 MeV. This machine would have a space-charge limit of 7.2 x 10^{13} protons and clearly be at the forefront of accelerator technology. To obtain higher currents one must either use linacs, in which case very large currents are possible, or another type of accelerator technology such as induction linacs or FFAG's. The most intense linac operating today is the LAMPF (Los Alamos Meson Proton Factory) which recently reached its design current of 1000 μA. The SNQ project is aiming for 4000 μA so is stretching the limits of linac technology. Such linacs have inevitably a relatively long pulse of protons. The macropulse length at LAMPF is now 750 μs, and would be 250 μs long at the SNQ facility. We will return to this point later in conjunction with moderators, but note here that pulse lengths of greater than ~ 1 μs do not allow the performance high resolution neutron spectroscopy in the epithermal energy range. These long proton pulse lengths may be compressed in a storage ring that "compacts" the proton beam without accelerating it. At Los Alamos the proton storage ring, PSR, will accept one 750 μsec macropulse containing 5 x 10^{13} protons from LAMPF (frequency 120 Hz) and compress it into a pulse of 0.27 μs length. This will occur at a 12 Hz rate. A compressor ring, IKOR, has also been considered by the Julich design team for an advanced stage of the SNQ project. At Argonne, on the other hand, a different accelerator concept, the so-called Fixed-Field Alternating Gradient (FFAG) design has been introduced by R. L. Kustom and his collaborators[1]. In this design, which leads to the advanced machine called ASPUN, the proton orbits increase in radius as the energy increases. The magnetic field also increases with radius to provide increased bending strength. However, these fields are fixed in time unlike a synchrotron. The dc magnetic fields allow more efficient injection and capture of beam and more effective use of the rf acceleration system. The design goals for the current and beam power in the FFAG designs exceed the conventional rapid cycling synchrotrons by at least an order of magnitude. The FFAG synchrotron also allows the opportunity to internally stack beams, thus having an extracted beam repetition rate different from the injected beam repetition rate leading to higher individual extracted pulse amplitudes. The prospective gain over linacs + compressor ring assemblies is so important that further work should continue on the FFAG.

We should stress here the crucial importance of containing beam losses at these advanced high current accelerator systems. Radiation losses in the accelerator cause damage to components and induce activity that inhibits maintenance and repair. Although remote handling capabilities will have to be used at any of the large new facilities, the control of radiation losses will remain a primary goal. Indeed it may well be the limiting factor in trying to attain currents as high as 4000 μA. At these power levels the beam circulating in the machine represents a few hundred Amps so that these problems are likely to be most serious.

III. Targets

Table I shows that the chosen target for medium intensity sources, as those operating in this decade, is depleted uranium. High-Z, high density targets are preferable because the neutron producing reactions are then most favorable, while the short range of the protons minimizes the size of the source. At moderate intensities the neutron intensity can be increased by using fissile material in a "booster" target. The gain factor is approximately $G \approx 1/(1-k)$, where k is the prompt-neutron multiplication factor. A booster with a gain factor of x10 was operated at the original Harwell Linac and is operating on the new accelerator, HELIOS for nuclear physics research. Plans are now fairly far advanced for a booster target for IPNS that will represent the first such target at a proton source when it is installed in 1986. The IPNS booster target should give a factor of ~3 in neutron beam intensity. Boosters may also be installed later at SNS and the WNR facility, although the power levels at both those facilities may be too high to allow correspondingly high gains. Because fission requires the dissipation of ~ 190 MeV per useful neutron produced, as opposed to ~ 50 MeV for the true spallation process, and boosters inescapably broaden the primary pulse and increase the number of delayed neutrons between pulses, their application is limited.

At higher power densities the heat deposition in stationary uranium is too great for any prospective cooling system. The SNQ project has devised a rotating water cooled target. This target consists of 5916 cylindrical capsules of U (earlier versions specified W) each 2.4 cm diameter and 10 cm height, mounted on a wheel of 2.5 m diameter rotating at 0.5 Hz. The very considerable cooling required means that at these power densities the efficiency of neutron production decreases somewhat as compared to the more modest sources.

IV. Moderators

Although accelerators are expensive and complex, and targets are technically challenging, the moderators and reflectors of pulsed sources might be said to represent the most arcane elements. Moderators could justifiably be called the "insertion devices" of pulsed neutron sources, for, similarly to the case of wigglers and undulators in synchrotron-light sources, they shift the radiation spectrum and tailor the time distribution differently, to suit different applications. It is obvious, that moderators and their associated reflectors must be placed close to the neutron source. Their function is to slow down the energetic primary (~ 1 MeV) neutrons to energies of use for solid-state studies. Generally we require the highest possible neutron fluxes, but insist on the narrowest pulse widths, demands which are contradictory. In short-pulse sources, dense hydrogenous moderators are preferable because they provide the shortest pulses.

Figure 3 illustrates the general features of the shape of the moderated pulse. The intensity (normalized to 1.0 at the peak of the pulse) is plotted vs. energy and a length which represents the normalized time for each energy (neutron speed x time after the source pulse). For high energies, in the "slowing-down" range, the normalized pulse shape is invariant with energy. For energies near kT, the exponential decay of thermalized neutrons produces a pronounced bulge, which remains roughly constant in absolute time, but becomes progressively narrower in normalized time, for energies below kT. We have two, orthogonally-placed handles on the time distribution through which we can optimize the response. Heterogeneous poisoning (subdividing the moderator with sheet(s) of absorber material) narrows the bulge by reducing the thermal neutron decay time. Cooling reduces kT, and moves the bulge to lower energy, thus extending the range of invariant pulse shapes to lower energy.

The time-averaged spectra for all moderators have two components: a thermal-neutron part dominant at low energies and a "slowing-down" (epithermal) part dominant at energies above about 5 kT. There are many tricks available to enhance moderator performance. Recently,[2] moderators with grooved surfaces have been developed, to provide higher fluxes, at some expense of pulse width. Different materials with different moderating characteristics related to the nature of molecular motions provide different responses. Their choices, however, are intimately tied up with questions of heat transport and radiation damage; thus for example solid methane, wonderful from the point of view of providing intense, short pulses at low energy, is difficult to incorporate in high-intensity sources. Moderator design and optimization is a field which is still rapidly developing.

Cold neutrons. Here there is no difficulty for experiments such as small angle scattering in which the time-averaged flux is the important factor. Using the equation,

$$\lambda(\text{Å}) = 0.3955\ t(\mu s)/L(cm)$$

and assuming L = 10 m, we find that a 5Å takes 12 ms to travel the distance. Thus if the timing uncertainty is ~ 100 μs this corresponds to only ~ 1% in $\Delta\lambda/\lambda$, as compared with the much greater $\Delta\lambda/\lambda$ used at reactor SANS instruments. Source pulse widths do not play a central role in cold neutron research, so that the SNQ source, for example, has proposed using a cold D_2 moderator and a series of guide tubes for slow neutron experiments. Absorption of neutrons in D_2 is, of course, small, and losses occur due to the finite size of the moderator, absorption in structural material, and neutrons escaping through the beam holes, so that a large moderator is required. The difficulty with cold neutrons is that frame overlap -in which neutrons from pulse n + 1 catch up those from pulse n with the long flight paths necessary for good resolution does not allow use of the full neutron bandwidth at repetition rates greater than ~ 40 Hz. To avoid these limitations we have recently pointed out that a pulsed source with two targets, one maximized for cold neutrons with, say, a cold D_2 source and ambient D_2O reflector, and operating at a repetition rate of 10 Hz, and the other using a hydrogenous moderator with a repetition rate of 40 Hz, would introduce a new flexibility into neutron research.

Thermal and Epithermal Neutrons. Moderators for these will certainly be hydrogenous, and it is here that the full technology of moderators, reflectors and poisons needs to be further explored. A general overview of these has been given recently[3]. Further progress has been made by the group at KENS who constructed a grooved moderator, which yielded a substantial increase in the neutron flux.

V. Pulse Lengths

Two general classes of accelerators and corresponding moderators are contemplated for pulsed sources. The "short-pulse" variety is based on accelerators which produce sub-microsecond pulses and incorporate rapidly-responding, small, dense, strongly-decoupled hydrogenous moderators which provide tailored, short [($\Delta t \sim$ (10-20 μsec/Å) x λ(Å)] pulses of moderated neutrons. The "quasi-steady" type is based on accelerators which produce several-hundred microsecond-long pulses, and incorporate large, weak ~~un~~decoupled, D_2O or hydrogenous moderators which provide highly-efficient moderation and long-time storage of thermal neutrons (~ 500 μsec, independent of energy.)

The moderators in quasi-steady sources are slower in response than those in short-pulse sources, roughly matching the source pulse length and capitalizing on the fact that these are more efficient in converting primary source neutrons to slow neutron beams, than rapidly-responding moderators. Time-average beam intensities of thermal neutrons per primary source neutron are thus greater in the case of the quasi-steady sources than in the short-pulse sources and their spectra are more-nearly thermally equilibrated (appearing like reactor spectra) than those from short-pulse moderators. One may, of course, provide a slow moderator in a short-pulse source, with this same motive, for applications in which pulse length is not important and intensity is the governing consideration. The short-pulse sources provide much higher ratios of epithermal to thermal neutrons than the quasi-steady sources.

These are very significant differences in source pulse structure; either can be used highly effectively, but the mix of applications (which we can now only speculate about) will certainly be different for the two. Very general arguments illustrating why short pulsed sources are desirable in spite of their typically-lower efficiency (in the sense of converting fast to slow neutrons) have been presented some time ago by Michaudon[4] and recently more precisely by Windsor[5]. The thread of the argument is as follows: in the fast pulsed sources, the beam is already prepared for wavelength sorting (by time-of-flight). When one compares the flux on sample in a beam from a fast pulsed source, prepared with the same resolution with that in a steady or quasi-steady source, prepared by some monochromating device, a "figure-of-merit" emerges which is proportional to the ratio of time-average flux from the moderator, to the <u>square</u> of the pulse length. This is the fundamental basis for choosing less-efficient, short-pulse moderators over more-efficient, slow moderators.

Generally these different pulse structures lead to different philosophies of instrument design and different applications. (An exception is the important case of conventional small-angle scattering discussed above, where wavelength resolution requirements are relatively lax, and long-wavelength neutrons, for which both types of source provide pulses of similar length, are usually used; for this purpose, both types lead to similar straightforward time-of-flight instrumentation.) For applications other than small-angle scattering, resolution requirements are much more severe; here the differences emerge.

In the quasi-steady sources, as in steady sources, monochromating devices such as crystals or choppers always define the incident-neutron energy. Although no direct use is made of the pulse, significant advantages accrue due to pulsing. In a chopper spectrometer, for example, (two choppers are needed in the quasi-steady source) the choppers can be phased to open so as to admit neutrons when the source flux is at its maximum, thus capitalizing on the duty cycle improvement in peak flux (but not capitalizing on the inverse <u>square</u> of the pulse length.) In crystal-monochromated beams, the counting can be arranged to take place while the source is "off" and the background is lower than average. In other applications, the fact that the source pulse is of considerable duration makes it possible to perform measurements at several distinct incident wavelengths all in the same setup. Instruments of these types rest on adaptations of the very-highly-evolved steady-source techniques.

In the short-pulse source, at least one aspect of wavelength sorting is always done based on the definition of neutron flight times by the source pulse, whose length determines the resolution. Thus in this case there is a more-or-less strict requirement on having short pulses, stringently dependent upon the demands of the particular type of spectroscopy. The situation at higher neutron energies is easily appreciated. There, above say E_0 = 300 meV, conventional monochromating crystals lose efficiency for most purposes, guide tubes are ineffective, and chopper design is constrained; use of the already-prepared source pulse provides one step of monochromation which is 100% efficient. The short-pulse sources inherently provide more epithermal neutrons in relation to thermals, than the quasi-steady sources; this, combined with the progressive shortening of pulses with decreasing wavelength, makes the short-pulsed sources more effective in the higher-energy range than the quasi-steady ones. Further, and for all wavelengths, time-of-flight instruments usually (provided the pulsing rate is low enough to avoid frame overlap) enable measurements over a greater range of measured variable (energy transfer and/or wavevector change).

VI. Scientific Applications

We cannot hope to cover even a fraction of the scientific applications of pulsed sources in the short survey presented here; nevertheless it is worthwhile speculating on a few experimental methods that may well become routine and illustrating them with scientific examples.

High-Pressure Powder Diffraction. The special advantages of time-of-flight energy-dispersive powder diffraction are that all the information can be extracted through a single window in the pressure cell - thus allowing higher pressures to be reached.

High pressure neutron diffraction implies a small accessible sample volume because of the limitations of the materials used to enclose samples under pressure. The range of devices currently in use extends from hollow-cylinder, gas or liquid cells which enclose large volumes of several cm^3 at pressures up to about 10 kbar, to the recently popularized diamond anvil cells which achieve pressures in the Mbar range for micron-size samples. Each order of magnitude increase in pressure is accompanied by a quantum reduction in sample size. Neutron diffraction studies are currently flux limited and can be done for 1 cm^3 samples in gas or liquid cells to 10 kbar or 0.1 cm^3 samples in supported piston-in-cylinder cells which can reach about 40 kbar. The next order of magnitude increase in neutron flux will allow the use of multiple anvil (cubic) presses which can achieve 100 kbar for effective sample volumes (accessible to neutrons) of about 0.01 cm^3. With still higher fluxes, opposed anvil designs similar to diamond anvil cells may extend this range to a few hundred kbar.

Synchrotron studies with diamond anvils can extend phase diagram studies up to the Mbar range. However, the absorption in the cell, preferred orientation with micron size samples, and other systematic problems prevent accurate intensity measurements and the studies are confined to determination of diffraction line positions., Neutrons, with low absorption and a well-characterized spectral function, can determine these intensities with samples of the order of 10 mm^3 and so determine atomic positions. This, of course, is in addition of the usual advantage enjoyed by neutrons of being able to "see" light atoms in the presence of heavy ones. This advantage is of particular importance for geophysical materials.

Science of interest at high pressure includes both structural and electronically-driven phase transitions, high-pressure reaction products, geophysical studies and the correlation of structural changes with other physical properties which vary with pressure. An example in the last category is the sharp pressure dependence of the superconducting transition temperature versus pressure for many high-T_C, ternary superconductors. High pressure diffraction studies could help establish the relationship between structure and superconductivity in these materials. In these and many other systems the range of novel behavior that can be observed is far greater as a function of pressure than of temperature.

Small-Q Magnetic Inelastic Scattering. A particularly challenging problem in neutron scattering from magnetic materials is to obtain data at small Q and relatively large energy transfers $\hbar\omega$. Pulsed sources are particularly good at probing the area of S(Q,E) space given by the coordinates $2 < Q < 5$ $Å^{-1}$, $50 \leq E \leq 500$ meV, because of the abundance of epithermal neutrons. Results from IPNS have already demonstrated[6,7] that this region of the (Q,E) diagram is rich in science. An area of potentially equal interest is that with $0.001 \leq Q \leq 1$ $Å^{-1}$ and $5 \leq E \leq 20$ meV. The low end of this Q and energy range can be reached with instruments at cold sources (either at reactors or pulsed sources) with incoming or analyzed beams of energy ~ 4 meV (reflection from graphite) and usually have excellent energy resolution. However, for larger energy transfers in down scattering (i.e. the neutrons losing energy to the sample) we need the analog of a small-angle machine with inelastic scattering. Such a machine has been considered both by Crawford et al.[8] and at the Shelter Island Workshop[9] and is sketched briefly in Fig. 4. For example, with L_1 = 20 m, L_2 = 1 m, L_3 = 20 m, E_1 = 1000 meV, ΔE = 40 meV, Q = 0.5 $Å^{-1}$, the energy resolution is 0.005 E_1 = 5 meV and the Q resolution is 10%. The scattering angle ϕ = 0.61°, is displaced from the straight through beam by ~ 22 cm. This design requires choppers rotating at 600 Hz (the present magnetic choppers bearing can achieve ~ 1000 Hz) and efficient ways to detect eV neutrons. Presumably scintillation detectors would be best.

What kind of scientific problems could one examine with such a capability? There are two areas of particular interest. The first is to examine the dynamic response function of the conduction electron states in metals, especially in intermediate valence and actinide systems. Such states are extended in real space so have a form factor that drops to zero by 1 $Å^{-1}$. The assumption is usually made that the response of the conduction electron states follows that of the f electrons in intermediate valence systems, but this is by no means obvious and the comparison of, for example, NMR and conventional neutron spectroscopy shows that such a correlation is not always present. A second type of scientific problem occurs in amorphous or glassy systems. These, of course, have no repeat distance in real space, nevertheless long-wavelength excitation modes (both atomic and magnetic in origin) exist at small wavevector. Such excitations occur at Q $\lesssim$ 1.5 $Å^{-1}$, which is characteristically the location of the first peak in the static structure factor, and have been predicted to extend in energy up to ~ 50 meV.

Also shown in Fig. 4 are polarization and analysis capabilities, that will often be essential in separating out the true magnetic contributions. The fact that we are discussing small-angle scattering with restricted beam geometry means that the white-beam polarizers presently developed, which rely on low-temperature nuclear polarization or differential absorption, can be used efficiently.

Momentum Distributions. At wave vectors sufficiently large for the impulse approximation to be valid, measurements of the scattering function S(Q,E) give information about the momentum distribution of scattering nuclei, n(p). In ^{3}He at temperatures well below T_F (1.6° K), n(p) is expected to have a discontinuity at the Fermi surface, p = p_F, (see insert Fig. 5). This is reflected by kinks in S(Q,E) at $E = \hbar Q^2/2M \pm Qp_F/M$ (see insert Fig. 5). Observation of these by neutron scattering would provide a direct observation of the Fermi surface in liquid ^{3}He, analogous to measurements made in metals with electron Compton scattering.

The requirement of large Q means that measurements of this kind are especially suited to pulsed-source instruments been considered both by Crawford et al.[8] and at the Shelter Island Workshop[9] and is sketched briefly in Fig. 4. For example, with L_1 = 20 m, L_2 = 1 m, L_3 = 20 m, E_1 = 1000 meV, ΔE = 40 meV, Q = 0.5 $Å^{-1}$, the energy resolution is 0.005 E_1 = 5 meV and the Q resolution is 10%. The scattering angle ϕ = 0.61°, is displaced from the straight through beam by ~ 22 cm. This design requires choppers rotating at 600 Hz (the present magnetic choppers bearing can achieve ~ 1000 Hz) and efficient ways to detect eV neutrons. Presumably scintillation detectors would be best.

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The requirement of large Q means that measurements of this kind are especially suited to pulsed-source instruments using epithermal neutron energies[10]. A preliminary measurement at IPNS[11] with $E_0 = 0.26$ eV yielded an approximate estimate of the width of n(p), i.e. the mean kinetic energy per particle. However, the very high absorption cross section of ^{3}He means that present pulsed sources cannot provide sufficiently intense beams for high-resolution measurements to be carried out. To properly observe the kinks in S(Q,E), we estimate that about five resolution elements will be needed on the relatively straight sections of the curve on either side of the kink. For $Q = 15$ Å^{-1}, the curve in Fig. 5 implies that a resolution $\Delta E = 1.5$ meV will be required. This resolution must be accompanied by sufficient flux on sample to provide adequate statistics for a detailed shape analysis of S(Q,E). An appropriate machine is the Ultra-High Resolution Chopper Spectrometer, Crawford et al.[8]. This instrument is designed for exactly the resolution required, 0.005 E_0, only times have to be scaled up by 2 appropriate for an E_0 of 0.25 eV instead of 1.0 eV, and gives the following parameters:

$E_0 = 0.25$ eV
$\Delta E = 1.25$ meV
$\bar{\phi}_s = 1.1 \times 10^5$ n/cm^2.sec

This flux is 20 times that available in the IPNS experiment, so that statistics should be 4-5 better, certainly adequate for shape analysis.

In addition to studies of the effect of pressure, addition of ^{4}He, etc. and other factors affecting the Fermi surface, we may anticipate the eventual capability to measure on polarized ^{3}He. (This will require high magnetic fields and very low temperatures; however, measurements on solid ^{3}He at 0.5 mk and 0.1 T are already being carried out at IPNS.)[12] In partially polarized ^{3}He one may expect two Fermi surfaces, for the majority and minority spins, both of which should show up in the n(p) measurement.

Neutron measurements at moderate to high Q have established the existence of the Bose condensate in ^{4}He. The measurement of the effects of temperature, pressure, and addition of ^{3}He on the condensate fraction is currently an active area of investigation at present sources. Looking ahead to technological developments, we can anticipate n(p) measurements on spin-polarized hydrogen, another monatomic Bose system. In addition to measurements of broad features of n(p) such as the kinetic energy, it may be possible to ascertain the existence of a Bose condensate in spin-polarized hydrogen.

VII. Conclusions

We have tried in this article to review briefly four areas of pulsed-neutron science, accelerators that provide the protons, targets into which they plunge, moderators which emit the neutrons for the scattering experiments, and certain aspects of pulse length. All four are areas requiring considerable research and it is safe to predict that ten years from now the ideas concerning all three will be radically different from those today. Moderators, in particular, are a rapidly developing field at pulsed sources and will continue to attract much interest.

We have ended this short paper with a discussion of three scientific areas that we believe will prosper at pulsed sources in the 1990's. This is, of course, by no means a complete list, but it is always important to realize that there is new science to be found and that neutron scattering in the 1990's will no doubt provide as many surprises and new results as it has over the last two decades.

Acknowledgments

We wish to thank the ANL staff for discussions on a number of points, in particular, R. K. Crawford, S. Ikeda, J. D. Jorgensen, R. L. Kustom, C. W. Potts, and D. L. Price.

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Table 1
Proton Spallation Sources

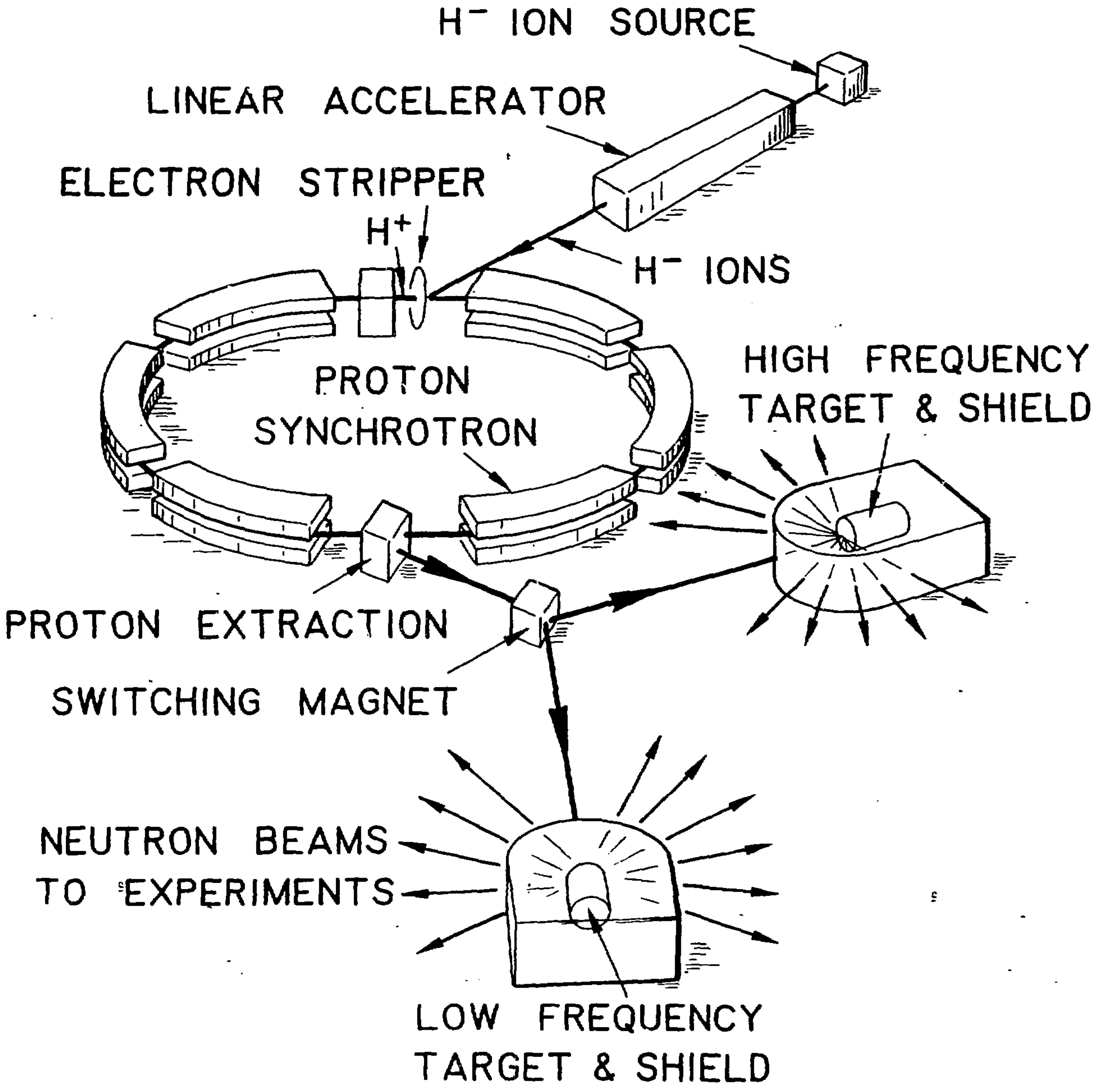
Facility	Accelerator	Particle Energy MeV	Time-Average Current μA	Average Pulsing Frequency Hz	Source Pulse Width μs	Target Material	Status
ZING-P' Argonne, U.S.	Synchrotron	500	3	30	0.1	^{238}U	Operated 1977-80
WNR Los Alamos, U.S.	Linac	800	3.5	120	4.0	W	Started 1977
KENS-I KEK, Japan	Synchrotron	500	2	15	0.07	W	Started 1980
IPNS-I Argonne, U.S.	Synchrotron	500	12	30	0.1	^{238}U	Started 1981
SNS Rutherford, U.K.	Synchrotron	800	200	50	0.2	^{238}U	To start 1985
KENS-I' KEK, Japan	Synchrotron	500	10	15	0.5	^{238}U	To start 1985
WNR-PSR Los Alamos, U.S.	Linac + Storage Ring	800	100	12	0.27	^{238}U	To star 1986
SNQ KFA Julich, Germany	Linac and Compressor Ring	1100	4000		100	^{238}U	Proposa Under Devel.
ASPUN Argonne, U.S.	FFAG Synchrotron	1600	4000	60	0.4		Proposa Under Devel.

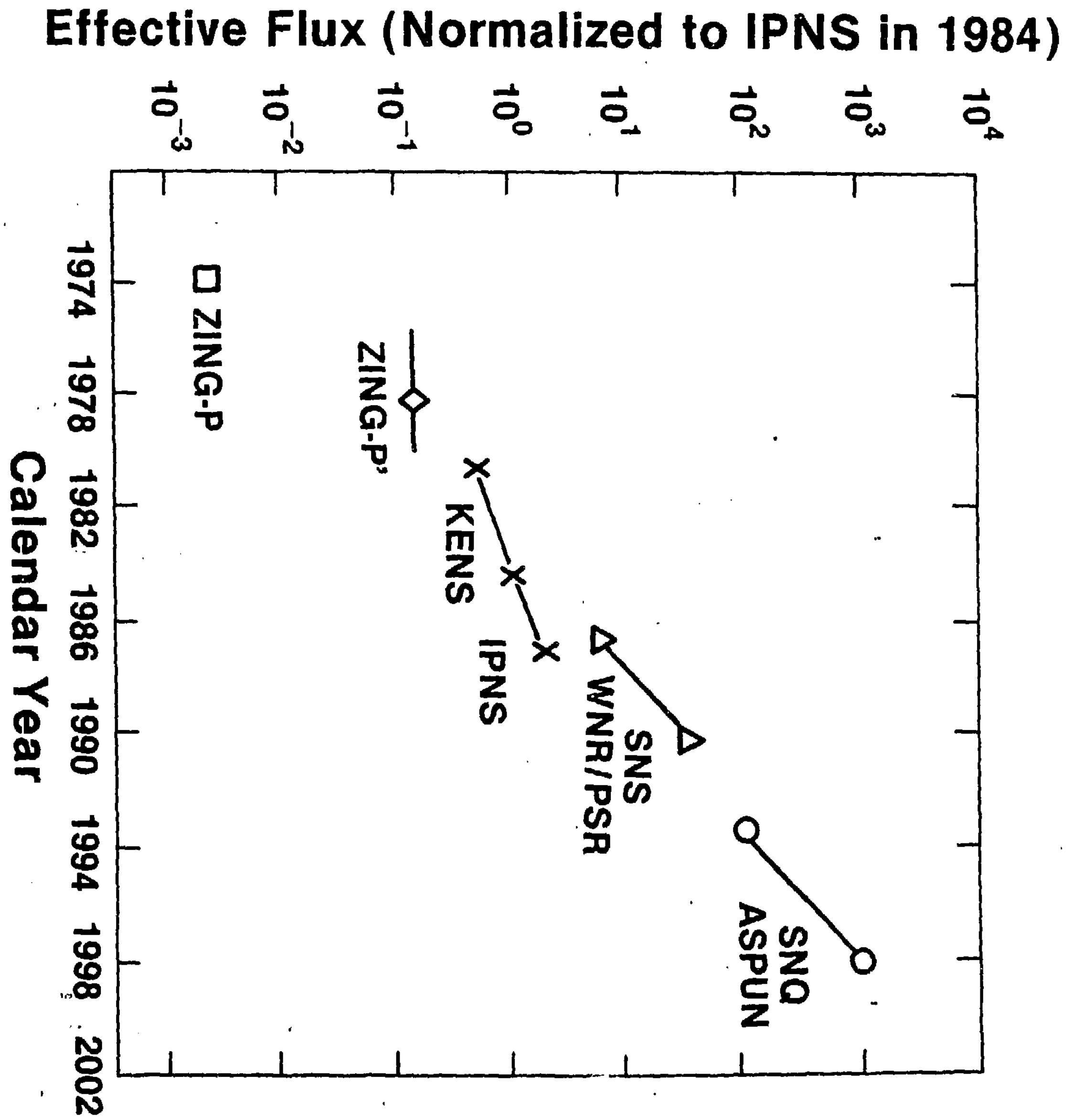
This table gives the specification of present (and proposed) proton spallation sources in the world. The first such proton source operated at Argonne in 1974-75 with 0.1 μA current and an energy of 200 MeV. We have not covered electron driven sources here, the largest of which HELIOS at Harwell, UK, also performs a good deal of condensed matter research.

Figure Captions

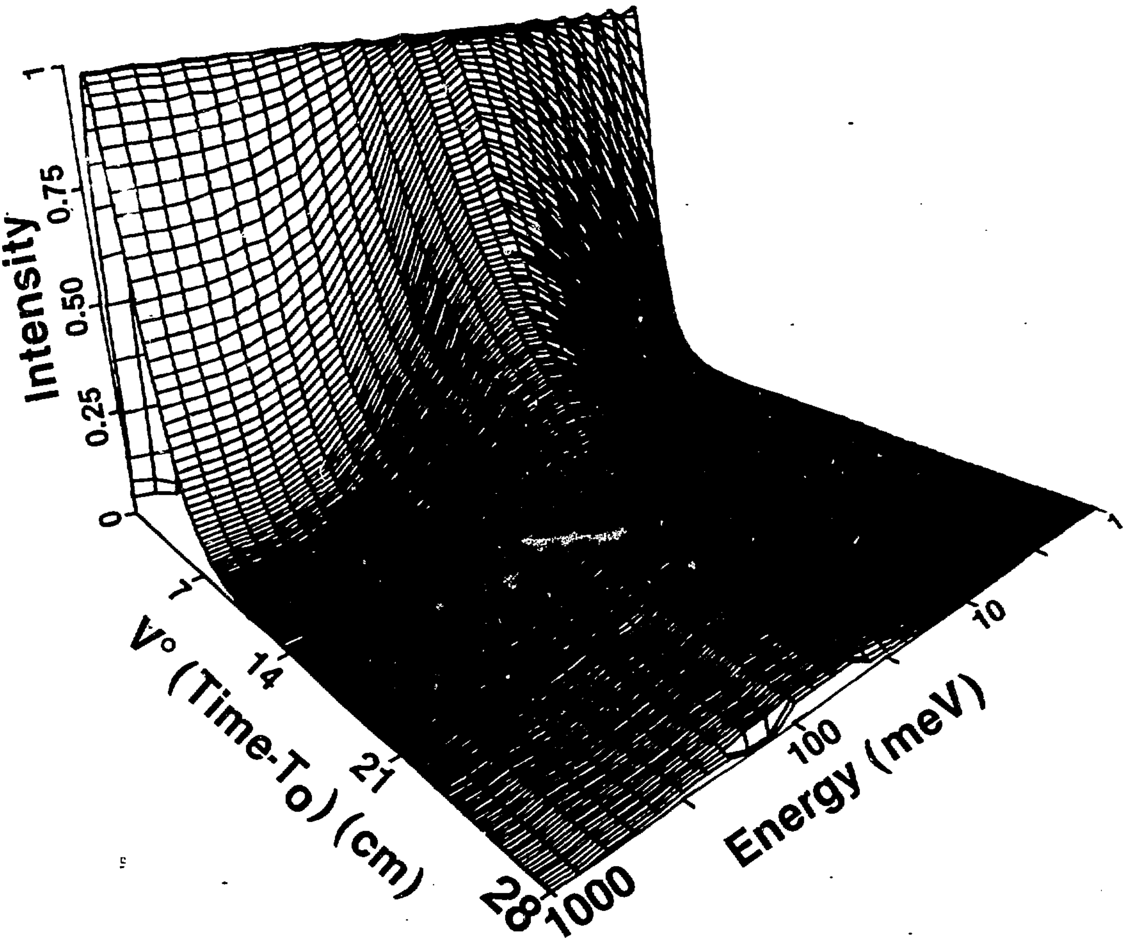
FIG. 1	Schematic of spallation source including linac and circular ring to produce short pulse proton bursts. Two targets are shown surrounded by scattering instruments.
FIG. 2	Plot of available proton intensity from spallation sources from 1974 to 2002.
FIG. 3	Pulse shape profile as a functin of energy and length (which represents the normalized time for each energy, velocity x time after the source pulse).
FIG. 4	Schematic of chopper spectrometer discussed in text. Incident flight path $L_0 = 20$ m, chopper to sample $L_2 = 1$ m, sample to detector $L_3 = 20$ m.
FIG. 5	The scattering function from ^{3}He calculated using the chopper spectrometer in Fig. 4. Incident neutron energy is 250 meV with a resolution at a scattering angle of $\phi = 91.8°$ of 1.5 meV. Note the change in slope that is a signature of the Fermi cut-off in the momentum distribution of ^{3}He (see insert).

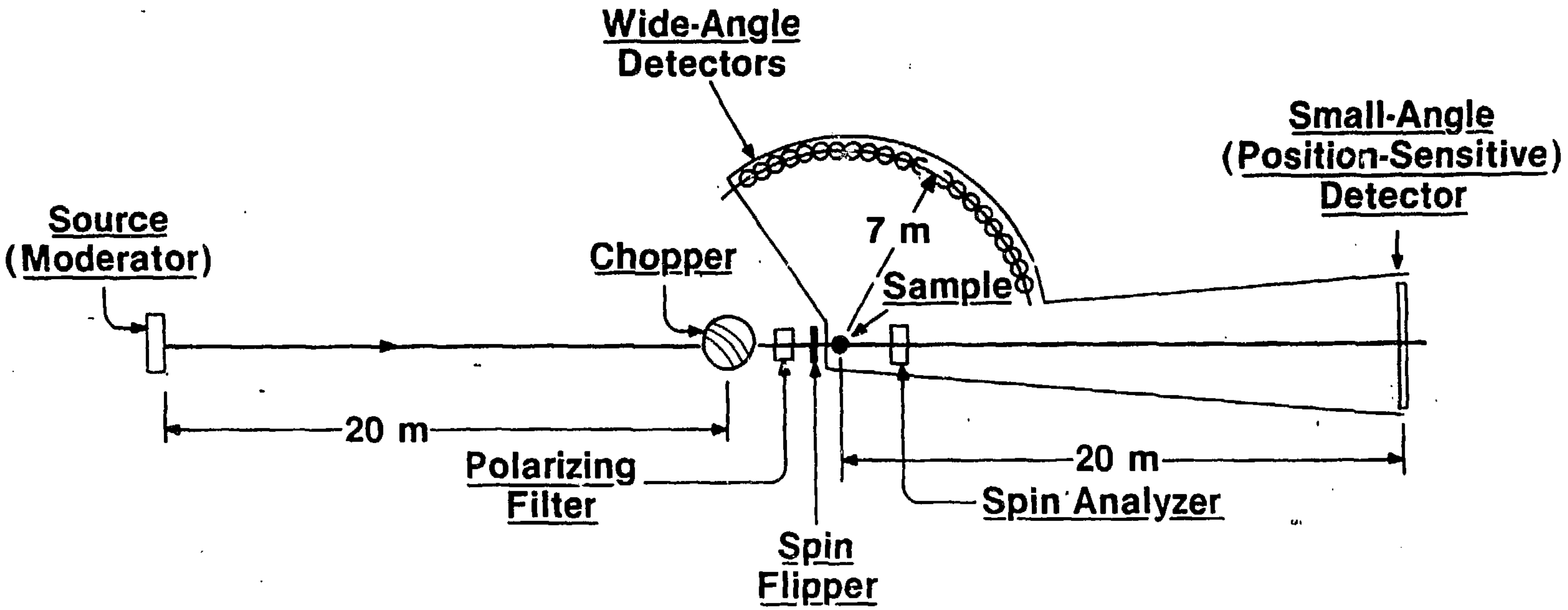
SCHEMATIC ARRANGEMENT OF A PULSED SPALLATION NEUTRON SOURCE

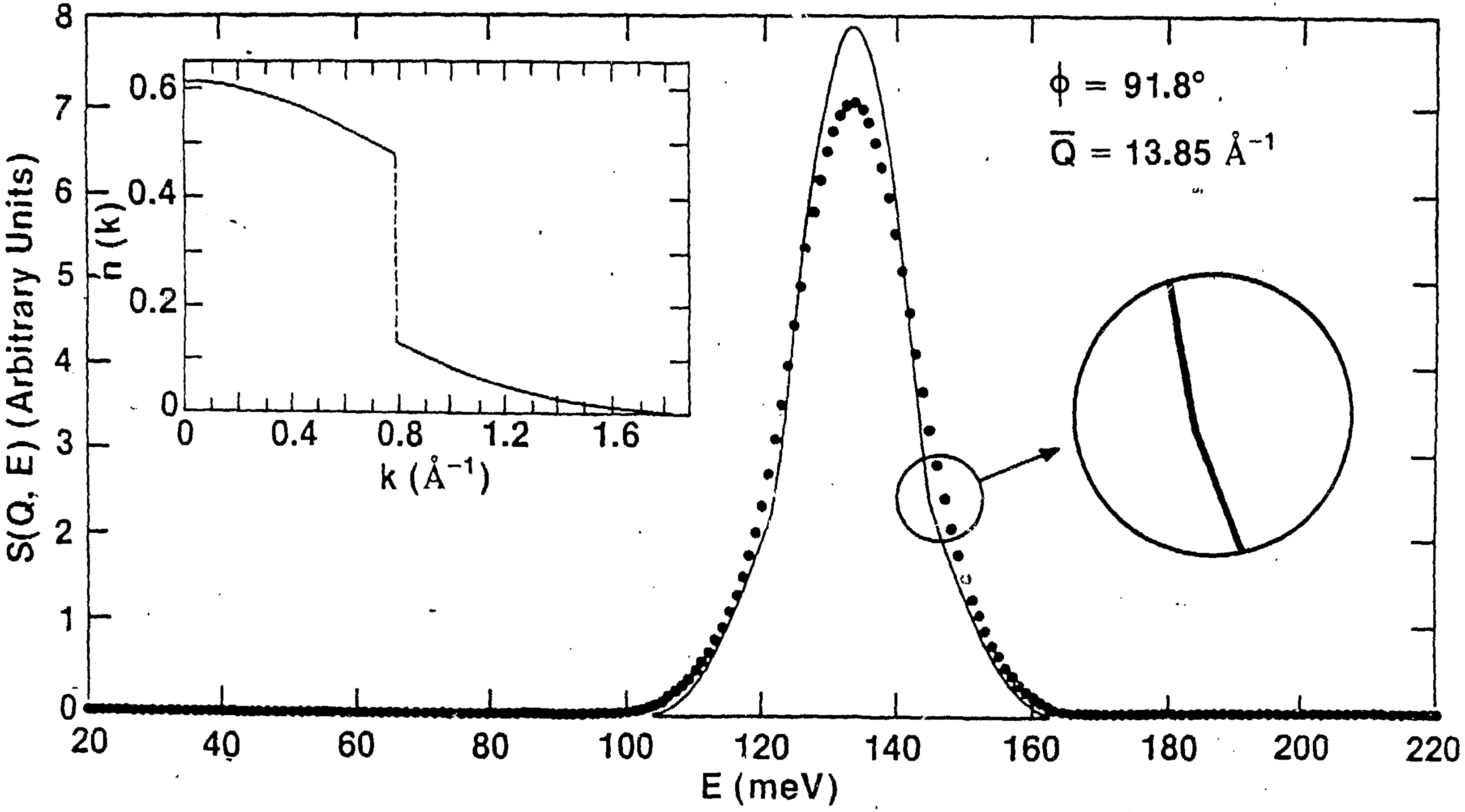



Effective Flux (Normalized to IPNS in 1984)
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Calendar Year
1974
1978
1982
1986
1990
1994
1998
2002
ZING-P
ZING-P'
KENS
IPNS
WNR/PSR
SNS
ASPUN
SNQ

Pulse Shape of IPNS H-Moderator




Wide-Angle Detectors
Small-Angle (Position-Sensitive) Detector
Source (Moderator)
Chopper
7 m
Sample
20 m
Polarizing Filter
Spin Flipper
20 m
Spin Analyzer


S(Q, E) (Arbitrary Units)
0
1
2
3
4
5
6
7
8
20
40
60
80
100
120
140
160
180
200
220
E (meV)
n (k)
0
0.2
0.4
0.6
0
0.4
0.8
1.2
1.6
k (Å^{-1})
ϕ = 91.8°
$\bar{Q}$ = 13.85 Å^{-1}