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Informal Report

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Study of Uses of a Proton Storage Ring

University of California

LOS ALAMOS SCIENTIFIC LABORATORY

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Informal Report

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Study of Uses of a Proton Storage Ring

Compiled by

D. Nagle

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PREFACE

An 800-MeV proton storage ring (PSR) is authorized for construction at the Weapons Neutron Research Facility (WNR) at the Los Alamos Meson Physics Facility (LAMPF). The goal of this study is to outline the several scientific and technical possible uses of a storage ring, together with the corresponding impacts on the LAMPF linac, switchyard, beam lines, and experimental areas. The meetings were sponsored by AT, MP, and P Divisions of the Los Alamos Scientific Laboratory (LASL). Approximately 75 people attended from 6 divisions in the laboratory, the Director's Office, and a number of universities.

The intent was to encourage the presentation of incomplete ideas, i.e., brainstorming, and with this in mind, none of the materials in here should be quoted or attributed to participants without their express permission.

The meeting was organized into a number of parallel working sessions, concentrating on specific topics as noted. No editing has been done, other than some revision of format.

Descriptions of the ring project are given in reports LA-5372, P-11-77-196, and progress reports of Group P-11 and AT Division.

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STUDY OF USES OF A PROTON STORAGE RING

Meeting organized by
D. Nagle, G. Keyworth, R. Macek, and G. Lawrence

Compiled by D. Nagle

ABSTRACT

Scientific applications of a proton storage ring (PSR) for 800-MeV protons are reported.

POLARIZED PROTONS

Working Group Subcommittee: *D. Nagle (MP-DO) and
J. Simmons (P-DOR), Co-chairmen*
R. Macek (MP-13), G. Lawrence (AT-1), M. McNaughton (MP-13), O. Van
Dyck (MP-13), and E. Hoffman (MP-13)

Medium-Energy Nucleon Experiments at the Proton Storage Ring

During the subcommittee meetings, a number of subjects were discussed concerning use of the stored polarized and unpolarized proton beams. These included proton precession measurements (described elsewhere), generation of medium-energy neutron beams and related experiments, and the potential advantages of a long duty-factor (DF) spill mode. While interesting and important in detail, these considerations lacked a central theme. However, in turning to the possibilities inherent in energy change of the circulating beam by an active synchrotron ring, we realized that considerable scientific potential was available in nucleon experiments over an energy range of ~ 0.3 to 2.0 GeV.

There is evidently a serious policy question as to whether or not such medium-energy experiments should be planned for the proton storage ring (PSR). The facility was conceived, designed, and justified as a neutron source for energies < 30 MeV. Considering this, our discussions were exploratory, if not speculative, and represent very restricted expression of opinion. It is in this sense that the following paragraphs should be taken.

A driving force behind these considerations comes from very recent analyses of experiments at Argonne National Laboratory (ANL). These are p-p polarized total cross-section measurements in the transverse and longitudinal geometries. From a recent meeting at ANL, it is understood that the experiments are being interpreted in terms of nucleon-nucleon resonances in the range of total energy from 2150 to 2500 MeV, or possibly 2800 MeV. These occur for incident

laboratory energies in the approximate range of 600 to 1800 MeV. However, the extent of future experimental work at ANL is uncertain. If the storage ring had energy-changing capability, then a significant scientific opportunity could open at the Los Alamos Scientific Laboratory (LASL) for the detailed exploration of these phenomena. The corresponding neutron-proton measurements have not yet been made at ANL or elsewhere. It is reasonably probable that the corresponding n-p measurements could be made at PSR over the comparable energy range with the possibility of uncovering new phenomena.

The generation of polarized neutron beams at the PSR would also allow a number of other n-p polarization measurements to be performed. The pulsed capability of the ring will generally improve neutron experiments by utilization of time of flight as an additional criterion. In this respect, deceleration as well as acceleration is interesting by allowing a firm overlap to be made with the lower energy machines now operating at TRIUMF and SIN.

Another important application of the PSR is concerned with study of the nucleon-nucleon inelastic processes from threshold to, say, 2 GeV. In this range, the process is predominantly single pion production. The process is very important to understanding of the N-N force. The data on n-p pion production are of relatively low weight in this energy interval. The channel $n + p \rightarrow \pi^- + 2p$ represents production from initial isospin zero states, as well as from isospin one, as given by p-p interactions, and is susceptible to measurement by modern track-defining counters. The storage ring has several advantages for the experiments, of which high average current and intense bursts are the significant ones.

It is true that the Saturne synchrotron will soon become operational over a comparable energy range. We are not aware in detail of the specifications of this machine. The simplest approach is to let Saturne take over this energy regime. However, the best physics would undoubtedly come from a competitive interplay between the Los Alamos Meson Physics Facility (LAMPF) and Saturne. The potential of the PSR would enhance our capabilities and provide a logical extension of fundamental nuclear physics at the LAMPF site.

The following specifications summarize our discussions on desirable features of an expanded PSR concept. In discussions with members of LASL's Group AT-3, it was realized that some of these may be unrealistic. Nevertheless, they are reproduced here as our initial efforts in this direction.

1. Variable energy:
 - a. Deceleration to 400 MeV.
 - b. Acceleration to 2000 MeV.
2. Circulating beam: polarized and unpolarized protons.
3. Injection:
 - a. Polarized protons: bunch at ion source to 50-n/s period at average current of 50 nA and inject into ring.
 - b. Unpolarized protons: standard 50-n/s chopping (or bunching) and injection at average currents of 10 μ A or greater.
4. Extraction:
 - a. Macroscopic duty factor: 50%.
 - b. Period: 0.3- μ s period during extraction with 1-n/s burst width.
 - c. Average repetition rate: $\sim$ 1 MHz.
 - d. Alternative mode: continuous extraction with no fine structure.

Adiabatic Bunching and Debunching

These schemes do not need acceleration for bunching or debunching. They do use an rf cavity; the stable phase is 90°. As the cavity voltage E is adiabatically raised or lowered, the

phase width of the bunch is decreased or increased as $E^{1/4}$, and the energy spread correspondingly increased or decreased. The bunching is deemed very difficult by storage ring people. It requires high-cavity voltages or reduced initial energy spread in the ring. Also, a debunching scheme would probably lead to longitudinal instabilities. The possibility was mentioned of debunching at 600 MHz and then rebunching at the cyclotron frequency. This would only work for weak beams, e.g., the polarized H^- beam. The ejection problem is probably okay.

Observations of the Resonances in Anomalous Precession of the Proton Magnetic Moment

The precession of the spin of a proton with respect to its velocity vector, for the case of motion around the ring in the presence of magnetic field only, is given by

$$\nu = \frac{f - f_c}{f_c} = \gamma[(g/2) - 1] ,$$

where

ν is the angular deviation of the spin per turn with respect to the orbit ,

f_c is the cyclotron frequency ,

f is the Larmor frequency ,

γ is equal to W/Mc^2 ,

and

g is the gyromagnetic ratio .

If we inject a polarized H^- beam into the ring and strip it to H^+ , the above equation governs the motion of the spin. For references on anomalous precession, see, for example, J. S. Bell, CERN-75-11, or R. Hagedorn, *Relativistic Kinematics*.

Several years ago, we proposed using the resonances $\nu = \text{integer}$ as a possible method of measuring g . At present, however, g is quoted to three parts in 10^7 , so this would be hard to improve upon. However, one would think of measuring γ , i.e., the energy of the proton beam from LAMPF, which is presently known to a few parts in 10^4 .

The principle of the measurement is to have single-turn injection of polarized H^- , then to strip, circulate for N turns, and extract. After extraction, p_T , the residual transverse polarization, would be measured. We would perhaps measure p_T to 10^{-4} , using the techniques developed for the parity-violation experiments,

$$\Delta p_T = \Delta \nu N p = \{\Delta \gamma [(g/2) - 1]\} N p .$$

As an example, for $N = 100$, $p = 0.85$,

$$\Delta\gamma = 10^{-6}/(100 \times 0.85 \times 1.73) \approx 10^{-8}.$$

Since we would be injecting in the normal way into the ring, very little special equipment would be needed for this measurement. The measurement requires no knowledge of the magnetic properties of the ring or of its orbit characteristics.

NUCLEAR PHYSICS AND THE PULSED NEUTRON

Working Group: G. A. Keyworth (P-DO), *Chairman*

G. F. Auchampaugh (P-3), R. C. Haight (LLL), P. W. Lisowski (P-3), J. J. Malanify (P-9), M. S. Moore (P-3), J. D. Moses (P-3), J. C. Solem (P-3), W. Talbert (Q-14), and R. Woods (P-9)

The study group on "Nuclear Physics and the Pulsed Neutron" met on five separate occasions on March 15-17, 1978. The objective was to discuss the scope and nature of nuclear physics experiments that could be conducted at the Weapons Neutron Research (WNR) facility and that would benefit particularly from the capabilities offered by the proposed PSR. Since considerable thought has already been expended in addressing applied areas of research, we devoted our efforts to consideration of the most potentially fruitful areas of basic nuclear physics. Throughout our considerations, we dwelled heavily on the most fundamental and unique measurements, with somewhat less attention paid to advances in conventional nuclear spectroscopy.

We addressed separately the different types of measurements that benefit particularly from the extremely short pulse capability available with one mode of PSR operation and the somewhat more general capability offered by the unique neutron intensity provided by the PSR. The short pulse capability is, in general, only of interest in measurements involving relatively fast neutrons, perhaps above 1 keV, whereas most conceivable experiments will benefit from maximum intensity.

Fast-Neutron Experiments

We began the discussion of fast-neutron measurements with a question to be addressed to the PSR designers as to what is the duration of the proton pulse from the PSR at the position of the WNR target. The two most frequently quoted numbers are 2 and 1 ns. We agreed that 2 ns did not represent a particularly unique capability, whereas 1 ns would effectively match the neutron source and detector timing capabilities in most experiments. George Lawrence and Dick Cooper pointed out it might be possible to produce even shorter pulses, perhaps 0.5 ns, but a commensurate loss of intensity would probably result. We concluded that, in the rather rare cases where subnanosecond pulses would offer a significant advantage, the factor of 2 loss in intensity would be acceptable.

The first class of experiments that would benefit from the high resolution available with 1-ns full-intensity pulses is the study of the spin-spin interaction in simple nuclei. We discussed examples of nuclei that are simple from a shell-structure point of view, such as ^{17}O or ^{207}Pb . In particular, if we could study the two p-wave strength functions for these spin- $1/2$ nuclei, we could obtain a sensitive, detailed test of shell-model calculations. The optimal experiment would be a simple transmission measurement, using both a polarized target and a polarized incident neutron beam. Because we would be interested in neutrons of considerably higher energy than those that may be polarized by transmission through our existing lanthanum-magnesium-nitrate (LMN) system, we would have to develop another source of polarized neutrons, perhaps

utilizing Mott-Schwinger scattering. With suitably polarized targets, simple transmission experiments are adequate. However, if such targets are excessively difficult to produce, then scattering measurements using polarized neutrons, but an unpolarized target, could provide sufficient information. Such measurements as these have not been feasible with existing white neutron sources, but could be done using the PSR.

A similar class of experiments would involve studying the spin dependence of strength functions in rare earths. Although somewhat more difficult to calculate than the near-closed-shell nuclei specified above, they are of particular theoretical interest because of their high deformations. In addition, these nuclei are generally relatively simple to polarize, due both to the high-magnetic moments associated with their large deformations and to the particular magnetic behavior of the metals and their compounds. Using the existing LMN system, transmission measurements on polarized samples of these rare earths should be made to permit extraction of strength functions and average widths as functions of spin and l values.

One of the most exciting questions today in the general area of fission concerns the structure near the fission thresholds in neutron-induced fission of $^{230,232}\text{Th}$. If this structure, which has been observed but not resolved with existing electron linacs, is truly resonance structure, then it will be necessary to determine both the resonance spins, J , and their projections, K , in order to demonstrate any band structure. Because these are both spin-0 nuclei, the only available means by which these resonance quantum numbers may be determined is to measure the angular distribution of the fission fragments from each individual resonance. The difficulty of this measurement lies in the fact that it requires very high resolution, e.g., <1 keV at 1.6 MeV in ($^{230}\text{Th} + n$), and that thin targets must also be used to permit a meaningful angular-distribution determination. With 1-ns pulses from the PSR, short flight paths (~ 25 m) could be used, permitting a very high intensity to be realized. This measurement, which has eluded clarification for several years, may well provide evidence for a possible third minimum in the fission barrier.

Measurements with Low-Energy Neutrons

The most potentially exciting experiment that was discussed by our study group was the result, reported by Lobashov in 1972, of measurements he made of the circular polarization of γ rays emitted in the thermal neutron capture on hydrogen. That experiment implied a parity violation ~ 100 times greater than any existing weak-interaction theory can produce. Consultation with members of LASL Group T-5 indicates that such a disagreement can only be reconciled by either assuming a gross error in weak-interaction theories or by postulating an otherwise unjustified parity violation in the strong interaction. The Lobashov measurement was conducted on a specially modified nuclear reactor and was an extremely formidable experiment with very great attention to systematic corrections required. If it were not for the fact that Lobashov has an extremely admirable past record in similarly difficult experiments, it might be logical to discard his startling result. However, it is our understanding that theorists are generally loath to discard those results, but are rather treating them as enigmatic.

After some incomplete discussion, we concluded that with the better geometry available with the WNR target, and utilizing the pulsed nature of the source, the Lobashov experiment could essentially be repeated with the existing facility. However, with the advent of the PSR, an experiment of *perhaps 10 times greater accuracy than that of Lobashov* could probably be made. In addition, if an improvement could be made in the analyzing power of the polarization analyzer, then even more significant increases in the experimental accuracy could result. We thus recommended that an effort should be made to reproduce the Lobashov experiment as soon as possible with a serial effort being conducted to exploit the applicable PSR capabilities to the greatest extent.

Other than the above mentioned measurement of the parity violation in the n-p reaction, the most fruitful area of nuclear physics that could be explored with the PSR involves the detailed examination of resonance structure using LASL's existing unique capability for providing polarized neutron beams and polarized targets. In general, these experiments have marginal count rates, and a completely new regime of isotopes and of precision would become available with the PSR. The most obvious class of experiments is the continued study of the spins of resonances in neutron-induced fission. This represents an extremely detailed microscopic tool with which to examine the complicated fission process. Although the Bohr theory of fission, wherein the concept of a fission channel characterized by the J and K quantum numbers is postulated, has been accepted for many years, the very basis of the theory has not been tested. Measurements of J and K of fission resonances, the former using polarized neutron beams and polarized targets while the latter uses an unpolarized neutron beam but an aligned target, permit detailed verification of the role of K throughout the fission process. In particular, the question of whether K is conserved is evident in the nature and type of K-mixing in individual fission resonances. In addition to measurements in which J and K are determined, one is also interested in determining how fission parameters, such as the kinetic energy and mass distribution of fragments, vary as functions of J and K from resonance to resonance. These latter experiments are feasible only with the PSR, except for particularly large, isolated resonances.

Inasmuch as J and K measurements on long-lived fissile isotopes such as ^{235}U are feasible, although marginally so, with the existing WNR, the PSR will permit extension of these measurements to nonfissile nuclei, such as the particularly interesting example of subthreshold fission in ^{237}Np (and more radioactive isotopes, perhaps including ^{239}Pu). Without the PSR, it is unlikely that these latter measurements could be conducted on any foreseeable pulsed-neutron source other than an underground nuclear explosion, with the attendant extraordinary experimental complexities.

Another method for determining the spins of nuclear resonances was proposed by the late F. L. Shapiro at Dubna, but has never previously been feasible because of lack of sufficient neutron-source intensity. That involves circumventing the requirement for providing a polarized target by using instead a second LMN system as a polarization analyzer. Specifically, one scatters a beam of neutrons polarized by transmission through LMN off an unpolarized sample and measures the polarization transfer by passing the scattered neutrons through another LMN sample. This method avoids the great complexity and limitations on choice of isotopes inherent in the target polarization problem. It does, however, limit one to resonances that are visible in scattering, and will not permit selection of a particular exit-channel process.

In addition to fissionable nuclei, the rare earths represent a particularly interesting class of nuclei, because of their broad range and types of nuclear deformations. We have already alluded to these measurements in the section above on fast-neutron measurements, and will simply reiterate a strong interest in doing transmission (n,n), (n, γ) measurements to provide determination of the spin dependence of strength functions. With the PSR, measurements could be conducted that would provide a new, detailed understanding of level systematics. It is, perhaps, worthwhile pointing out that, to date, there exists only one measurement of a reasonably complete set of nuclear resonances, with spin assignments, for nonzero-spin nuclei.

Several subjects were briefly discussed regarding feasible experiments that are interesting but of less significance than those described above. Among them is evidence for possible time dependence in nuclear resonances, which would be evidenced by, for example, observed widths of structure in nuclear cross sections considerably different from what one would predict either from experimental resolution or from nuclear systematics. The possibility of correlation between capture and fission widths in intermediate structure should also be examined. There seems to be some evidence for this in ^{237}Np , but it is extremely difficult to explain in the framework of existing fission theories.

A last category, albeit a tenuous one, could be of considerable future interest. It involves the use of ultracold neutrons to permit some fundamental measurements. In particular, we discussed with Jerry Stephenson, LASL Group T-5, the fundamental benefit of a direct determination of either the n-n scattering length or of the lifetime of the di-neutron. He pointed out that both these measurements would address the same fundamental question, which is the nature of charge symmetry. We did not seriously attempt to make a detailed proposal for an experiment to address these quantities, although it seemed interesting to explore the use of a neutron storage ring such as that recently implemented at Grenoble. Also, improvements in the capability of providing a "neutron bottle," wherein ultracold neutrons are totally contained, might impact the feasibility of measurements of the n-n interaction.

Summary

In conclusion, it appeared to us that with the advent of the PSR, a number of unique and exciting measurements in both fundamental nuclear physics and in nuclear-structure physics will become possible. In particular, an accurate measurement of the parity violation in the capture of thermal neutrons by hydrogen would be a particularly significant experiment. A comprehensive program to study the detailed nature and distribution of nuclear resonances using polarized neutron beams and polarized targets would be unique to LASL and would offer a new dimension in the field of nuclear structure. A number of more specific measurements were discussed, some of considerable fundamental significance, whereas many others simply contribute to extending the data base of nuclear spectroscopy. However, it is clear that the unique capabilities available with the PSR will give us a meaningful advantage in addressing a number of problems in nuclear-structure physics that may arise in the future. Finally, we concluded that research possibilities using ultracold neutrons should be explored. Some fundamental measurements may well be possible, but some innovation will certainly be required to effect them.

BIOLOGY

Working Group: *George Bell (T-10) and*

J. N. Bradbury (MP-3), Co-chairmen

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Introduction

In recent years, the elastic scattering of slow neutrons from biological materials has given valuable information on biological structures. Slow neutrons are used because these have wavelengths of the same order as the spacings between atoms in biological (or any condensed) materials. For example, a neutron of 0.01 eV (0.001 eV) has a wavelength of 2.9 Å (9 Å). In addition, such low-energy neutrons cause little or no radiation damage to the biological material.

When slow neutrons are scattered from crystallized biological samples, diffraction patterns are obtained, much as in the case of x-ray diffraction. Neutron diffraction has a number of advantages, including the ability to reveal proton positions and the avoidance of radiation damage. In addition, since neutron scattering arises from neutron-nucleus interactions, different isotopes may scatter neutrons quite differently. In particular, hydrogen and deuterium have very different scattering lengths so that selective substitution of deuterium for hydrogen can be a powerful tool for revealing structure. Against these advantages must be balanced the far greater ease of obtaining x rays than neutrons.

When slow neutrons are scattered from randomly oriented biological macromolecules, structure information may be gained by examining the angular distribution of scattered neutrons at small angles. For example, information about the size and spatial relationships of biomolecules with distances of ~100 Å may be found. Such information may not be obtainable in other ways.

The slow-neutron sources that have been used for such experiments have been reactors, with choppers or other devices to give monochromatic neutrons. The preeminent facility is the reactor of the Institute Laue-Langevin at Grenoble, which is used by scientists from throughout Europe and elsewhere. In the U.S.A., Brookhaven has the only major facility, but a national user-oriented small-angle neutron-scattering facility is being added at the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL).

The WNR facility at LAMPF can be used as a pulsed neutron source for scattering from biological samples. Small-angle neutron-scattering (SANS) experiments should be undertaken first because they do not require as extensive instrumentation as diffraction experiments. In such experiments, one measures the scattered-neutron intensity as a function of the neutron momentum change ($\div \hbar$),

$$K = \frac{4\pi \sin \theta/2}{\lambda}, \quad (1)$$

where θ is the scattering angle and λ the neutron wavelength. Therefore, equivalent information can be obtained by using a monochromatic source (fixed λ = monochromatic source from reactor) and observing at various θ values, or by taking one or a few fixed θ values and letting λ vary (by time of flight from a pulsed source). Hence, a very simple detector array would give valuable information with a pulsed source.

The WNR SANS Facility and Storage Ring

At the WNR, flight path 12 is currently being designed and instrumented for SANS experiments on biological samples. Analysis, by Seeger, has shown that optimal resolution is obtained when the sample is placed twice as far from the source as from the detector. The present design has flight-path distances of 11 m (source to sample) and 5.5 m (sample to detector). With flight paths that are this long, there is a problem in overlap of successive pulses. For example, a neutron of 0.01 (0.001) eV takes 12 (37) ms to move 16.5 m. Therefore, if a second pulse follows the first too closely (say ≤ 30 ms), information will be lost due to pulse overlap. [Note also that the above neutrons fall under gravity 0.7 (7) mm during flight.]

In a particular configuration giving an angular resolution of 0.0004 rad, an aperture near the sample defines the beam with a diameter of 3.7 mm. This means that biological samples need be no larger for such resolution. In this high-resolution configuration, a time-average slow-neutron flux of 10^4 n/cm²/s at the sample will be obtained using <1% of the current LAMPF beam (partly to avoid pulse overlap). Although it appears (see below) that this will be a useful neutron intensity, increased intensity is much to be desired. The storage ring will eliminate pulse overlap difficulties by running at 2.4 Hz, and, therefore, a larger fraction of the LAMPF beam will be used. In addition, a small section of cold moderator could shift the neutron spectrum to longer and more desirable wavelengths. It appears that each of these two effects will increase the neutron intensity by about a factor of 10. It should also be pointed out that installation of cold moderator is far easier at WNR than inside a reactor.

The above neutron intensity may be compared with "monochromatic" intensities at Brookhaven National Laboratory (BNL) and Grenoble of 10^4 - 10^7 n/cm²/s. However, it should be noted that the LASL beam had a design angular divergence of $\theta_{\min} = 1.5 \times 10^{-3}$ rad, whereas that at BNL had an angular divergence of 20-30 min = $6-9 \times 10^{-3}$ rad. Hence, by using a larger area source and a lower resolution beam (corresponding to that at BNL), the LASL intensity would be increased ($\sim \Delta\theta^2$) by a factor of 20-40. Thus, using the current WNR, intensities of about one-tenth those at BNL or Grenoble are to be expected.

Estimates were made of counting rates expected from biological samples placed in the present beam and are contained in the next section.

Intensity of Small-Angle Diffraction and Estimated Counting Rates

Suppose particles, each containing N nuclei, are dispersed in solution; let the particle density be n . The diffraction intensity depends on the scattering contrast between particle and solvent. Define an average effective scattering length per nucleus as

$$\bar{a} = \frac{\left(\sum_i p_i a_i \right)_{\text{particle}} - \left(\sum_i p_i a_i \right)_{\text{solvent}}}{\left(\sum_i p_i \right)_{\text{particle}}},$$

where p_i, a_i represent density (nuclei/cm³) and coherent scattering length (cm) of the i th nucleus.

Then, if $A \exp(i\mathbf{K}_0 \cdot \mathbf{r})$ is the amplitude of the incident neutron wave ($A^2 = \phi$, the incident flux in neutrons/cm²), the scattered amplitude from one particle at a detector located at $\mathbf{R}$ relative to the sample is

$$\psi(\mathbf{R}) = \sum_i A e^{\frac{i\mathbf{K}_0 \cdot \mathbf{r}_i}{a_i}} \frac{e^{i\mathbf{K}_S \cdot (\mathbf{R} - \mathbf{r}_i)}}{|\mathbf{R} - \mathbf{r}_i|},$$

the numbering over all nuclei in the particle. If the sample has volume V_s , the total scattered intensity in the forward direction ($\mathbf{K}_s = \mathbf{K}_0$) is

$$I = V_s n \psi^2 = \phi V_s n \frac{\bar{a}^2}{R^2} N^2, \quad (2)$$

where we have assumed that R is large compared with the sample dimensions.

To estimate the order of magnitude, let us take

$$\bar{a} = 10^{-12} \text{ cm}$$

and

$$nN = f(5 \times 10^{22}) \text{ nuclei/cm}^3,$$

where f is the weight fraction made up by particles in the solution.

In the proposed instrument, at the highest resolution,

$$\phi \approx 8^4 \text{ n/cm}^2/\text{s},$$

$$R = 550 \text{ cm},$$

$$K_{\min} \approx 0.015 \text{ nm}^{-1} (\theta_{\min} \approx 1.5 \times 10^{-2}, \lambda \approx 6 \text{ \AA}),$$

and

$$V_s \approx 0.1 \text{ cm}^3.$$

Then, $I = 1.6 \times 10^{-4} N f n/cm^2/s$. A detector of area 0.75 cm^2 would then give a count rate of $1.2 \times 10^{-4} N f$ neutrons/s. This K_{min} is matched to the radius of a scattering particle with $N \sim 10^7$; if the concentration f is 1%, then the expected neutron counting rate is $\sim 12/s$.

For many biological samples, f is in the range $0.01 \leq f \leq 0.1$, whereas for many proteins and other molecules, $10^4 \leq N \leq 10^6$. We should then use poorer resolution (for example, $K_{min} \sim 0.1 \text{ nm}^{-1}$) to obtain a higher flux, $\phi \propto K_{min}^2$. In addition, larger samples and detectors could, in principle, be used, with $V_s \propto K_{min}^2$ and $A_D \propto K_{min}^2$. For example, with $N \approx 10^4$, $f = 0.01$, and $K_{min} = 0.1 \text{ nm}^{-1}$, a counting rate of $\sim 10^3/s$ could be achieved. For such experiments, area detectors would be very desirable. At BNL, a 20-cm by 20-cm helium/argon area detector is used, with an efficiency of 80% and a resolution of $\sim 2 \text{ mm}$ in each direction.

What Can Be Learned from SANS?

The theoretical basis of SANS was reviewed by Lee and Goad, who made a number of important points.

Contrast Matching and Selective Deuteration

In order to distinguish a macromolecule in solution, the neutron-scattering powers of the molecule and solvent must differ. Usually the solvent is largely water, and since H_2O and D_2O have very different scattering powers but are equally good solvents, one can vary the hydrogen/deuterium ratio in the solvent to maximize contrast with the macromolecule or to eliminate the contrast with some part of it, e.g., a DNA component of a DNA/protein complex. By obtaining data at various hydrogen/deuterium values, one can also obtain information about the internal structure of the molecule.

Moreover, it is sometimes possible to selectively deuterate one or more components of a macromolecular complex. By comparing data with and without deuteration, information can be gained on the separation between components. Consider, for example, a complex containing components 1 and 2, which may or may not be deuterated, plus some invariant remainder. Let the scattering amplitude from 1 be H_1 (or D_1 when deuterated), and similarly for H_2 (or D_2), and let R be the remainder scattering amplitude. Consider four measurements of the intensity in which zero, one, or two components are deuterated. On forming the sum

$$\begin{aligned} & |H_1 + H_2 + R|^2 + |D_1 + D_2 + R|^2 - |H_1 + D_2 + R|^2 - |D_1 + H_2 + R|^2 \\ &= (D_1 - H_1)(D_2 - H_2)^* + \text{c.c.} \end{aligned} \quad (3)$$

we see that it contains interference between 1 and 2, and, hence, information on their separation, independent of the remainder.

The Small-Angle Limit

For randomly oriented macromolecules, the angular distribution of scattered neutrons will be, for small θ ,

$$I(\theta) = M^2 [1 - (K^2/3)r_g^2] \quad (4)$$

where M^2 is a constant $\sim (\bar{a})^3 N^2$, as in Eq. (2), K is given by Eq. (1), and r_g^2 is the mean-square radius of gyration. As indicated above, just what constitutes the observable macromolecule can be varied by adjusting the solvent hydrogen/deuterium ratio to match the scattering power of one or another portion. The apparent value of r_g^2 will thus depend on solvent hydrogen/deuterium.

If one seeks to determine r_g by measuring $I(\theta)$ at small angles, it appears from Eq. (4) that K values $\leq 1/r_g$ are of interest, i.e., $\theta \leq \lambda/2\pi r_g$. Thus, for example, for 0.01-eV neutrons and $r_g = 100 \text{ \AA}$, $\theta \leq 5 \times 10^{-4}$, whereas for $r_g = 1000 \text{ \AA}$, $\theta \leq 5 \times 10^{-5}$. In the WNR SANS apparatus, a minimum θ of 1.5×10^{-4} is designed.

The First Zero

When the scattering distribution from two deuterated subunits is evaluated [as from Eq. (3)], the first value of θ at which the intensity goes to zero is often interpreted as given the separation, d , of the subunits according to the relation $K \approx \pi/d$. However, Lee's analysis has shown that this conclusion depends on the shape of the subunits, so that if one or both are markedly nonspherical, the deduced d may be significantly off, as may also be the case if either particle possesses significant internal structure. The scattering distribution at moderate angles may be used to support or disprove various models of subunit organization, but is insufficient to determine the organization.

Some Biological Applications

Attention was focused on two kinds of biological systems of the greatest importance in modern biology, namely, 1) the structure of nucleic acids and their interactions with proteins, and 2) structure and dynamics of membranes and membrane-bound proteins. The first is of great interest because the genetic information of a cell, which is contained in its DNA, has its expression regulated by interactions with diverse and numerous protein molecules. Very little is known regarding the structures of these interacting units, which have dimensions $\geq 100 \text{ \AA}$. The second is important because many critical cellular proteins are buried in the cell membrane where they are difficult to study by conventional methods. Four examples of nucleic acid-protein interactions and two of membrane structure were discussed as possible systems for SANS.

Repressor-Operator Binding

The lac repressor in *E. Coli* is a protein tetramer of molecular weight $\sim 2 \times 10^4$, which binds very tightly to a specific DNA sequence, the operator, of ~ 30 base pairs. When the repressor is bound to the operator, it blocks transcription of adjacent genes. The operator DNA sequence has been isolated and is available through cloning techniques in milligram amounts. In addition, milligrams of repressor molecules are also available. Therefore, one could prepare samples of operator-repressor complex for SANS. By suitable contrast variations, it should prove possible to elucidate some aspects of the geometry of binding; e.g., does the repressor tetramer encircle the operator or just fit into a groove?

Structure of Chromatin

Chromatin is the complex of DNA and proteins that is present in interphase eukaryotic cells. In somatic cells, the protein consists of five histone proteins plus diverse nonhistone protein molecules. SANS and other experiments have revealed the nucleosome, a fundamental unit of chromatin that resembles a bead, 100 Å in diameter, and contains two each of four different histone molecules associated with DNA. The electron micrographs of chromatin sometimes show these beads on a string of DNA, but in the cell they may be condensed into fibers, which are in turn organized into helices, etc.

Various preparations of chromatin were suggested as of special interest. For example, satellite DNA contains multiple (sometimes $\geq 10^6$) repeats of simple few-base sequences and may have a simple and unusual structure. It can be obtained in adequate quantities for SANS study. In addition, it has been shown that histone phosphorylation and the tightness of its association with DNA appear to vary through the life cycle of a mammalian cell. Therefore, it would be of great interest to see how the chromatin structure varies with histone phosphorylation. Finally, it was noted that in sperm, the histones have been displaced by protamines and that the chromatin is very compact, but of uncertain structure. All of these systems appear to be good candidates for study with SANS.

It was noted that chromatin may be degraded, by enzymes or otherwise, during an experiment, and it was suggested that low temperatures would facilitate preservation. It was also observed that chromatin samples may be partially or largely oriented. In such cases, and depending on the degree of order, additional information could be obtained from the scattering distribution, but a two-dimensional array of detectors would, in general, be needed.

Binding of Receptors to Chromatin

The activation of cells by steroid hormones involves a binding of specific receptor molecules (proteins) to chromatin, which somehow activates transcription of certain genes. Such genes are being isolated, cloned, and sequenced. Their binding to histone, nonhistone, and receptor proteins will be intensively studied in the near future and could be investigated by SANS. It is believed by many that this system will be a paradigm for the regulation of mammalian gene expression.

Interaction of Transfer RNA (tRNA) and Ligase

A tRNA molecule must be recognized by its corresponding ligase (protein) molecule, which in turn attaches the appropriate amino acid. The nature of the recognition is quite unclear and may involve large contact areas between the ligase and tRNA. It has been reported recently, from Grenoble SANS experiments, that two ligase molecules associate with one tRNA. The components are available in large enough quantities for SANS experiments. Contrast matching could be used to elucidate the tRNA/ligase conformation.

Structure of Membrane-Bound Proteins

Many cell proteins function while bound in membranes. They are retained in the membranes by having hydrophobic amino acids in contact with the lipid phase and are often non-functional or insoluble if placed in water. They may be soluble and functional in detergent solutions, but when they are binding detergents, it is difficult to determine molecular weights and do biochemistry.

For example, neutron scattering of the photochemically active protein-chlorophyll complex, the reaction center isolated in solution from photosynthetic bacter *Rhodospseudomonas spheroides* R-26 and *R. rubrum* cell membranes, could be initiated. The isolation and purification of the reaction center, a biological energy converter, has been demonstrated. Three basic questions of its operation, which can be resolved by neutron scattering, are proposed: 1) *molecular weight* of the complex and of the subunits in the presence of detergents necessary for their solubleness (other methods of molecular-weight determination are made inaccurate by the presence of detergents); 2) localization of the region that requires close association with water, which is essential for the function of the molecule of this highly hydrophobic complex; and 3) spatial relation of the subunits in the active complex. These questions can be resolved using two techniques of neutron scattering: D_2O/H_2O contrast variation, and scattering from specifically deuterated molecules. The results from the neutron-scattering study will allow other techniques currently used to study the operation of the photochemically active reaction center to be calibrated, and thus hasten our understanding of the mechanism of a biological energy converter used in photosynthesis.

Vesicle-Membrane Fusion: Dynamic (?) Studies

In many cells, molecules are exported by fusion of vesicles with the cell membrane. Such events may be simulated *in vitro*, where fusion of vesicles may be initiated by addition of calcium to the medium. We discussed the question of whether the time dependence of fusion could be followed by SANS, e.g., by preparing vesicles and adding calcium just before a pulse. This would appear to be harder than the earlier experiments because of the requirement of preparing a sample before each pulse. A flowing system was considered. There was also some doubt as to whether aggregated vesicles could be adequately distinguished from fused vesicles. Other time-dependent processes, such as muscle contraction and tusulin polymicrization, were discussed briefly.

On the whole, we concluded that there are numerous exciting experiments that can be done with SANS, and that a stronger source (i.e., cold moderator plus storage ring) and area detectors are much to be desired and could result in a facility at least competitive with the best reactor sources.

Biologists must be intimately involved in the experiments so that proper attention can be paid to solvent and sample properties, and tests can be made of the biological functioning of the sample.

MATERIALS RESEARCH

Working Group: T. Kitchens (P-8), Chairman

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Introduction

On March 15-17, 1978, a study meeting was held at LAMPF to assess technical and scientific potential of the proposed WNR proton storage ring and to uncover impacts on LAMPF operation, the linac, and the beam lines. The following is a summary of the thoughts generated during the discussion of the Materials Research Working Group and other LASL staff members on various occasions. Our deliberations were devoted to 1) certain classes of neutron-scattering and irradiation studies, where we discovered nothing startlingly new, and 2) traditional and some not-so-traditional positive-muon spin-rotation (μ SR) spectroscopic techniques. The latter would allow much improved data-collection rates, and the working group has made some suggestions that, if followed, would lead to modifications of the PSR. These and our other recommendations follow our report.

PSR Implications to Materials Research Utilizing Neutrons at the WNR

The working group assessed the implications of the proposed PSR to the future materials research program with neutrons from the WNR. First, the essential technical aspects of the WNR and its proposed PSR which are significant to materials science were reviewed. This was followed by an account of the well-established and the new areas of materials science where the WNR will be useful, along with an assessment of the impact of the PSR. The conclusion of this analysis is that the major impact of the proposed PSR will be to increase the complementary capabilities of WNR pulsed source to those of the present steady-state research reactors for materials research. The PSR will enhance the effective flux in both the very cold ($E < 5$ meV) and the very hot, or epithermal ($E > 100$ meV) regimes, and for all experiments involving pulsed environments. The PSR will thereby open up new areas of materials research to neutron scattering. The PSR will also improve the compatibility of all neutron experiments and will thereby enhance the utilization of the WNR facility by a factor of 2 or 3.

Technical Background

By 1979, the WNR will provide a peak thermal neutron flux of more than 1.0×10^{16} neutrons/cm²/s by using 2% of the 1-mA proton LAMPF beam. This compares favorably with the most powerful steady-state research reactor in the United States, the 100-MW HFIR at Oak Ridge, whose thermal flux is $< 1.4 \times 10^{16}$ neutrons/cm²/s. Furthermore, the WNR source has some potential advantages over the steady-state reactors. Some general advantages are

1. The pulsed character of the WNR, which allows the use of time-of-flight spectroscopy with potentially better signal-to-noise and resolution than the standard neutron techniques for many experiments.
2. The spallation source, which has an inherent property of a large epithermal neutron intensity. For example, the intensity of neutrons with an energy of 0.3 eV will be more than 100 times the intensity at this energy from the HFIR at Oak Ridge, the most powerful U.S. neutron source.
3. The target-moderator assembly of the WNR, which may be easily tailored to produce suitable neutron energy distributions for particular experiments.

The two characteristics of the proposed PSR that are most important to the materials research program are

1. *Repetition-Rate Modification.*

Without the PSR, the WNR spallation neutron source may operate at a maximum pulse rate equivalent to the repetition rate of the LAMPF proton source, or 120 pps. The pulse rate may be reduced only by dropping pulses, and the average proton current will be reduced accordingly. With the PSR, the average proton current may be maintained while pulse rate may be optimized to the range of 720 to 1 pps for a given experiment. For example, this capability is very important to experiments utilizing very cold neutrons and time-of-flight spectroscopy. The PSR allows the rate to be reduced without losing average neutron intensity, which eliminates frame-overlap problems. Frame overlap occurs when fast and extraneous neutrons from a later pulse arrive at the detector assembly before the slow neutrons from the previous pulse arrive. For such experiments, the PSR could provide 10 times the effective neutron intensity otherwise available.

2. *Pulse Compression.*

Each LAMPF pulse accepted by the WNR facility may be as long as 50 μ s. The proposed PRS would compress the proton pulse to 0.15 μ s, while maintaining the average proton current. This short proton pulse allows the neutron pulse width to be determined by the target-moderator assembly only. As mentioned above, the target-moderator assembly can be optimized to produce the best energy distribution and, thereby, energy resolution for a given experiment. For example, this capability of the PSR will be especially important to epithermal neutron experiments. Without the PSR, the proton pulse would have to be reduced to 2 μ s or less to provide the necessary energy resolution in most experiments at epithermal energies. With the PSR, a 20- μ s proton pulse could be compressed with an effective gain in neutron intensity of 10 or more for such experiments.

Areas of Impact of the Proposed PSR on Materials Science

Below is an account of several important areas of materials research, with a brief assessment of the role of the proposed PSR at the WNR.

Research with Pulsed Environments

It is often possible to produce more extreme pressures, magnetic fields, or other environmental effects if they are pulsed. It is also important to understand the transitory characteristics of materials to pulsed environments. These nearly untouched areas of neutron scattering are

naturally matched to the WNR facility, and the ability to tailor the pulse rate with the proposed storage ring would allow the environmental pulse rate to be optimally matched. Even slower pulse rates than presently planned for the PSR, say 1 pulse every 10 seconds, would allow even more extreme pulsed environments to be developed. Large effective flux increases are again possible.

Irradiation Studies

The PSR is not expected to have a large impact here since fluence (time-integrated flux), not peak flux, is the most significant parameter. Nevertheless, this has not been proved for the large peak fluxes that would be available at the WNR with the proposed PSR — and encountered in pulsed fusion reactors. The WNR, with its storage ring, would be a unique facility to use to investigate this point. The pulsed source also allows the study of the dynamic effects associated with radiation damage.

Materials Research with Very-Cold ($E < 5\text{-meV}$) Neutrons

The capabilities of very-cold neutrons is only now being appreciated in materials research. The cold-neutron source at the high-flux reactor at the Institut Laue-Langevin, operated by Great Britain, Germany, and France, and other European cold-neutron sources, has been successful in making major advances through low-angle neutron-scattering techniques in our understanding of polymers, biological substances, defect structures in metallic materials, and to the behavior of materials near phase transitions. The scientific potential for very-cold neutrons appears to be immense. Very little work of this type has been done in the U.S.A., and the planned cold-source modifications to the High-Flux Beam Reactor at Brookhaven and at the National Bureau of Standards together will not have the capabilities of the Grenoble facility.

The repetition rate of the LAMPF proton beam is not optimum for very-cold neutron research because of the frame overlap problems described above. An optimum-target cold-moderator assembly has not been designed, but there appear to be no outstanding difficulties. The proposed PSR would allow the proton pulse rate to be optimized, leading to very-cold neutron intensities near those available at Grenoble. The WNR installation could also accommodate a research facility as extensive as the one at Grenoble. If such a program were to be successfully instigated, it would be necessary to have additional funds for instrumentation development and the acquisition of an expert local staff, especially in the biological materials and polymer science areas.

Materials Research with "Thermal" ($E = 10\text{-}50\text{-meV}$) Neutrons

This is the neutron energy range available from steady-state research reactors whose moderators are near room temperature. It is the range where neutrons have a proven capability in probing structures as well as vibrational and magnetic properties of materials.

Thermal neutrons have been extensively used for many years in such investigations. In the future, many scientifically significant but technically routine measurements with thermal neutrons are expected in the areas of metallurgy and crystal chemistry. The major hindrance to these investigations has been the lack of neutron intensity, even using the most powerful steady-state reactors to investigate the largest available specimens with the required resolution. The

new technique of "profile analysis," which allows many structural parameters to be determined from the diffraction peak profiles from crystalline powders, removes the necessity of large single-crystal specimens but still requires high resolution. This technique is matched to the time-of-flight techniques that are optimally coupled to pulsed sources.

The LAMPF pulse structure is nearly perfect for producing WNR neutron pulses in the thermal regime. Generally, the ability to reduce the repetition rate while maintaining the time-average neutron intensity allows the signal-to-noise ratio to be improved. The PSR could, however, enhance the thermal neutron fluxes by two or three — into the range of the flux expected from a 150- to 200-MW steady-state reactor. (Such a reactor would cost more than \$200 M, have an operating budget >\$5 M/yr, and would be subject to the increasingly difficult operating procedural regulations of the Nuclear Regulatory Commission.)

Materials Research Utilizing Epithermal ($E = 0.1$ - to 1 -eV) Neutrons

One of the exciting new vistas for neutron research made possible with spallation neutron sources is in the epithermal region. As mentioned earlier, the energy distribution of the neutrons from the WNR spallation source extends to this region with intensities more than two orders of magnitude larger than the most powerful steady-state reactor. Since the energy realm of chemical bonding, molecular dynamics, and electronic and some magnetic processes is 0.1 to 1 eV, these phenomena may be probed for the first time by neutrons. Neutron spectroscopy will have several advantages over the more conventional spectroscopies of this energy range — Raman and infrared. Neutrons are sensitive to all energy levels (not dependent on selection rules), are highly sensitive to motions involving hydrogen, and can be used as a probe of the structure as well as the dynamics of the system under investigation. Two examples of important applications of epithermal neutrons are the study of absorbed hydrocarbon molecules on surfaces, which is one of the initial research programs at the WNR, and the study of single-particle magnetic excitations — the Stoner excitations.

The pulse structure of the WNR spallation source is not optimum for the epithermal region. Only 0.5% of the LAMPF proton beam could be utilized, because the pulse length would be otherwise too long for good energy resolution. The proposed PSR would allow the proton pulse to be compressed as described above, thereby enhancing the flux by an order of magnitude. This capability will be important to the extension of neutron techniques to these areas of research.

PRS Implications to Materials Research Utilizing Muons

The working group discussed the implications of the proposed PSR on the future materials program utilizing muons. It was recognized that the 6% duty cycle on the main beam line of LAMPF was causing spin-rotation data-collection rates to be 1/16 of those available on several other muon sources around the world, and that the PSR might eliminate this difficulty. The group quickly concluded that this was the major impact to muon materials research. First, the typical spectrometer used for positive-muon spin rotation (μ^+ SR), such as the one used by the LASL μ SR team at the LAMPF Stopped Muon channel (SMC), was reviewed. We concluded that although the limitations of the 6% duty cycle at LAMPF could be eliminated by utilizing a "slow-spill" wire septum on the PSR, the current from such a slow spill would not provide μ SR data rates much greater than those provided on the SMC. Next, the working group considered some more novel μ SR techniques. First of these is the so-called stroboscopic approach. Again, it was concluded that the data-collection ratios would not be substantially increased. Finally, a

μ SR technique was considered which utilizes the intense pulse capability of the PSR. Here a substantial increase in μ SR data-collection rates was predicted.

The μ SR technique is relatively new, and the working group considered only a rather generalized experiment. For this reason, it concluded that if a PSR ejection port were developed for μ SR, such a port should be made flexible enough to utilize the slow-spill technique because this unusual ability may prove to be more useful than is presently foreseeable.

Finally, the working group wished that it had considered more carefully μ^- SR and other materials research involving muons, but the data-collection rates in these experiments have not been a major limitation.

Some Technical Background

The μ^+ SR technique generally used today requires a determination that a muon has stopped in the sample to establish a base time, and the positron count is vetoed if a second stopped muon occurs before the count comes or before a given time passes, usually about 4 muon lifetimes or 8 μ s. (For a more detailed account of the μ SR spectrometer, see R. H. Heffner *et al.*, " μ^+ SR Studies at LAMPF," *Hyperfine Interactions IV*, North Holland Pub., Inc., 1978, p. 839.) This limits muon-stopping rates to 1.6×10^6 cps. Because LAMPF has a duty cycle of 6%, the stopping rates for experiments on the SMC are limited to $<10^4$ cps. These rates are already obtained with a LAMPF proton current of 250 μ A, equal to 25% of the design current, even though the SMC is not optimized for μ SR experiments. However, this maximum useful stopping rate was not obtained at 100 μ A, or 10% of LAMPF, because of the large beam diameter at SMC. In what follows, we assume that a well-optimized muon channel would provide the limiting count rate of 10^4 at 10 μ A, with a small beam diameter.

Various μ SR-PSR Techniques

Extending the Duty Cycle for μ SR Experiments Using the PSR. Here, we assume a μ SR spectrometer of the conventional type. For the most optimistic case, we assume that the PSR can store 2%, say the first 10 μ s of each 500- μ s macropulse, of the LAMPF current, and it is run in the debunched mode. The muons are produced by a proton beam extracted from the PSR by a slow-spill wire spectrum. Even if this could be arranged so that we had a constant $0.02 \times 1000 \mu\text{A} = 20\text{-}\mu\text{A}$ proton beam on a production target of the type presently used, and the muon channel were carefully optimized, it would not be possible to reach the optimum stopping rate of 1.6×10^6 cps mentioned in the previous section. Calculations showed that the PSR might produce stopping rates near 2×10^4 cps, about two times less than the rate now available on the main LAMPF beam. A surface muon beam would help only in the sense of greater flux, and thereby allow smaller samples to be used; it would not increase the intrinsic data-collection rates.

Stroboscopic Techniques. The concept in the stroboscopic technique is to arrange the muon beam to have a periodic modulation within the useful range of μ SR, say 1-100 MHz, and with sufficient intensity that a current detector, rather than a discrete count detector, can be used. If the current is measured in phase with this modulation as the transverse magnetic field is slowly swept, a "resonance" will be observed when the muon spin-rotational frequency matches that of the beam modulation. Experiments of this type should be much simpler electronically,

and much faster. (For a more detailed account, see LAMPF Proposal No. 379 by K. Crowe, S. Rosenblum, *et al.*)

As tabulated in Table I, the present PSR design may be loaded with protons, in distributions to produce modulations with frequencies of 3.33 to 100 MHz, nearly perfect for this technique. The muons are produced by the modulated proton beam extracted from the PSR by a slow-spill wire septum. The difficulty is again in the intensity of the muon beam. The 2% of LAMPF loading of the PSR is more questionable, so we can assume data to be discrete counts and only about 10^4 cps.

This discussion also does not strongly support the development of a muon channel from the PSR. Nevertheless, this technique has not been extensively used and may have some unforeseen advantages.

A Pulsed-Muon Spectrometer. If a sufficiently short pulse of muons were stopped in a target and the next pulse of muons followed many muon-lifetimes later, then knowing the time of arrival of the pulse would be the base time and no coincidence or veto circuits would be needed — all "counts" could be accepted. This scheme thereby eliminates the stopping-rate limitation on the conventional muon spectrometer. This Pulsed-Muon Spectrometer (PMS) can be accomplished with the PSR, using the standard ejector septum. For the PMS operation, every tenth micropulse from LAMPF would be stored, which would cause the PSR to be loaded with six proton bunches <2-ns long. A 2-ns pulse is short enough: most μ SR spectrometers run with 1- to 5-ns time resolution. If one pulse is ejected to the muon-production target every 9μ s, 180 micropulses have been overlapped in each pulse after the initial and before the final transient effects. The PSR is filled with 240 micropulses, or 0.24% of a LAMPF macropulse, at the maximum, yet is delivering 10% of LAMPF to the muon-production target. Table II shows this operation scheme. Other filling and unloading schemes which reduce the repetition rate of the ejection system, but which maintain the 2-ns bunch length, are also acceptable. This method would provide an order of magnitude improvement in muon stopping rates over the conventional muon spectrometer on the main LAMPF beam line. The difficulty is that, under the present design, this operation would require the total H^- production of LAMPF.

The working group believes this mode of operation deserves careful consideration, and that if a muon channel is developed on the strength of the PMS, then the wire septum operation should also be considered.

TABLE I

**50-50 CHARGE DISTRIBUTIONS IN THE PSR USEFUL FOR
THE STROBOSCOPIC μ SR TECHNIQUE**

3.33-MHz distribution	150- μ s "debunched" structure
10.0 -MHz distribution	3 bunches of 10 micropulses, evenly spaced
16.7 -MHz distribution	5 bunches of 6 micropulses, evenly spaced
20.0 -MHz distribution	6 bunches of 5 micropulses, evenly spaced
33.3 -MHz distribution	10 bunches of 3 micropulses, evenly spaced
50.0 -MHz distribution	15 bunches of 2 micropulses, evenly spaced
100.0 -MHz distribution	30 bunches of 1 micropulse, evenly spaced

TABLE II
PULSED-MUON-SPECTROMETER OPERATION

<u>Pulse Number</u>	<u>#1</u>	<u>#2</u>	<u>#3</u>	<u>#4</u>	<u>#5</u>	<u>#6</u>	<u>#7</u>	<u> </u>
Time after macro-pulse start	9 μ s	18 μ s	27 μ s	36 μ s	45 μ s	54 μ s	63 μ s	
Number of overlapped micropulses ejected	30	60	90	120	150	180	180	
<u>Pulse Number</u>	<u>#54</u>	<u>#55</u>	<u>#56</u>	<u>#57</u>	<u>#58</u>	<u>#59</u>	<u>#60</u>	<u>#61</u>
Time after macro-pulse start	486 μ s	495 μ s	504 μ s	513 μ s	522 μ s	531 μ s	540 μ s	549 μ s
Number of overlapped micropulses ejected	180	180	167	137	107	77	47	17

Recommendations from the Materials Research Working Group

Relative to Neutron Scattering:

To modify the PSR to be capable of running at 1/10 cps without reducing the time-average proton current below 2% of LAMPF.

Relative to Muon Spin Rotation

To provide a slow-spill wire septum and fast-ejection mechanism on a port that can feed an optimized channel for muon spin-rotation experiments and

1. to be able to store the 50%-on/50%-off proton distributions in the PSR listed in Table I.
(The "debunched" operation should be 150-ns on/150-ns off);
2. to be able to operate the PSR in the mode described in Table II.

A General Statement

All materials research programs would gain significantly from increased storage capacity of the PSR.

REPORT OF THE SUBCOMMITTEE ON LONG AND SHORT DUTY-FACTOR APPLICATIONS OF THE PSR

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Short Duty-Factor Applications

Neutrino Physics

The major advantage of the PSR for neutrino physics is a reduction in cosmic-ray backgrounds. A number of interesting neutrino experiments will benefit from use of the PSR, *provided the average current is $\geq 100 \mu\text{A}$* . One mode of PSR that provides $100 \mu\text{A}$ can also spill the beam in 10 pulses 200-ns wide. The "effective" duty factor, considering the response time of ~ 500 ns in a large (30- to 100-ton) detector, is $\sim 6 \times 10^{-4}$, which corresponds to a 10^4 reduction compared to the usual LAMPF duty factor of 6%.

The value of such a reduction can be appreciated from the experience gained by Exp. 31, a search for $\bar{\nu}_e$ in beam-stop neutrinos. This group saw 500-600 events/day from cosmic rays, compared with an anticipated signal of ~ 20 /day when the muon number conversion is multiplicative and there are as many $\bar{\nu}_e$ as ν_e . The experimental upper limit on the fraction of $\bar{\nu}_e$ would be much better if the cosmic-ray backgrounds were absent.

Several neutrino-producing facilities were discussed:

- 1) beam-stop neutrinos,
- 2) a neutrino beam channel for ν_μ from $\pi^\pm$ decay, and
- 3) a Budker/Lobashov magnetic trap.

The LAMPF beam-stop neutrino facility provides a neutrino flux of $1 \times 10^7/\text{cm}^2/\text{s}$ at 8 m for an incident proton beam of $\sim 200 \mu\text{A}$. The average energy for the neutrinos is ~ 35 MeV.

A neutrino beam from a large solid-angle (2-sr) pion channel with an 8-m decay section was proposed. Assuming 0° production from a 20-g carbon target, one can expect a ν_μ flux of around $3.6 \times 10^6/\text{cm}^2/\text{s}$ with an average energy of ~ 140 MeV. The pion channel could be a superconducting orange peel, such as at SIN, or a horn, or possibly a large-aperture conventional magnet channel.

A mirror-type magnetic trap filled with π and μ can be a source of both electron and muon neutrinos of energies higher than from a beam stop. In this scheme, the production target is placed in the magnetic bottle, which can trap a large fraction of the pions and the decay muons. For a 20-g carbon target, $100\text{-}\mu\text{A}$ average proton beam, we expect an average energy of around 100 MeV and a flux of ν_μ of $(\sim 4) \times 10^6/\text{cm}^2/\text{s}$ at 8 m.

Because of the different lifetimes for π and μ , there will be a separation in time of ν_s from π decay, and ν_s from μ decay in the magnetic trap or from the beam stop in the mode where the beam spills are ~ 200 ns.

A comparison of the three methods is shown for $100 \mu\text{A}$ of protons in Table III.

TABLE III
COMPARISON OF THREE ν BEAMS

<u>Method</u>	<u>E_ν (MeV)</u>	<u>Flux ($\nu_\mu/\text{cm}^2/\text{s}$)</u>
Beam stop	35	5.0×10^4
2-sr channel	140	3.6×10^4
Lobashov bottle	100	4.0×10^4

Some examples of interesting experiments to study at such facilities include

- 1) coherent inelastic scattering from nuclei such as $\nu_\mu + {}^{12}\text{C}(0^+, T = 0) \rightarrow \nu_\mu + {}^{12}\text{C}^*(15.1 \text{ MeV}, 1 + T = 1)$ followed by ${}^{12}\text{C}^* \xrightarrow{(100\%)} {}^{12}\text{C}_{gs} + 15.1\text{-MeV } \gamma$. The expected cross section at 140 MeV is around $5 \times 10^{-41}/\text{cm}^2$, which should yield around 20 events/day in a 30-ton detector,
- 2) elastic scattering of ν_μ from protons and electrons, and
- 3) neutrino oscillations.

Clashing Beams of Pions and Muons

Studies of $\pi\pi$ scattering with clashing beams of pions is an alluring possibility enhanced by the low duty factor of the PSR. For the PSR mode with 1.2-Hz⁺ rate, 200-ns spill, and 100- μA average current, the anticipated $\pi^+\pi^-$ interaction rate in Precetron as originally designed would be optimistically around 50 event/h. In the Precetron design, the target is placed in the weak magnetic bottle in order to capture a high fraction of all the pions produced. Interesting luminosities for $\pi\pi$ collisions are possible, but the presence of the production target in the same region will produce large backgrounds of neutrons and photons even after the end of the proton spill.

The Precetron is a weakly focusing magnetic mirror trap. A larger fraction of pions can be captured in more strongly varying fields. Larger luminosities will result, but the background problems with the target are correspondingly worse.

It may be possible to remove the production target some distance from the clashing beam region and transport the pions to the mirror region where they can dwell for a time comparable to the pion lifetime. C. Gruhn has traced orbits in mirror fields that have the required dwell times. His preliminary calculations indicate that an input phase space of 50 $\pi/\text{mr}/\text{cm}$ ($\Delta p/p \sim 0.01$, $p_0 = 450 \text{ MeV}/c$) would occupy an oval shell $\sim 1 \text{ cm}$ thick, 10 cm in radius, and 25 cm long for $\sim 80 \text{ ns}$ in a 150-kG field if the initial p_z is $\sim 60 \text{ MeV}/c$. For 0° production on a 20-cm carbon target with a 0.5-cm-diam beam spot, the 50- $\pi/\text{mr}/\text{cm}$ acceptance corresponds to $\Delta\Omega \sim 0.1$. A luminosity of $\sim 3 \times 10^{24}/\text{cm}^2/\text{h}$ is estimated for this situation when the PSR operates at 1.2 Hz, 200-ns spill, and 100- μA average current. For the ρ region, $\sigma_{\pi\pi} \sim 10^{-28}$, and an event rate of 0.33%/h would result.

The formation of exotic atoms, such as $\pi^+\pi^-$, $\pi^\pm\mu^\mp$, and $\mu^+\mu^-$, would be very interesting. Formation of such atoms by $\mu^+ + \mu^- \rightarrow (\mu^+\mu^-) + \gamma$ requires a very low relative velocity for a significant cross section. For $\sigma \sim 10^{-20} \text{ cm}^2$, $\beta_{\text{rel}} \approx 2 \times 10^{-8}$. Such low velocities are not easily reached in head-on collisions. In Precetron, they are most likely reached when the two particles are traveling side by side. Event rates of 0.1/yr are estimated for PSR operating at the most favorable mode.

Long Duty-Factor Applications

Many experiments at LAMPF, perhaps as many as 25%, suffer from the low duty factor. A duty factor in excess of 50% would be a great help. Once again, the interest is in long duty factor at a reasonable intensity $\geq 50\text{-}\mu\text{A}$ average. It is recommended that the capability for slow extraction from the PSR be incorporated in the design.

Maximum utilization of the slow spill may entail considerable expense in bringing the beam back to Areas A or even B and C. It may prove to be more desirable to build a new experimental area with secondary beams. For Areas B and C, the beam splitting and phase-space tailoring of H^+ is a more difficult problem than for H^- .

For rare μ -decay experiments, a long duty-factor mode with $\sim 1\text{-}\mu\text{s}$ chopping is desirable. The ideal would be a repeated sequence of one short intense beam pulse (ideally a δ function in time) of $1\text{ }\mu\text{s}$ followed by a period of beam-off (of order $2\text{-}5\text{ }\mu\text{s}$) to observe the μ decays in the absence of beam-associated backgrounds. At SIN, chopping of the beam was essential for the fine results on $\mu \rightarrow e$ conversion. At LAMPF, chopping of the primary beam affects all users. At the PSR, it would not. It could also be used at a high duty factor (as averaged over periods of $10\text{ }\mu\text{s}$ or larger).

Acceleration to Several GeV/c

The subcommittee was quite interested in the possibility of accelerating protons to $\sim 5\text{ GeV/c}$ in the PSR provided the intensity was $\geq 100\text{-}\mu\text{A}$ average. This would be the "kaon factory" region. Currents of $< 10\text{ }\mu\text{A}$ are probably not competitive with the present AGS for stopping K beams. It was felt that $100\text{ }\mu\text{A}$ would be needed to remain competitive several years from now when the PSR becomes operational.

Discussions with the PSR designers indicated that redesign of the PSR to make the ring three times larger in diameter and provide capability for acceleration to 5 GeV/c would add several million dollars to the cost of the project. An experimental area to exploit such a capability would be even more. The final consensus was that acceleration of $100\text{ }\mu\text{A}$ to several GeV/c would greatly extend the scope of the PSR project, and that it would be better to have a separate synchrotron project explicitly justified for a "kaon factory."

IMPACT ON SWITCHYARD AND EXPERIMENTAL AREAS

L. Agnew (MP-7)

During the plenary and committee working sessions of the WNR Storage Ring Study Meeting, a number of ideas and proposals were raised for new experimental facilities or alternate operating modes that may be possible with the PSR. An assessment of the impact of these ideas on the existing LAMPF accelerator, switchyard, and experimental areas is needed before decisions can be made to pursue these ideas in a serious way. In this section, the ideas that have an impact on the switchyard and the experimental areas are listed, and an appraisal of their impact is given.

Proposals That Have Impact on the Switchyard and Experimental Areas

1. Simultaneous beam to all areas — Areas A, B, and C, and WNR
2. Compressed duty factor
3. Lengthened duty factor
4. Return of beam from PSR to Area A
5. Return of beam from PSR to Areas B and C
6. Relocation of storage ring
7. Larger storage ring — future options
8. New experimental floor space
 - a. for nucleon-physics experiments
 - b. for μ SR experiments
 - c. for neutrino experiments
 - d. at H^0 dump area
9. 400- to 500-MeV beam storage for nucleon experiments
10. Accelerated and decelerated beam
11. Clashing beams of unstable particles

General Approach to Appraisal of Impact

Our task is to appraise the various ideas in terms of their impact on the LAMPF switchyard and the existing (or projected) experimental areas. An evaluation of the merit or justification for the proposals is outside the scope of this section. It is acknowledged that the type of appraisal reported here is, in some cases, little more than a guess; firmer estimates based on detailed studies should be made before final decisions are rendered on proposals that offer unique experimental capabilities. For the purposes of this report, the following levels of impact are defined:

Minor: No conflict with present facility or realistic long-range plans. Technical feasibility is assured. Design effort, <2 man-years; cost, <\$1 M; shutdown, $\leq$ 2 months.

Moderate: Minor conflicts with rest of facility. Technical feasibility appears okay, but detailed study needed. Design effort, 2-5 man-years; cost, \$1-2 M; shutdown, 3-4 months.

Major: Moderate conflict with the rest of the facility. Technical feasibility not yet demonstrated. Design effort, >5 man-years; cost, $\geq$ \$3 M; shutdown, 6 months.

Specific Appraisals

- *1. Simultaneous beam to all areas: minor impact. Hardware changes in the switchyard appear to be straightforward and relatively minor. A high-intensity H⁻ source is needed; it is already well along in development.
2. Compressed duty factor: no impact. This feature is already a basic part of the PSR proposal.
3. Lengthened duty factor: no impact on switchyard and experimental areas. Minor-to-moderate impact on PSR effort.
4. Return of beam from PSR to Area A: major impact. Modification of existing tunnels and shielding required. Substantial changes in PSR delivery leg and Line D transport required. Changes in switchyard transport required. PSR shielding and activation level is a concern at typical Area A average currents. Timing problems must be solved. This idea does not seem to be worth pursuing.
5. Return of beam from PSR to Areas B and C: major impact. Modifications of existing tunnels and shielding required. Substantial changes in PSR delivery leg and Line D transport required. Substantial changes in Line X transport required. Would lose ability to share beam at HRS, Line B, and EPB by use of strippers. Line C beam tailoring is more difficult. This idea does not appear to be worth pursuing.
6. Relocation of storage ring: major impact. New design studies, siting studies, cost estimates, etc., would be required. Studies alone would be a major impact on PSR project.
7. Larger storage ring to permit future options: moderate impact on PSR project (no impact on switchyard or experimental areas).
8. New experimental floor space: no impact on switchyard and LAMPF experimental areas. Present PSR and WNR design would accommodate a pass-through beam to new experimental facilities south of WNR. Use of the H⁰ dump area for experiments would create a moderate impact on the PSR project.
- *9. 400- to 500-MeV beam storage: minor impact on the switchyard.
10. Accelerated and decelerated beam: practicability is doubtful.
11. Clashing beams of unstable particles: practicability is doubtful.

*Items that also have impact on the accelerator.

STORAGE RING IMPACT ON THE LAMPF ACCELERATOR

D. C. Hagerman (MP-DO)

The proposed storage ring in the form described by G. P. Lawrence and R. K. Cooper¹ will require some significant changes in the operation of the LAMPF accelerator. However, it seems quite probable that these changes can be made in such a manner as to minimize impact on the present users of the facility. Further, while the storage-ring requirements are somewhat beyond the present state-of-the-art, the necessary development work is either a continuation of the present program of accelerator development or is under study elsewhere.

The ideal solution for serving the storage ring and the present users of LAMPF will be to provide beam on a fully time-shared basis. That is, during the same macropulse we shall have simultaneously a high-intensity H^+ beam for Area A, and a low-intensity or polarized H^- beam for Areas B and C; later during this macropulse, a high-intensity H^- beam will be provided for the storage ring.

In order to achieve this ideal solution, we must first achieve full average current, and also have sufficient acceptance in the accelerator radial space for the desired beam combinations. This radial space cannot be altered during a macropulse since all focusing and steering elements have slow time-response characteristics (a few fast-switching elements in the low-energy transport and switchyard will be needed).

Some evaluation of the probability of achieving the ideal solution can be made by considering the present operation of the accelerator. The LAMPF accelerator now provides a 300- μ A, 6% duty-factor H^+ beam, along with a 5- μ A H^- beam. Transmission of H^+ beam (70 to 800 MeV) is 99.9%, and the H^- beam has a similar low-loss level. The emittance of these beams at 750 keV is approximately as shown in Table IV.

The emittance increases as the current is increased. With the present source and a peak H^+ current of 10 mA, the emittance is about doubled, and transmission through the machine is an acceptable 99.6%. It is believed that the brightness of the present H^+ source can be increased by

TABLE IV
 H^- AND H^+ BEAM EMITTANCE
AT 750 keV

	H^+ (cm mrad) (~5-mA peak)	H^- (cm mrad) (~100- μ A peak)
Horizontal	0.97 π	1.00 π
Vertical	0.90 π	1.06 π

(These phase-space areas are believed to contain 98% of the beam.)

perhaps a factor of 2, and that with some experience at the higher currents, transmission will be further improved.* Thus, it appears that we can be confident that we shall achieve peak currents in excess of 10 mA. This means that 1-mA average current operation is quite close to reality, particularly if the duty factor can be made larger than the present maximum value of 7.5%.

The amount of steering in the machine is small now, and probably can be reduced. Once this has been done, and if an H^- source can be obtained with a brightness about the same as the expected H^+ source brightness, then we can serve all users on the full time-shared basis, with an average total accelerated current of ~ 1 mA.

After the full time-shared mode has been achieved, other improvements, such as different beam energies for the storage ring and the other users by time switching of the accelerator rf, might be possible.

*The H^- loss due to electromagnetic or gas stripping will be well within allowable loss criteria.

REFERENCE

1. R. K. Cooper and G. P. Lawrence, "The Proposed Proton Storage Ring at WNR," Los Alamos Scientific Laboratory internal document, June 16, 1977.

APPENDIX A

THE PROPOSED PROTON STORAGE RING AT WNR

by

Richard K. Cooper and George P. Lawrence

Relation of Proton Storage Ring to WNR

The WNR facility at LASL is a new pulsed-neutron source, now approaching operational status. It achieved operational status in 1977. Neutrons at WNR are produced by $p(s,n)$ spallation reactions using 800-MeV protons from the LAMPF accelerator. When both LAMPF and WNR are in full operation, WNR will use up to 2% of this beam in pulses ranging from 10 μ s in duration down to a single accelerator micropulse (≈ 200 ps), at a basic repetition rate of 120 Hz.

Much of the experimental program for which WNR is intended is based on time-of-flight (TOF) energy-measurement techniques. Since the neutron spectrum produced is "white" or polyenergetic, the TOF method is fundamental to use of the facility. For good-resolution high-energy neutron TOF work, one requires the shortest possible pulses with a sufficient number of neutrons in each pulse. In the case of WNR, this is one LAMPF micropulse, which contains 5×10^8 protons and yields about 10^{10} neutrons at the WNR target. For many experiments this results in an insufficient number of neutrons per pulse. For slow-neutron (thermal, epithermal, and sub-thermal) TOF work, much longer pulses can be used, up to 10 μ s in length. These contain 10^{12} protons and produce 2×10^{13} neutrons per pulse.

The proposed PSR, which would be an addition to, or second phase, of the WNR facility, is a device which would enable very much more of the LAMPF proton beam to be converted to pulses suitable for neutron TOF work at *all* neutron energies produced at the facility. It operates both as a pulse compressor, squeezing long (500- μ s) LAMPF pulses into much shorter ones (1 ns — 200 ns), and as a duty cycle or repetition-rate shifter, accepting pulses from LAMPF at the normal rate of 120 Hz and ejecting them at rates from 1 to 720 Hz. It accomplishes these operations with no loss of or reduction in time-averaged beam intensity. Thus, it makes it possible to achieve consistently high average neutron source strengths (10^{13} - 10^{14} neutrons/s) with pulse characteristics optimally matched to experimental TOF requirements for neutrons ranging over 9 decades (0.03 eV to 30 MeV) of energy.

At the high-energy end of the spectrum, the experimental requirements call for high repetition rates, a high intensity of neutrons per pulse, and short pulse lengths (1 ns or less). At the low-energy end of the spectrum, there are TOF frame-overlap problems if too high a repetition rate is used, and, therefore, a low frequency is needed (1-10 Hz). Some pulse compression is also required since the optimum pulse length is short compared to the moderated neutron evaporation time, i.e., about 100-200 ns.

At present, WNR target systems and experimental area shielding are designed to accept up to 2% of the LAMPF proton beam on a time-averaged basis. Greater percentages of the LAMPF beam are not useful in WNR-TOF work (without the PSR) because of pulse length. The PSR improves the picture here, too. Assuming that reasonably low beam spills can be achieved in the

ring and that appropriate shielding and power-handling capacities can be built into the existing WNR facilities, it is possible to think of using 10% of the time-averaged LAMPF beam, or an even greater fraction, for short periods of time.

Summary of PSR Characteristics

The PSR is basically a ring of bending and focusing magnets, separated by straight sections of various lengths, which forms a closed path in which protons circulate and are accumulated. The present design calls for an eight-sided structure. Design is governed by ejection and injection considerations, as well as desired beam dimensions, rf-bunching demands, and beam-stabilization techniques. Basically, the PSR works by continuous accumulation of protons in a closed orbit, using an injected H^- beam that is stripped to H^+ inside the machine. This technique (proven at ANL) permits accumulation of high-quality very-intense beams, and effectively circumvents Liouville's constraints on constant density in phase space. It cannot be matched by conventional proton injection. Figure A-1 shows the WNR facility and the orientation of the proposed PSR with respect to it. After protons have been accumulated to the desired current level, they are ejected by a fast pulsed-magnet system and transported to the WNR neutron-production target or some other area for possible uses other than neutron production. Figure A-2 shows the schematic operation of the ring, and Fig. A-3 is a plan view of the ring components. Table A-I gives the PSR dimensions, and Table A-II the PSR operating characteristics.

Fig. A-1.
WNR Facility.

Fig. A-2.

Schematic of PSR increases pulse intensity 200 times, increases repetition frequency 6 times.

Modes of PSR Operation

At present, we visualize two extremes of operation for the PSR, which reflect its performance abilities in different circumstances. Between these extremes fall a whole range of other options that have only begun to be explored.

In one extreme, which we call the high-frequency mode of operation, the PSR would increase the number of protons/pulse by a factor of 200 or more, and the WNR repetition frequency by a factor of 6 (to give 720 Hz). These increases improve the short-pulse capabilities of WNR by up to three orders of magnitude.

In another extreme of operation, the PSR can accumulate protons, more or less uniformly around its circumference, in a single long bunch. In this mode, protons can be accumulated up to a limit imposed by space-charge forces and beam instabilities due to coherent and incoherent interactions of the circulating particles with themselves and with the machine environment. A single LAMPF macropulse contains 5×10^{13} protons. The PSR, as presently conceived, can accumulate at least this many particles and eject them in a bunch about 200-ns long ($\sim 66\%$ of the ring circulation period). Stability limits are not well known, but it is thought that perhaps 10 or more such pulses can be accumulated in the ring. Storage of a whole LAMPF macropulse will provide 10^{14} neutrons/pulse in a burst width of ~ 200 ns. The repetition frequency of these pulses will be limited by the time-averaged current, which can be deposited in the WNR target, and may be as low as 1 Hz.

Between the 720-Hz short-bunch operation (1 ns) and the 1-Hz unbunched operation (200 ns) are many possible parametric variations of pulse intensity,

Fig. A-3.

Proton storage ring.

TABLE A-I

RING DIMENSIONS

Circumference (length of central orbit)	75.240 m
Mean radius	11.975 m
Orbit radius in bending magnets	4.881 m
Length of bending magnets	3.834 m
Gap height	0.080 m
Gap width (useful field)	0.120 m
Length of quadrupole magnets	0.400 m
Bore of quadrupole magnets	0.110 m
Length of straight section	4.171 m

TABLE A-II
OPERATING CHARACTERISTICS

Betatron oscillations per revolution (nominal)	
Radial, ν_x	2.25
Vertical, ν_y	2.25
Transition gamma, γ_t	2.07
Bending magnet field strength	1.000 T
Focusing quadrupole gradient	3.116 T/m
Defocusing quadrupole gradient	-3.980 T/m
Bunched operation	
No. of bunches	6.
Length of bunch	Ins
rf frequency	603.75 MHz
Harmonic number	180.
Space-charge limit for	
$E_x = E_y = \pi \times 10^{-6}$ m-rad ($\Delta\nu = 0.2$)	1.23×10^{11} p/bunch
Unbunched operation	
Space-charge limit for	
$E_x = E_y = \pi \times 10^{-6}$ m-rad	3.69×10^{13} p
Chromaticity $\delta\nu/\delta$ ($\Delta p/p$)	
Radial	-0.30
Vertical	-0.33

length, and frequency. Table A-III summarizes the important characteristics of some of these operating modes.

TABLE A-III
STORAGE RING OPERATING MODES

% LAMPF Output	Pulse Width	Pulses In Ring	Ejection Frequency	Protons/Pulse	*Neutrons/Pulse	Neutrons/s (Average)	Neutrons/s (Peak)	Energy/Pulse (Joules)
1.2	1 ns	6	720 Hz	1.0×10^{11}	2.0×10^{12}	1.4×10^{13}	2.0×10^{21}	13
3.2	15 ns	4	480 Hz	4.0×10^{11}	3.0×10^{12}	3.7×10^{13}	5.3×10^{20}	52
3.6	40 ns	2	240 Hz	9.0×10^{11}	1.8×10^{13}	4.2×10^{13}	4.5×10^{20}	117
2.0	200 ns	1	120 Hz	1.0×10^{12}	2.0×10^{13}	2.4×10^{13}	1.0×10^{20}	128
2.0	200 ns	1	12 Hz	1.0×10^{13}	2.0×10^{14}	2.4×10^{13}	1.0×10^{21}	1 280
2.0	200 ns	1	2.4 Hz	5.0×10^{13}	1.0×10^{15}	2.4×10^{13}	5.0×10^{21}	6 400
10.0	200 ns	1	120 Hz	5.0×10^{12}	1.0×10^{14}	1.2×10^{14}	5.0×10^{20}	640
10.0	200 ns	1	40 Hz	1.5×10^{13}	3.0×10^{14}	1.2×10^{14}	1.5×10^{21}	1 920
10.0	200 ns	1	12 Hz	5.0×10^{13}	1.0×10^{15}	1.2×10^{14}	5.0×10^{21}	6 400
10.0	200 ns	1	1.2 Hz	5.0×10^{14}	1.0×10^{16}	1.2×10^{14}	5.0×10^{22}	64 000

*Assumes 20 neutrons/proton.

^b"Assured" performance level for PSR.

^cMaximum "anticipated" performance level.

Neutron Spectra; Figure-of-Merit

Figure A-4 shows the figure-of-merit for the WNR as a pulsed-neutron source, both with and without the ring. This quantity is, roughly speaking, a measure of the time required to perform a TOF experiment (at some neutron energy) for fixed-energy resolution. It assumes that all factors relevant to the experiment are optimized, such as flight-path length, pulse width, etc., and does not take account of other pertinent and sometimes dominant factors such as backgrounds, count-rate limitation (detector dead time), TOF frame overlap, and other practical considerations. Nevertheless, the figure shows at a glance how the PSR radically improves the WNR performance, especially at medium- and high-neutron energies.

For completeness, the calculated neutron spectrum from the WNR target (at 90° to the incident proton beam direction) is shown in Figs. A-5 and A-6 for the bare target and for the target surrounded by moderating (hydrogenous) material, respectively. Both spectra will be available at WNR.

PSR Performance Goals and Limits

The PSR design currently visualized has been examined (during a summer study held at LASL in August 1976) by a panel of the nation's experts in the field of circular accelerators and storage rings. While many uncertainties remain as to high-current limitations, both in bunched and unbunched modes, it was felt by this group that the "assured" performance specification indicated in Table A-III can be reached with no large extensions of existing technology. It is now generally accepted by the accelerator community that a machine like the PSR can be built and will work. It is likely that, as our understanding of instabilities improves, these initial performance expectations will be greatly exceeded. However, in this field it has generally been the case that theory has been preceded by experiment. New kinds of instabilities (unpredicted) have appeared with each succeeding increase in stored current level or major change in some other critical parameter. In other words, we will have to build the device itself and anticipate a period of development and experimentation before its ultimate operating limits are understood and reached. Instability theory can indicate conservative or assured performance levels, and act as a guide to where difficulties will occur in going beyond these points, but it can do no more.

Fig. A-4.
Figure-of-merit vs neutron energy.

Fig. A-5.
Neutron leakage spectrum (averaged over a 1-sr conical-shell solid angle) from a 25.4-mm-diam by 150-mm-high tungsten target.

Fig. A-6.
Neutron leakage spectrum (averaged over a 0.5-sr conical solid angle) from a 150-mm-diam area centered on the large surface of the WNR target/moderator. The moderator is polyethylene, 65-mm-thick by 300-mm-wide by 200-mm-high. The target is tungsten, 25.4-mm-diam by 150-mm-high. Leaking from the 150-mm-diam area of interest, there are 0.12 n/p·sr with energies >10 MeV and $\bar{E} = 38.5$ MeV. Similarly, there are 0.98 n/p·sr with energies <10 MeV and $\bar{E} = 2.0$ MeV.

APPENDIX B

USE OF THE LAMPF PROTON STORAGE RING FOR REACTOR COOLANT SIMULATION EXPERIMENTS FOR CODE VALIDATION

by

Mahlon T. Wilson

ABSTRACT

The WNR PSR will have the capability of compressing the protons from a 500- μ s LAMPF macropulse into a 200-ns burst. A stream of water moving at sonic velocity will travel 75 cm in 500 μ s, but only 0.03 cm in 200 ns. This greatly enhances the resolution of experiments involving the tagging of flowing streams to provide hydrodynamical data for use in validating computer codes developed to predict reactor performance during accidents.

Protons will transmute the atoms of a flowing fluid into radioactive species that can be detected to reveal the path of the tagged volume of fluid.¹

The WNR PSR can accept a complete LAMPF macropulse (500 μ s) and compress it for a 200-ns delivery. It is proposed to direct this compressed bunch of protons through a test section. The test section could simulate a portion of the plumbing of a nuclear reactor to observe the effects on flow of various failure modes. The test section could also be a simple configuration to provide flow data for basic fluid-dynamics studies or to validate the prediction of numerical codes.

The concept involves the tagging of a small volume of water in a known location at a known time and following that tagged volume through the test section. The ability to follow the tagged volume is a linear function of how many fluid atoms can be made radioactive, and an inverse function of the size of the tagged volume. The proposed PSR's ability to shorten the macropulse length by a factor of 250 reduces the distance a sonic stream of water travels during the irradiation time from 75 cm to only 0.03 cm, making possible the investigation of transient phenomena.

LASL's Q Division is developing codes to aid in the prediction of the consequences of various failure modes as an alternative to costly model tests. One's confidence in the validity of such codes is increased when they can be checked against well-measured flow experiments. The proposed technique aids in providing such checks. Q Division (Kay Lathrop, March 17, 1978) has requested to be put on record as having an interest in the capability of the PSR to perform such flow experiments.

One of the PSR parameters desirable for such experiments is the ability to deliver the maximum number of protons possible in a short bunch. It would be desirable to load more than one, but probably less than a few tens, of whole LAMPF macropulses into the ring per output bunch. A few bunches/s for the few seconds of an experiment a few times a day is the maximum rate postulated (where few is <10). Pulse widths <200 ns do not appear necessary, as fluids do not move fast enough to elongate the tagged volume measurably.

REFERENCE

1. Mahlon T. Wilson, "A Technique for Studying Fluid Dynamics Using the LAMPF Proton Beam," Los Alamos Scientific Laboratory internal document, June 1977.

APPENDIX C

A TECHNIQUE FOR STUDYING FLUID DYNAMICS USING THE LAMPF PROTON BEAM

by

Mahlon T. Wilson

ABSTRACT

A burst of protons passing through a test fluid stream will tag that volume of the flowing system. Signals received from collimated detectors looking at downstream areas of interest will provide velocity information. The signal signature should also convey information as to density changes, void fraction, shearing, vortices, and separate phase velocities.

Physics of the Technique

The phenomena employed are most easily explained with the following example. The bombardment of water with 800-MeV protons produces reaction products from the oxygen,¹ as shown below.

Oxygen Product	Production Cross Section (mb)	Half-Life (m)	Decay Mode	End-Point Energy (MeV)
¹⁶ O	38.7	2.03	β^+	1.73
¹⁵ N	6.2	10.0	β^+	1.19
¹⁴ C	10.6	20.5	β^+	0.96
¹³ C	4.0	19.5 s	β^+	1.9 + 0.72 γ (98%) 1.04 γ (2%)

The positrons will scatter down and annihilate, producing a pair of 0.51-MeV γ s. Unfortunately, they can wander almost a centimeter during the scattering down, and this will cause a certain fraction of the positrons to annihilate outside the original tagged volume, creating fuzziness or halo. Therefore, for extreme positional accuracy, it is desirable to discriminate against the 0.51-MeV annihilation radiation and only look at the 0.72-MeV γ from ¹³C. For a brief time

following irradiation, ~16% of the γ s are directly from the decay of ^{10}C ; the remainder are from positron annihilation.

The structure of the LAMPF beam is such that micropulses of ~0.25-ns duration occur each 5 ns. A nominal macropulse (0.5-ms duration) contains 10^6 micropulses and occurs each 8.3 ms (120 times/s). The near term average beam current is expected to be 300 μA . Therefore, each micropulse contains 1.5×10^9 protons, and each macropulse contains 1.5×10^{13} protons. The LAMPF beam Line D is capable of delivering bursts, as short as a few micropulses, into a variety of experimental enclosures.

A macropulse of protons passing through 1 cm of water in a test apparatus will produce

$$\begin{aligned} \phi N \sigma &= 1.5 \times 10^{13} \frac{\text{protons}}{\text{macropulse}} \times \frac{6.025 \times 10^{23} \frac{\text{molecules } \text{H}_2\text{O}}{\text{g-mole}}}{18 \frac{\text{g-H}_2\text{O}}{\text{g-mole}}} \\ &\times \frac{1 \text{ g } \text{H}_2\text{O}}{\text{cm}^3} \times \frac{1 \text{ atom O}}{\text{molecule } \text{H}_2\text{O}} \\ &\times 4 \times 10^{-27} \text{ cm}^2 \frac{^{10}\text{C created}}{\text{atom O-proton}} = 2 \times 10^9 \frac{^{10}\text{C created}}{\text{cm macropulse}} \end{aligned} \quad (\text{C-1})$$

that is, the volume of water that the beam passed through for the 0.5 ms that the macropulse was on now contains 2×10^9 ^{10}C nuclei/cm of water thickness traversed by the beam.

The γ flux from the ^{10}C decay is

$$\frac{dN}{dt} = -\lambda N = - \frac{0.693}{19 \text{ s}} \times 2 \times 10^9 = 7 \times 10^7 \frac{\gamma}{\text{s-cm-macropulse}} \quad (\text{C-2})$$

Passing a pulse of protons through the fluid of a flowing experiment would tag a volume of that fluid. Collimated detectors downstream would see the passage of the tagged volume and should be able to detect transit time, cross-stream mixing or movement, wall drag, and spot stretchout. This technique could follow fluid flow in experiments* investigating two-dimensional slit injection (downcomer simulation) (Fig. C-1), two-dimensional pipe junctions (Fig. C-2), two-dimensional holes (Fig. C-3), separated flow exiting an orifice (small leak constrictions) (Fig. C-4), blowdown with tee (Fig. C-5), and coring phenomenon (Fig. C-6).

Directing the proton beam through a stationary fluid would permit multiple pulses through the same volume to increase the gamma flux. Experiments such as emptying a reservoir-bulk vs wall-boiling (Fig. C-7), level swell in a reservoir (Fig. C-8), chugging in water (Fig. C-9), and vapor injection into subcooled liquid (Fig. C-10) could be investigated by observing the motion or dimensional changes of a tagged volume of fluid when the reservoir is vented or heated.

*The experiments (Figs. C-1 through -10) are taken from a Los Alamos Scientific Laboratory unpublished report by T. D. Butler, Group T-3, "Suggested Light Water Reactor (LWR) Small-Scale Experiments," December 1975. The figures are overlaid (by Mahlon Wilson) with crosses and circles to indicate possible beam and detector locations.

Fig. C-1.
Two-dimensional slit injection.

Fig. C-2.
Two-dimensional pipe junction.

Fig. C-3.
Two-dimensional hole.

Fig. C-4.
Separated flow exiting an orifice — small leak constrictions.

Fig. C-5.
Blowdown with tee.

Fig. C-6.
Coring phenomenon.

Fig. C-7.
Emptying from a reservoir — bulk vs wall boiling.

Fig. C-8.
Level swell in reservoir.

The ability to determine the position and shape of the tagged volume depends on the counting statistics that are a function of the detector efficiency, solid angle, and the velocity of the tagged volume. A NaI (TI) crystal, 3.8-cm-thick, has an efficiency of $\sim 45\%$ for 0.7-MeV γ . A 3.8-cm-diam crystal, located 10 cm from the source, has a 1% solid angle; therefore, it should detect 1 event for every 200 γ s emitted by the source. The initial counting rate for a stationary source would be $7 \times 10^7 / 200 = 3 \times 10^5$ γ /s-cm-macropulse detected from the ^{10}C .

For high-velocity flows, one would look at the annihilation γ s also. This gives

a source strength increase of six times at the cost of a positional uncertainty of ~ 1 cm. Sixteen 3.8-cm-diam crystals can be placed around a 10-cm-radius ring, so, effectively, $6 \times 16 \times 3 \times 10^5 = 3 \times 10^7$ γ /s-cm-wide detected.

The velocity of sound in water is $\sim 1.5 \times 10^5$ cm/s; therefore, $\sim 3 \times 10^7 / 1.5 \times 10^5 \approx 200$ γ s can be detected from sonic water passing a 1-cm-wide collimator wrapped around a 1-cm-diam flow channel.

The use of cryogenics, as suggested by E. F. Hammel,² simplifies the experimental apparatus as lower pressures and power inputs are required to simulate reactor water-flow situations. Glass components can be used in many cases, permitting high-speed photography to be used to aid flow visualization. Most cryogenics are nonconductors of electricity, and, therefore, hot-wire anemometers may be used to probe turbulence effects. Capacitance techniques are useful for observing density variations. The use of liquid oxygen at about one-fourth of the pressures required of a water system results in a similar flow regime: a proton beam passing through liquid oxygen would have about one-fourth more activity induced in it.

The proton beam can be used to induce heating within bulk fluid through interaction with the fluid or impinging on a dense object submerged in the fluid. The energy loss for an 800-MeV proton in water is 2.34 MeV/cm.³ In a volume of water intercepting a 1-cm-diam beam,

Fig. C-9.
Chugging in water — heat transfer.

Fig. C-10.
Vapor injection into subcooled liquid.

$$\Delta T = 2.54 \frac{\text{MeV}}{\text{cm-p}} \times 1.6 \times 10^{-13} \frac{\text{J}}{\text{MeV}} \times \frac{\text{g } ^\circ\text{C}}{4.2 \text{ J}} \times \frac{1 \text{ cm/g}}{0.785 \text{ cm}^3}$$

$$\times 1.5 \times 10^{13} \frac{\text{p}}{\text{macropulse}}$$

= 1.7°C/macropulse temperature rise in the tagged volume of water due to beam passage. Comparable temperature increases would be observed in liquid nitrogen and in liquid oxygen.

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3. Joseph F. Janni, "Calculations of Energy Loss, Range, Pathlength, Straggling, Multiple Scattering, and the Probability of Inelastic Nuclear Collisions for 0.1- to 1000-MeV Protons," Air Force Weapons Laboratory report AFWL-TR-65-150 (September 1966).