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NUCLEAR AND PARTICLE PHYSICS WITH HIGH INTENSITY PULSED NEUTRON SOURCES

T. Dombeck

University of California
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Summary

Prospective high intensity pulsed neutron sources should have profound implications in nuclear and particle physics not only in studies involving neutrons but also neutrinos and muons. This talk surveys the physics interests in the experiments that can be performed. The running conditions and target requirements necessary to optimize each experiment are also discussed. A comparison is made between the experimental results possible at current facilities and those possible with the highest intensity sources under consideration for the future.

Introduction

The development of high intensity pulsed neutron sources (10 to 200μA) at Tsukuba,[1] Argonne,[2] Los Alamos,[3] and Rutherford[4] laboratories will open new frontiers in nuclear and particle physics just as they are now doing in condensed matter research. Other sources of still higher intensity (5mA) as porposed at Julich[5] and Argonne[6] should extend this research even further. As scientists look deeper into the potential of these sources, it becomes evident that they will be important not only for neutron related studies but also for neutrino[7,8] and muon[9] studies; all of which have generated great interest in the physics community.

For nuclear physics studies the energies of the various probes, neutrons, neutrinos and muons available from these pulsed sources (~ many MeV) match the levels inside the nucleus. Furthermore, the high intensities produced permit searches for rare processes to test symmetry rules in particle physics. The pulsed nature of these sources reduces backgrounds and allows energy determination by time-of-flight techniques. In the next section I will discuss in detail the advantages and unique capabilities that pulsed sources provide for each type of particle probe. I will emphasize the running conditions that will optimize each case. Because of familiarity, I have relied on event rates, etc., as observed at the neutron scattering (WNR) complex at Los Alamos (see Fig. 1); however, extrapolations can easily be made for performance at other sources.

The last section of this talk describes specific experimental topics to be addressed at high intensity pulsed sources of neutrons, neutrinos and muons. The list is by no means intended to be a complete overview but to provide more of a flavor for the physics of interest.

Optimized Running Conditions

Neutrons

A large class of nuclear scattering experiments require neutrons from the high energy part of the spectrum (0.1 to 800 MeV) generated in spallation sources, but not found in reactor beams (see Fig. 2). Short pulse widths are required to allow a determination of the neutron energy by time-of-flight techniques. Because of the higher energies involved moderators and reflectors are not relevant and usually thinner diameter or shorter length targets than used for condensed matter research are employed so as not to degrade neutron energies or pulse widths. Also, as discussed below, the target has a higher-Z to enhance neutron production than that required for neutrino or muon production.

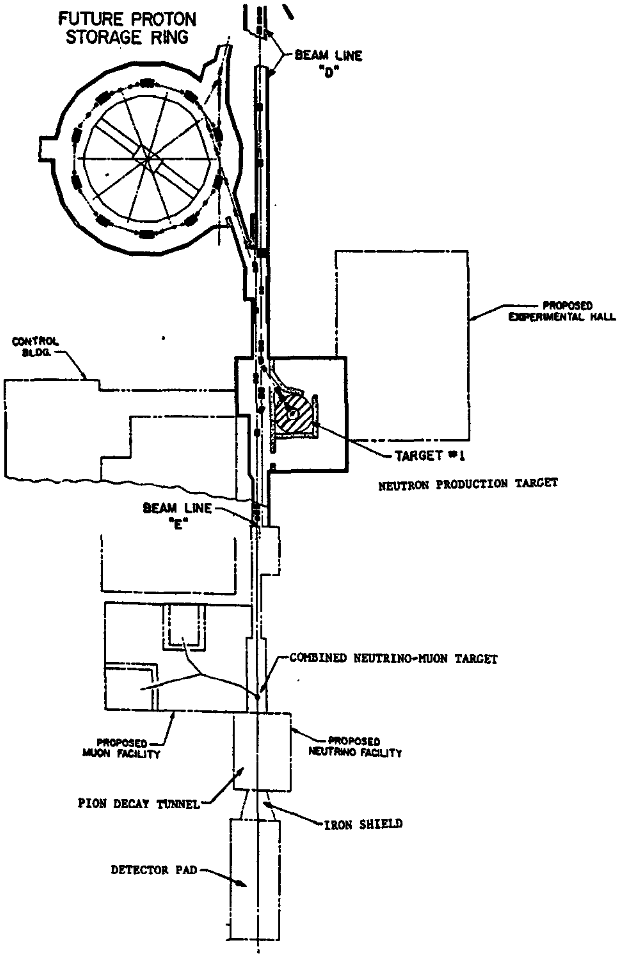

Fig. 1 A schematic diagram of the WNR complex at Los Alamos National Laboratory is shown. Existing and future facilities are pointed out.

Neutrons in the 0.1 to ~100 MeV range can be viewed at right angles to the incident proton direction. This requires a thin diameter (~1cm) target in order not to degrade pulse widths. The best energy precision in time-of-flight requires pulses ≤1ns wide, which is more restrictive than that required for condensed matter research. The very high energy neutrons (>100 MeV) are produced at small angles and require a short target to maintain pulse widths. Here pulse widths of a fraction of a nanosecond are required for best results. For neutrons produced near 0° there is another potentially useful feature. A high polarization due to Schwinger scattering[10] can be achieved.

Another class of particle physics experiments requires neutrons at the opposite end of the spectrum, i.e., ultracold neutrons (UCN). These long wavelength neutrons can be stored for long periods in material bottles[11] thus increasing the measurement time for experiments on fundamental properties of the neutron. A Doppler-shifting technique has been developed at Argonne[12] to generate UCN at pulsed neutron sources. It has been shown that UCN can be stored with this technique at a density corresponding to the peak intensity of the source, which can be much higher than at a reactor.

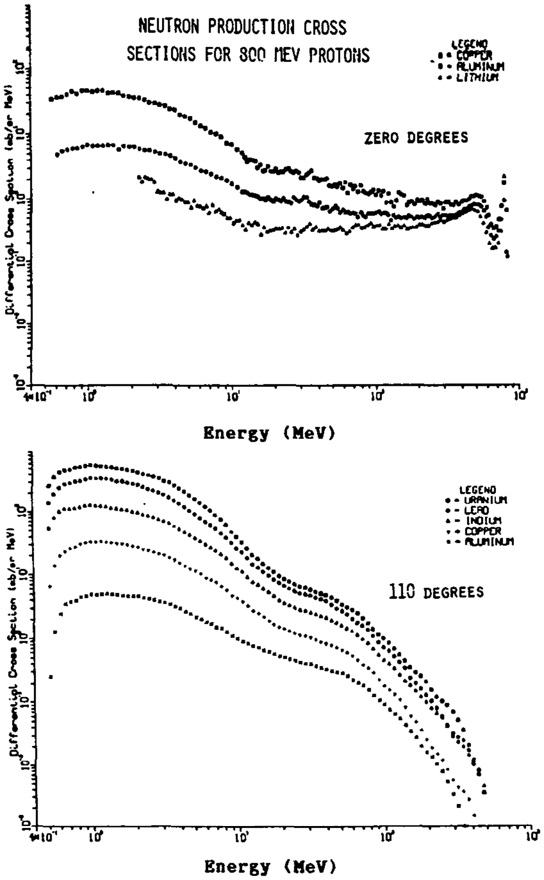

Fig. 2. High energy neutron production cross sections for various target materials are given for 800 MeV incident protons. The data were taken at Los Alamos.

A UCN source can use the same target-reflector system required for condensed matter research with the addition of a cold moderator. However, for optimum running conditions the moderator should be isolated from decouplers and poisons that absorb the low energy tail of the neutron spectrum. Furthermore, to take full advantage of the peak intensity of the source, the Doppler-shifter should be placed as close to the moderator as practical to avoid pulse broadening due to a long flight time. For example, if the Doppler-shifter were placed 500 cm from a cold moderator at the WNR and using 100μA of Proton Storage Ring (PSR) beam, it is estimated that a 30ℓ bottle can be filled to ~250 UCN/cm^3. The Doppler-shifter makes use of neutrons around 400m/s. Their pulse width after the 500 cm flight path is ~250μs which matches the pulse width emerging from the cold moderator that is dominated by the neutron slowing-down time. Of course if the pulse rate can be increased, as planned at higher intensity sources,[5] the filling rate will permit larger bottles. Nevertheless, the stored density of UCN cannot be increased unless the peak neutron flux is increased. This may be possible at the higher intensity sources[5] with the addition of accumulator rings or at the WNR with a boosted target yielding more neutrons per proton.

Neutrinos

Neutrinos result from pion production in the source. The pion decay chain yields neutrinos through the reactions

$$\begin{array}{l} P+N \rightarrow \pi^+ + X \\ \quad \llcorner\!\!\rightarrow \mu^+ + \nu_\mu \\ \qquad \llcorner\!\!\rightarrow e^+ + \bar{\nu}_\mu + \nu_e \quad . \end{array} \tag{1}$$

If a π^- meson decays, the neutrinos and anti-neutrinos in (1) are interchanged. Thus by sign selection of pions, a pure beam of one type of neutrino over another type can be generated. Another way to isolate a specific type of neutrion is by timing. The pion decay time is 26ns while that for the muon is 2.2μs, allowing in principle a separation of the various neutrino types in the decay chain (1) if the incident proton burst has a width no more than a few hundreds of nanoseconds. In the discussion that follows I will discuss the three major methods to produce neutrino beams and their properties; (i) beamstop sources; (ii) in-flight pion decay beams, and (iii) muon bottle sources.

In the beam stop source, such as the one in operation at the Los Alamos Meson Facility (LAMPF) line A beamline,[13] a long target with a large diameter is employed to interact all the protons, to contain the generated pions and to degrade their energy until they come to rest. Capture rates for π^- mesons are large in all substances and they are eliminated by absorption before they can decay. Capture rates for π^+ are small if low-Z targets are used. Thus, only π^+ mesons and their associated neutrinos survive. The

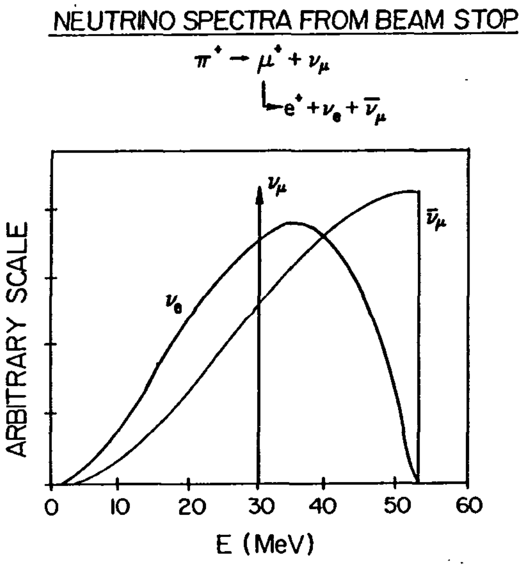

Fig. 3. The neutrino energy spectra for each type of neutrino produced in a beam stop source is shown.

subsequent μ^+ from these decays will also come to rest in the target and decay. The energy spectrum of the resulting neutrinos is shown in Fig. 3. Note that the stopped pion decay is two-body and results in a nonoenergetic ν_μ ~30 MeV and with a line width of a few keV. The muon decays yield neutrinos with a Michel spectrum.

Fluxes of 5×10^7 ν/cm^2-s for each neutrino type have been observed at a 6 m distance from the LAMPF line A beam stop with an incident current of 600μA of protons at ~600 MeV. One disadvantage of the LAMPF source is the long pulse width (~500 μs) making it impossible to separate neutrinos by timing. At LAMPF this will be rectified when the PSR is available.[7] At the Spallation Neutron Source (SNS) in England, a stopping beam of neutrinos has been proposed using the same target where spallation neutrons are being produced.[8] This latter source will not be optimized because of the high-Z material in the target which will result in half the π^+ mesons being absorbed when compared to the Cu-water beamstop at LAMPF. Even so, the reduced pulse width at the SNS (~100ns) does permit timing separation of neutrino types and the SNS experiment will have a lower cosmic ray background rate in the detector than the on-going LAMPF experiment.[13] This should permit lower energy thresholds to be used resulting in comparable event rates for the two experiments.

Higher energy neutrino beams can be produced by in-flight decays of pions and muons. In each case, a low-Z target (generally carbon) with a small diameter is employed which permits the generated pions to escape without much absorption or energy loss. The pions are permitted to traverse a 12-m-long free region of space and decay in-flight (see Fig. 1). Because the pions are moving upon decay, the neutrinos are generally directed forward so the detector is placed at the end of the decay channel but behind about 9 m of iron shielding which keeps neutrons from the target from striking the detector. Both π^+ and π^- escape the target and decay in-flight yielding ν_μ and $\bar{\nu}_\mu$ fluxes with energy spectra shown on Fig. 4 for an 800 MeV incident proton beam.

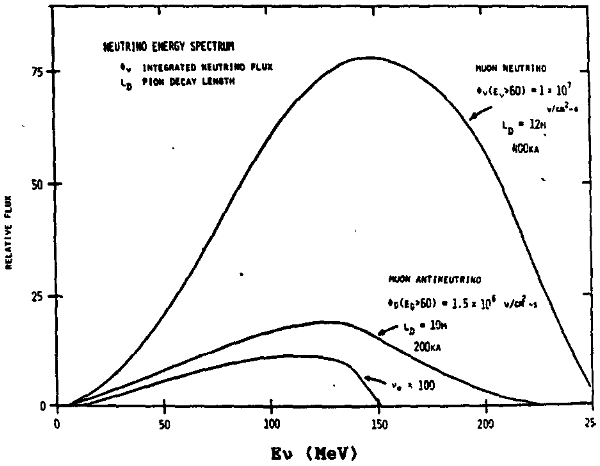

Fig. 4. The neutrino energy spectra for an in-flight pion decay source are shown for 800 MeV protons incident on a carbon target.

The pion beam originating off the target has a broad angular divergence and as much as an order of magnitude increase in neutrino flux can be gained through a magnetic focusing device placed in the pion beam. This "horn" device is a shaped current sheet as shown on Fig. 5. It turns the large angle pions parallel to the decay channel axis such that their decay neutrinos are more likely to hit the detector. In Ref. 7, it has been estimated that ν_μ fluxes in excess of $10^7 \nu/\text{cm}^2$-s and $\bar{\nu}_\mu$ fluxes of 1.5×10^6 ν_μ/cm^2-s are possible for 100μA of incident protons at 800 MeV. The horn can sign select the pions by defocusing the unwanted ones, yielding pure beams of either ν_μ or $\bar{\nu}_\mu$. The beam is also free of ν_e background to the 0.1% level. These can arise from the muons which originate from pion decays in the channel. However, muons require a decay path of many kilometers due to their long lifetime and this accounts for their low number of decays for a 12m decay channel. (Below, I discuss how pure ν_e beams can be generated by employing muon bottles.)

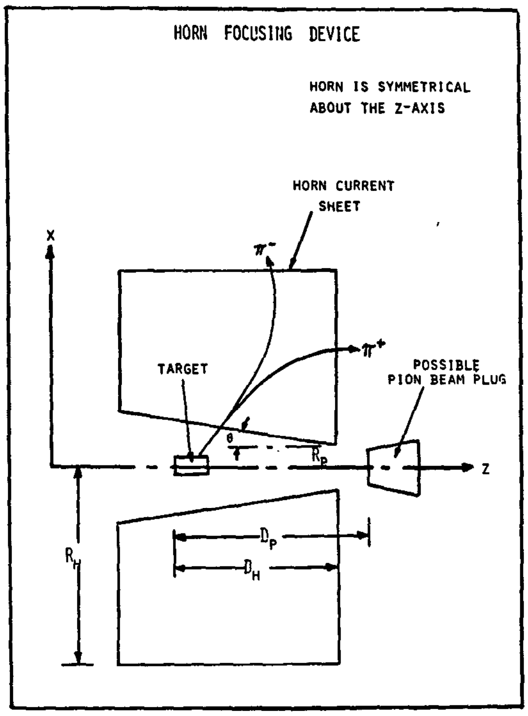

Fig. 5. A magnetic pion focusing device composed of a single current sheet is shown schematically relative to the production target.

The parent pions in the decay channel have relatively low energies and are not relativistic. This fact and the large pion energy spread results in a useable correlation between the kinetic energy of the neutrinos and their arrival times in the detector. If a pion decayed close to the target, the neutrino moving at the speed of light would arrive in the detector (a distance ~21m) in ~70ns. If part of the flight path were taken up by the pion before it decayed, the time of arrival would be later for the neutrino with the time difference given roughly by

$$\Delta t = \frac{\ell}{c}\left(\frac{1}{\beta} - 1\right), \qquad (2)$$

where ℓ is the pion flight path. Taking ℓ ~6m (half the decay channel length), and $0.75 \leq \beta < 1$ for pions produced by 800 MeV protons, the arrival time differences have a range from 0 to 5ns. The higher energy neutrinos are the products of the higher energy pions (larger β) and it is expected these neutrinos will arrive sooner in the detector than the lower energy ones.

Another factor which enhances the timing separation is that the neutrino production angle is thrown more forward in the laboratory as the pion energy increases. Thus, a low energy pion decaying near the target is less likely to have its neutrino hit the detector than a similar pion decaying at the far end of the decay channel. This is because the ratio of detector solid angle to the decay solid angle is less at the target end of the decay channel than it is at the detector end. Therefore, the low energy neutrinos in the detector will have resulted from pions that travelled a large portion of the flight path at the relatively low β yielding the longest arrival times.

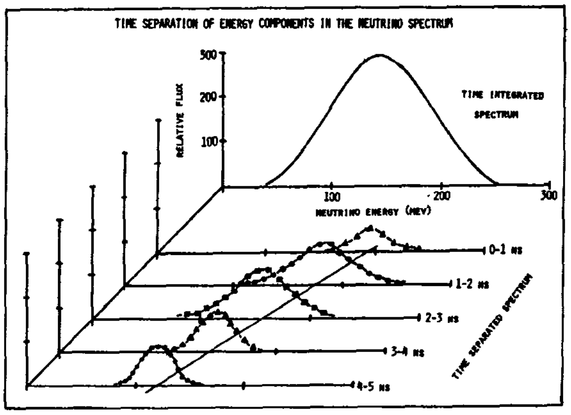

Fig. 6. The neutrino-energy-arrival-time correlation in the detector is shown as computed using a Monte Carlo calculation.

The results from our Monte Carlo computer simulations[7,33,34] for the WNR neutrino beam is shown on Fig. 6. All neutrinos above ~60 MeV cross the same plane in the detector separated by at most 5ns in arrival times. This fortuitously matches the LAMPF pulse microstructure which is 1/4ns wide pulses separated by 5ns. We find that the average neutrino energy decreases by ~20 MeV/ns and in each 1ns wide bin the energy spectrum has a $\Delta\sigma/E \sim 12$ to 16%. This can be compared to the time integrated spectrum which has a 35% width. Therefore measuring neutrino arrival times in the detector relative to the LAMPF microstructure should yield an unprecedented precision on the incident neutrino energy for such experiments.

As I pointed out, the timing-energy correlation is a result of the relatively low energy pions generated at LAMPF. Some portion of this correlation will probably survive for incident proton energies up to a few hundred MeV higher in energy, but probably disappears around 1.5 to 2 GeV where most pions are relativistic. Though I have not investigated the correlation at higher energies, I believe that longer decay channels (>12m) will be necessary to enhance any residual effect.

As one final remark about the timing correlation, neutron backgrounds in the neutrino detector resulting from proton interactions in the target and beam stop arrive at times >20ns relative to the neutrinos. Unfortunately, frame overlap does not permit a separation of these neutron backgrounds using the LAMPF microstructure. In some neutrino experiments where event rates are relatively high but low neutron backgrounds are important, the PSR in the short pulse mode (1ns wide pulses at 720HZ) may provide a means to perform these measurements in a background free environment while allowing full advantage of the neutrino energy-timing correlation as well.

All of these timing considerations should be kept in mind for future generations of pulsed sources. It may be important to retain some microstructure in the beam at the highest intensities, even if this means throwing away some of the flux by chopping, to obtain the highest precision measurements.

The last neutrino source I wish to discuss uses a muon bottle.[14] In order to obtain higher energy electron neutrinos (ν_e) from muon decays than result in a stopped source, an in-flight method is necessary. However, the long muon decay times translate into long flight paths. The only practical means to produce a source is to bend the muon path into orbits in a magnetic trap. A low-Z target is embedded into a dipole magnetic field such that pions emerging from the target are trapped in orbits in the magnet gap. The pions decay and a portion of the muons are also trapped by the field. In Ref. 14, it is estimated that a source of ν_e can be produced with a relatively planar flux of about 10^6 ν/cm^2-s for 100 µA protons incident on the target. The optimum proton energy depends in part on the magnet pole face diameter and on the field strength. For a 5T field in a 1.5m diameter gap a proton energy near 650 MeV is optimal. Noone has yet made a muon bottle as it requires superconducting technology in a high radiation field. It should be pointed out that all the timing separation of neutrino types discussed above for the beamstop source apply to the muon bottle as well.

Muons

Muons are the decay products of pions through reactions given in (1). There are two types of muon sources; (i) a surface beam, and (ii) an in-flight pion decay beam. Both sources require a target of low-Z material with a thin diameter (~5cm) to reduce absorption of the parent pions. In general, low momentum muons (<80 MeV/c) are desired for most applications and these are the products of low momentum pion decays (<160 MeV/c) which have a maximum production at angles greater than 90° off the target (backward angles).[9] Because the target parameters are similar for in-flight neutrino production as well as muon production it may be possible to have a combined production target; the neutrinos originating from higher energy forward pions and muons originating from lower energy backward pions.

A surface muon beam arises from the decay of positive pions at rest in the skin of the target. Such muons have a momentum of 30 MeV/c and are 100% polarized. Negative muons cannot be made this way because all stopped π^- mesons are absorbed in the target. Negative muons or higher momentum positive muons are obtained only from in-flight pion decays. In this case, a beam transport including a long superconducting solenoid in which the pions decay is necessary to enhance the yield of muons. With either type of muon source the spread of momenta is large and requires a special achromatic transport to allow a large acceptance of muons. For instance in Ref. 9 it is estimated that a 100 µA beam of protons at 800 MeV will produce 8 x 10^7 μ^+/s from an in-flight source with a 20% momentum acceptance. This beam will have about 70% polarization. A negative muon beam will be down by a factor of four or five from the positive. A surface beam of 2 x 10^7 μ^+/s and with a 10% momentum spread can also be produced by this source.

The timing characteristics of the muon beam are also important and can change from one class of experiments to another. Some experiments require high powered pulsed lasers to pump transitions. These are best matched by muon beams having a width of one nanosecond up to a few hundred nanoseconds. Enhancements of up to 10^5 in event rates over a dc-experiment are possible.[9]

Discussion

The characteristics and special requirements for neutron, neutrino, and muon pulsed sources are given in Table I. These requirements of target parameters and pulse widths for the incident protons are generally incompatible, except perhaps for muon and in-flight pion decay neutrino beams. This suggests that shared operations will be required to meet all requirements, either by real-time scheduling of beam or by multiplexing proton current to different target stations. Both of these methods are being employed at the WNR complex at Los Alamos to allow a broad physics program to exist.

The Los Alamos facilities; some of which are in operation, under construction or proposed, are shown schematically in Fig. 1. Not shown is the Line A beam-stop neutrino source which is to the east of LAMPF whereas all WNR facilities are to the south. The main WNR target cell can be used for nuclear neutron experiments by the replacement of the target for condensed matter research with one more appropriate for nuclear physics. Because the proton beam strikes the target vertically, the flight paths can only view the target at 90°. For the highest energy neutrons a separate target and beam is situated in the Line D tunnel and is viewed at 0° by a flight path going straight out to the south. These two target stations cannot be used simultaneously because different settings of dipole bending magnets in the proton channel are required in each case. At present both beams use chopped LAMPF macropulses to achieve high resolutions in time-of-flight.

The in-flight neutrino facility is under construction just to the south of the Line D channel. It will have a target about 50m away from target cell one. At present it will be fed LAMPF macropulses in a multiplexed mode eventually sharing pulses with PSR and running simultaneously with all other programs at the WNR. It is hoped that PSR beam can also feed the neutrino target by further multiplexing with the WNR. This would permit a muon physics program veiwing the neutrino target at backward angles as well as an extension of the neutrino program using the PSR duty factor reduction, simultaneously a neutrino program using LAMPF macropulses, and if current permits a full neutron scattering program at the WNR, all at the same time.

As can be seen by the above remarks, there are many targets stations at Los Alamos and a complex plan for multiplexed operation to allow beam time to each user. The reason that this scheme is possible is due to the high intensity of proton currents (~1mA) available from LAMPF and the fact that no single user at this time can use it all. In fact, shielding in the WNR limits the maximum current to about 100μA of protons for neutron scattering, leaving current for other targets. This is perhaps an historical accident and will not be the case at other pulsed sources.

The research program at the SNS at Rutherford Laboratory is more concentrated than at Los Alamos. The full 200μA beam at the SNS can be accomodated by the neutron target and almost all of the available current will be used for neutron production. Therefore, the neutrino source (stopped) must use the same target which has not been optimized for neutrinos. Also, I do not believe there is an in-flight neutrino source planned at this time.

The SNS machine will have a pulsed muon program centered around a 5-cm-long carbon target placed upstream of the neutron target. The muon source is designed primarily as a surface beam without an in-flight decay beam. It should provide a total μ^+ flux in two 100ns bursts about twice that quoted in Ref. 9 for Los Alamos. However, a chopper will be required for shorter pulse widths which will reduce the muon flux to about 1/3 that at Los Alamos where PSR can

Table I. Characteristics and Requirements for Pulsed Sources of Neutrons, Neutrinos, and Muons for Nuclear Physics Studies

Source	Energy or Momentum Range	Target Specifications	Pulse Width Requirements	Comments
Neutron	10^{-6} eV (ultracold)	High-Z, large diameter	~200μs	requires cold moderator
	0.1 to 25 MeV	High-Z, thin diameter (~1 cm)	$\lesssim$-1ns	neutrons viewed at 90°
	>25 MeV	High-Z, short length	~500 ps	neutrons viewed at 0°
Neutrino	0 to 53 MeV (ν_μ,ν_e stopped source)	Low-Z, large diameter, stopping length	~200 ns	timing allows separation of neutrino types
	60 to 300 MeV (ν_μ in-flight source)	Low-Z, thin diameter, ~1 interaction length	$\lesssim$1ns	timing allows E_ν determination
	50 to 150 MeV (ν_e in-flight source)	Low-Z, thin diameter	~200 ns	Muon bottle required
Muon	30 MeV/c (μ^+ surface beam) 50 to 80 MeV/c (μ^+ and μ^- in-flight)	Low-Z, ~5 cm diameter	<1 to 300 ns	view target at backward angles

generate the short pulse widths. The double target scheme will probably degrade the proton flux on the neutron target by about 15% which should be acceptable to the condensed matter program.

The basic incompatibility between the different nuclear physics and condensed matter sources is inherent in the target specifications and pulse width requirements for each case. This incompatibility will persist at the higher intensity sources being designed now unless they have enough current to service all users simultaneously. I suspect this is a hollow dream because each user would like to take full advantage of all the available current for his specific program; this is especially true for neutrino experiments where event rates are so low. Thus, each target station will probably be designed for the maximum current. Therefore, if a broad program including nuclear and particle physics is desired, special consideration must be given to scheduling the proton beam. This sharing should be possible as no user can use all of the beam all of the time. However, it implies that the laboratory will require a broad based program advisory committee to help set its priorities.

Details of the Physics Interest and Experiments for Nuclear Physics Studies at Pulsed Sources

Theoretical Introduction

The following discussion about modern ideas of particle structure and the forces of nature is cursory and intended to provide a backdrop for the experiments that can be performed at high intensity pulsed sources. The discussion borrows from various reviews and popularized articles to be found in the literature, such as Abdus Salam's Nobel Prize acceptance speech[27] and Ellis-Nanopoulos on cosmology.[28]

Most experiments in nuclear and particle physics are designed to test symmetry properties in nature. Some of these symmetries involve the space-time properties of the interactions between particles, such as parity and time. Other symmetries involve the underlying classification or grouping of particles by their similar properties, such as charge, spin, color, isospin, etc.

The "standard model" claims that the universe is composed of fermions interacting by the exchange of bosons. All observed fermions are left-handed, i.e., spining counter-clockwise along the direction of motion, which would be an exact statement if the fermions were massless. Anti-particles are right-handed. The elementary fermions can be grouped into families, known as the SU(3) xSU(2)xU(1) grouping

$$\begin{matrix} \begin{pmatrix}u\\d\end{pmatrix} & \begin{pmatrix}c\\s\end{pmatrix} & \begin{pmatrix}t\\b\end{pmatrix} \\ \begin{pmatrix}\nu_e\\e\end{pmatrix} & \begin{pmatrix}\nu_\mu\\\mu\end{pmatrix} & \begin{pmatrix}\nu_\tau\\\tau\end{pmatrix} , \end{matrix} \qquad (3)$$

the top row refers to quarks which comprise the hadrons. The bottom row refers to the leptons which can be placed in one to one correspondence with the quarks. There are specific questions which such a classification scheme produces. How many families are there? Are the leptons on the same elementary level as the quarks which compose protons and neutrons, rather than on the level of the protons and neutrons? For example, we know that the quarks found in nature are admixtures of the ones given in (3), i.e, they exhibit mixed properties. Do leptons exhibit a similar behavior, and is the relative admixture the same as for quarks? Such a mixing of leptons could appear as a transformation or oscillation of one type of neutrino into another.

Another question is whether the scheme (3) is the manifestation of a higher group symmetry, i.e., do quarks and leptons have a substructure such that they are all composed of the same subparticles? This unification of leptons and quarks into the same larger group, say SU(5), permits new interactions which can transform quarks into leptons. In this scheme Baryon number is not conserved and protons can decay. Furthermore, neutrons may be able to oscillate into antineutrons ($\Delta B = 2$ interaction).

The boson exchange involves particles such as the γ, $W^{\pm}$, Z^0, gluons and gravitons, which mediate the forces in nature. Are all of these particles just different manifestations of the same substructure? Can all the forces be unified within the same picture? Indeed Weinberg and Salam recently found a theory that joins the electromagnetic and weak forces; the γ, Z^0, and $W^{\pm}$ particles. They predicted neutral currents in weak interactions and many other effects in nuclei; the testing of which is the goal of many planned experiments. Out of this theory came one fundamental parameter, the Weinberg angle θ_W, giving the relative weak-electromagnetic strengths. A precision measurement of θ_W would yield information such as how many families of quarks and leptons there are, and which of the higher groups, (SU(5), O(10), etc) used in unification schemes is correct.

The space-time symmetries of the interactions in nature are not necessarily conserved. For instance, parity is not conserved by weak interactions and this is related to why only left-handed fermions have been found. Is the universe truly asymmetric or can we find evidence for right-handed particles? Another violated symmetry is time, which has appeared in nature in only one interaction in the K^0 -$\bar{K}^0$ system. What is its nature and are there other reactions where T is violated? In fact, it has been suggested that the small T violation that has been observed may explain the basic asymmetry of the universe, why we live in a matter dominated world as opposed to one with equal amounts of matter and anti-matter. Understanding the origins of T-violation could explain this fundamental question.

There are other space-time symmetries to be tested in particle interactions, such as whether they exhibit scalar (S), pseudoscalar (P), vector (V), axial-vector (A), or tensor (T) properties. Each of these can be related to the properties of the bosons being exchanged. In some cases, we only know this property of the forces to the 10 to 20% level.

The quest to answer these questions do not necessarily require the high energies found at CERN, Fermi Lab or Brookhaven. Useful information can be obtained from background free, precise measurements of fundamental quantities. This is the way many of the nuclear experiments that can be done at high intensity pulsed sources can have an impact in this field. In some cases the interactions are between elementary particles, such as neutrino-electron scattering or atomic states in muonium. In other cases, fundamental properties of neutrons and muons are studied, such as the neutron electric dipole moment. In still others the nucleus itself is considered a laboratory in which to study the interactions, such as compound resonances. A list of such experiments is given in Tables II through IV. Because of time limitations I can only give a brief description of a few selected from this list, but these should demonstrate the techniques involved and precisions that can be obtained.

Neutron Electric Dipole Moment (EDM)

If observed, the EDM would be an example of parity and time symmetry violations. Theoretical models explaining the violations seen in the K°-$\bar{K}^\circ$ system predict a finite EDM. As observed in Ref. 30, progressively smaller limits placed on the EDM have eliminated certain theories from contention.

The experiment uses the nuclear magnetic resonance method[15,30] extended by Norman Ramsey in which the EDM coupled to an electric field causes a shift in the NMR line. The line width is inversely proportional to the time a neutron spends in the perturbing electric field and inversely proportional to the square root of the neutrons counted. Therefore, storing neutrons in a bottle throughout the measurement can increase the

Table II Nuclear Physics Experiments Using Neutrons

Reaction	Present or Planned Limits	Possible Limits	Comments
Electric Dipole Moment	5×10^{-25} e-cm[15]	10^{-28}e-cm	Test Fundamental Symmetries of Time and Baryon conservation. Use ultracold neutrons stored in bottles
n-$\bar{n}$ oscillations	10^6s [16]	10^9s	
Gravity Effects			Use room temperature and long wavelength interferometers [29]
$n\rightarrow pe^-\bar{\nu}_e$	10^{-3} [17]	10^{-5}	Search for T-violation, use polarized neutrons
Compound Resonances			Search for T-violation
Giant Dipole Resonances			Nuclear Structure Studies: High ℓ-states, non-nuclear degrees of freedom. Use polarized neutrons and TOF techniques in 0.1 to 25 MeV range
Nuclear Fission			
$He^3(n,\gamma)He^4$			look for few body correlations
$He^3(n,\gamma\gamma)He^4$			tests of QED-presently disagrees by factor of 30
Cross Sections of unstable nuclei			Astrophysics implications
$A(n,n)A'$			Nuclear data measurements of cross sections. A' may be unstable. Take advantage of MeV range of neutrons in pulsed sources.
$A(n,p)A'$			
$A(n,\alpha)A'$			

Table III Nuclear Physics Experiments Using Neutrinos

Reaction	Present or Planned Limits	Possible Limits	Comments
$\nu_\mu\rightarrow\nu_e$ osc.	0.001 eV^2 [7] $\sin^2 2\theta < 10^{-5}$	10^{-4} eV^2 10^{-7}	Need low backgrounds. Cosmic ray backgrounds reduced by pulse source
$\nu_\mu\rightarrow\nu_\mu$ osc.	0.01 eV^2 [7] 10^{-3}	10^{-3} eV^2 10^{-4}	
$\nu_\mu e\rightarrow\nu_\mu e$	100-1500 events [7,8,19,20]	10^5 events	Measure y-distribution and $\sin^2\theta_W$ to 1%
$\nu_e e\rightarrow\nu_e e$	300 events [8,18]	3000 events	Use muon bottle to get higher energy neutrinos. Use pulse structure to eliminate backgrounds from other neutrino types.
$\nu_\mu P\rightarrow\nu_\mu P$	1200 [19]	12000	Look for induced pseudoscalar, at low energies have no problem with form factors
$A(\nu,\mu)A'$			Nuclear structure studies [31]
$A(\nu,\nu)A'$			Map out axial-vector strength in nucleus. Complimentary to electron scattering which gives vector strength [32]

Table IV Nuclear Physics Experiments Using Muons

Reaction	Present or Planned Limits	Possible Limits	Comments
muonium	10^{-5} [21]	10^{-8}	Test QED, Weak Interactions -- study hyperfine structure using pulsed lasers matched muon pulse length
muonic atoms	4 $\times 10^{-4}$ [22]	10^{-5}	
$\mu e \rightarrow \bar{\mu}\bar{e}$	muonium produced in vacuum [23]	10^{-5}	lepton conservation, T-violation
$\mu^- A \rightarrow e^- A$		10^{-8}	lepton conservation
$\mu^- A$ capture	~15-20% [24,25,26]	~2-3%	Nuclear structure studies -- use lasers and observe decays, need polarization information tests PCAC, CVC
Rare μ decays			Test for right-handed currents [35]

sensitivity over beam types of experiments. Ultimately, the limit can be pushed to $\sim 10^{-28}$ e-cm using this method, about three orders of magnitude beyond present experimental limits.

The advantages of a pulsed source over a reactor for this experiment include a higher peak flux of neutrons meaning the bottle can be filled to a higher density. As future pulsed sources increase in intensity the EDM limits should be progressively improved.

Nuclear Data Measurements

These measurements are intended to study and catalogue in a systematic fashion neutron-nucleus cross sections over a broad range of nuclei. Total, capture, elastic and inelastic cross sections will be measured as well as (n,p) and (n,α) processes. Such measurements are currently carried out at the Oak Ridge Electron Linear Accelerator but planned proton spallation sources will have much higher intensities in the higher energy region (>10 MeV) which should permit observation of smaller cross section processes and correlation measurements in multiparticle final states. Backgrounds should also be decreased at a proton accelerator especially when attempting to observe gamma transitions from excited nuclear states. Electron machines produce gamma rays profusely by Bremstrahlung making it difficult to perform such measurements.

Even though these measurements are interesting in their own right, they also provide useful numbers for application in the fission and fusion reactor programs. Embrittlement of materials due to hydrogen build up through (n,p) reactions can be studied. Also, neutron cross sections up to tens of MeV are of interest for materials used in fusion reactors. Capture cross sections of neutrons on various isotopes are unknown and needed for fission reactors.

Neutrino Oscillations

At low energies neutrino oscillations can be looked for in the transition $\nu_\mu \rightarrow \nu_e$ (appearance mode) or in the $\nu_\mu \rightarrow \nu_\mu$ (disappearance mode) in which a faster than normal flux drop off with distance is searched for. This last mode is complimentary to the $\bar{\nu}_e \rightarrow \bar{\nu}_e$ mode observed at reactors.

For neutrino transitions to take place in free space there must be a finite mass difference between the neutrino types. Thus, if observed, neutrino oscillations will also provide evidence for neutrino masses. The oscillation wavelength is given by

$$\lambda = \frac{E_\nu}{1.27\ \Delta m^2}\ , \tag{4}$$

where λ is in meters, E_ν is the neutrino energy (MeV) and Δm^2 is the square of the mass difference between neutrino types (eV^2). For a viable experiment, it is optimal to have a low E_ν to have a short wavelength.

Another parameter to be determined is the mixing angle ($\sin^2 2\theta$) that gives the strength of the transition. This parameter may be related to quark mixing. The sensitivity to the mixing angle is given by the statistical uncertainty in the measurement,[7] and the backgrounds present. This is why pure beams of ν_μ are important as small amounts of ν_e contamination can be misinterpreted as a $\nu_\mu \rightarrow \nu_e$ transition.

In principal the experiment would attempt to map out an oscillation length to prove the effect is due to oscillations. This could be accomplished by changing the detector position which is no small feat for a multi-hundred-ton device. Another approach is to change λ by varying the neutrino energy as given by (4). Because of the E_ν-arrival-time correlation discussed above, different E_ν components can be isolated simultaneously during the measurement.

Neutrino-Electron Elastic Scattering

Neutrino electron scattering is a fundamental reaction involving only the weak neutral current for $\nu_\mu e$ and a combination of neutral and charged currents for $\nu_e e$. This latter process is the only interaction available in which the interference term between the two currents can be observed.

The Weinberg angle can be determined by comparing $\nu_\mu e$ and $\bar{\nu}_\mu e$ scattering.[7] A high precision measurement is conceivable because of low backgrounds at the low neutrino energies generated at these pulsed sources. For instance a neutral current reaction producing backgrounds is

$$\begin{aligned} &\nu N \rightarrow \nu N \pi^{\circ} \\ &\qquad \hookrightarrow \gamma\gamma \\ &\qquad\quad \hookrightarrow e^+e^-e^+e^- \ . \end{aligned} \tag{5}$$

On Fig. 7, we show the production cross section for (5) as a function of neutrino energy. At low energies (~200 MeV) the cross section is five orders of magnitude below the observed rate at the Brookhaven AGS (~1000 MeV).

Another unique feature of the low energy experiment is the differential y-distribution where y is the energy sharing given by

$$y = E_e/E_\nu \quad . \tag{6}$$

Because of the broad neutrino spectrum (σ/E~100%) at the AGS energies, no determination of the y distribution has ever been accomplished. With the E_ν-arrival-time correlation the precision on E_ν will be ~10%[33,34] allowing a determination of y by measuring the electron energy and its time of production in the detector.

The y-distribution for neutrinos has a constant and quadratic term, the coefficients in front of each is related to Θ_W. If a linear term exists, it will be evidence for other space-time components in the neutral current beside vector and axial-vector.

Neutrino-Nucleus Interactions

J. D. Walecka[32] has pointed out that our knowledge of the nucleus is half-missing. The distribution of its vector currents has been studied in detail using electrons and photons as probes, but we have little experimental knowledge about the axial-vector currents. These are best studied with neutrinos having low energies that can exchange energies to the nucleus comparable to its energy levels (~ tens of MeV).

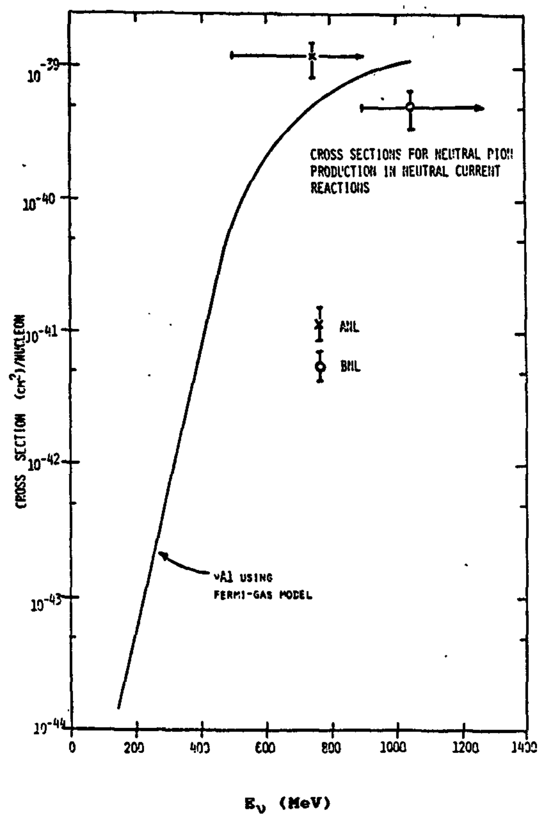

Fig. 7. The neutral current pion production cross sections are given as a function of the neutrino energy.

Also, so as not to disturb the nucleus excessively, there actions should involve only the weak neutral currents which do not change protons to neutrons as the charged currents do.

An interesting theoretical question of astrophysics interest is whether neutrinos can coherently interact with all the nucleons in the nucleus at the same time.[7] If so these coherent cross sections will vary with increasing mass number as A^2. Such coherent processes for νHe scattering could play an important role in supernovae as outgoing neutrinos could exert a pressure preventing collapse.

Experiments can be performed using liquid detectors; some cryogenic such as He and O^2. Only the recoil nucleus is seen and its energy is determined by the natural scintillation light generated in the fluid. Thus a large vat with phototubes immersed in it may suffice for the measurement. It may be necessary to segment the detector to observe any gamma rays emitted from nuclear excited states. The same detector may be used for a large number of experiments by replacing the liquid.

The study of neutrino-nucleus scattering could not have been contemplated in past years at LAMPF because of the long pulse length (~500μs) which would have allowed cosmic ray induced backgrounds to swamp the detector. With the prospect of a duty factor reduced by five orders of magnitude or more using the PSR, the prospect of performing these measurements is once again being investigated,[7] especially in view of the use of the energy-arrival time correlation that defines the incident neutrino energy. In this case, it is only necessary to measure the recoiling nucleus energy to obtain all the relevant information in the interaction, such as the cross section dependence on the exchange of the four-momentum squared.

Because the recoil is very low energies (<10 MeV for He and decreases with A of the nucleus) it is imperative to have a background free environment for the experiment. Beside cosmic rays, neutrons generated in the neutrino beamline can cause knock-on scatters imitating neutrino events with cross sections fifteen orders of magnitude higher. As I mentioned above, the PSR short pulse mode (1ns-wide pulses at 720Hz) seems appropriate to eliminate this source of background by timing as the neutrons arrive at times beginning 20ns later than the neutrinos. Unfortunately, the PSR in this mode will only be able to deliver ~12μA of current and event rates will be only a couple per day per ton of detector. These events will also be divided among the 5-timing bins. This is a study where future high intensity pulsed sources could certainly improve the experiments in a direct way by increasing the event rate.

Muonium Production

Muonium is an atomic system composed of a μ^+ and an electron. The interesting measurements involve the hyperfine splitting, Δν (between the ground state triplet and singlet states), and the Lamb shift ($2S_{1/2}$-$2P_{1/2}$ splitting). Because the system does not involve a nucleus, precision comparisons with quantum electrodynamics between the two elementary particles are possible.[9]

The experimental technique stops μ^+ in a gas cell in a magnetic field. Microwave radiation induces transitions between Zeeman levels by flipping the muon spin. The effect is then monitored by measuring the μ decay asymmetry. A high incident μ^+ polarization is therefore required.

The experimental precision is related to the Zeeman line width. A significant reduction can be effected by using only muonium atoms that have been immersed in the magnetic field for a relatively long time, $t \sim 2.2 \mu s$ (muon decay time, τ_μ). Taking into account counting rates, the optimal source would have a pulse width $\Delta t < \tau_\mu$ and a repetition rate $\nu \ll 1/\tau_\mu$. A proposed experiment at Los Alamos[7] using the PSR would improve present QED test precision by a factor of 4. Higher intensity sources of muons may provide an additional order of magnitude improvement.

Conclusion

A broad program in nuclear and particle physics at a pulsed source would include neutrinos and muons as probes as well as neutrons. Optimization of experiments for each probe requires different target parameters and pulse widths. With proper scheduling or multiplexing of the proton current, I believe that a successful program in nuclear physics can proceed and can co-exist with a condensed matter neutron scattering program. This may require a broad based program advisory committee to help set priorities.

The pulsed nature of the source is most useful in determining energies by time-of-flight. The energy-timing correlation is present even for neutrinos due to the non-relativistic nature of the parent pions. However, the energies are such for nuclear probes that short pulse widths are necessary for a large class of experiments, on the order of one nanosecond or a fraction of a nanosecond. This implies that future sources should allow for some microstructure in their pulses, even if this means reducing intensity by chopping the beam.

For the nuclear and particle experiments I have considered in this talk, the upcoming generation of pulsed sources offer significant improvements in precision over present results. All of these experiments are and probably will remain statistics limited for the immediate future, therefore, as intensities increase at planned pulsed sources precision in these experiments should improve even further.

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