PROPOSAL
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To the SPSL Committee

Investigation of fast neutron production by 100 to 250 GeV muon interactions on thin targets

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Abstract

The production of fast (1MeV-1GeV) neutrons in high energy muon—nucleon interactions is poorly understood. Yet it is essential to the understanding of the background in many underground neutrino experiments and, in particular, may hold relevance for the atmospheric neutrino anomaly. We propose an experiment to investigate fast neutron production using the M2 muon beam at the CERN SPS.

1 Introduction

We propose to measure the production cross sections, energy spectra, and angular distributions of spallation neutrons, pions and gamma rays produced by the inelastic scattering of 100–250 GeV muons on nuclei. The M2 muon beam at the CERN SPS [1] is well suited to this investigation, and at 100–250 GeV, the energy of the SPS muons is very similar to the mean energy of cosmic—ray muons at many underground neutrino detectors.

The results of this experiment will shed light on the interaction mechanism, poorly understood at present, and also provide critical information for background estimation in present and future generations of underground detectors, where fast neutrons produced by cosmic—ray muon interactions in the surrounding rock are important sources of background. Experiments such as the San Onofre neutrino oscillation experiment [2], the LBL/Stanford Low Temperature dark matter detectors [3], the Kamioka detector [4] and the Soudan underground detector [5] are all concerned about neutron backgrounds which are difficult to eliminate by fiducial volume cuts. The atmospheric neutrino anomaly reported by several underground experiments [6],[7], [8], [9] has received immense attention because of its implication of non—zero neutrino masses. With this as motivation, proposals for long—baseline neutrino—oscillation experiments have been made at San Onofre, Chooz, Fermilab, BNL, KEK and CERN [2], [10], [11], [12], [13], [14]. It has been suggested recently that the atmospheric neutrino anomaly could be explained by background due to fast neutrons produced by the inelastic scattering of high—energy muons [15].

2 Interaction of high energy muons with matter

Muons propagating through matter lose energy essentially continuously by ionization. In addition, they lose energy in discrete bursts along the muon trajectory by bremsstrahlung, direct pair production, and nuclear interaction [16]. The last process, poorly explored
at present, is the topic of the present proposal.

The discrete energy loses are assumed to be proportional to the muon energy, and are expected to be equal to the ionization loses at $E \approx 500$ GeV. The nuclear process, $\mu + \text{nucleus} \rightarrow \mu + \text{hadrons}$ has important practical consequences for underground experiments, since the resulting hadrons, and in particular neutrons, represent background which is often difficult to eliminate [3], [4], [5].

The total neutron production yield has been measured at different depths [17], but very little is known about the energy and angular distribution of the neutrons. Moreover, one expects that many neutrons are produced in secondary processes following the primary muon-nucleus interaction, and it is difficult to separate the two in the inclusive measurements performed underground.

To describe the process theoretically one assumes that the muon scattering occurs primarily at very small angles. Such a process can be viewed as produced by a beam of nearly real equivalent photons [18]. Even with this drastic simplification, it is by no means a trivial matter to obtain reliable estimates for actual yields and spectra of the neutrons and pions. The difficulty lies in the estimation of the equivalent photon flux, as well as in the shortage of experimental nuclear photo-disintegration data for high energy photons. The proposed experiment will establish a basis for the extension of the theoretical understanding of the muon–nucleon inelastic scattering process.

3 The neutron detector

A schematic of the detector arrangement with respect to the beam is shown in Figure 1. Each detector, as depicted in Figure 2, is a cylindrical glass vessel measuring $20 \text{ cm} \times 20 \text{ cm}$. Each is filled with Bicron 501A liquid scintillator which possesses excellent pulse shape discrimination properties for neutron identification [20]. On each vessel are coupled two 5-inch, Philips XP4512 photo-multipliers with fast 1.1 nsec RMS timing. The entire assembly is mounted inside a light-tight wooden dark box. We cover a large dynamic range from 1 MeV to 1 GeV by operating one tube at low gain and the other at high gain. The particle energy is measured via the time of flight (TOF) from its production site in the target. The neutron detector provides a timing start, and a segmented beam counter, T1, placed 6 m upstream of the target, is delayed to provide a stop. For a given particle mass and TOF one obtains the particle energy as shown in Figure 3.

The beam counter, T1, is placed directly in the muon beam and is
thus exposed to rates of about 20 MHz during the two-second beam-on phase. For this reason, it is segmented into four strips, each read out by a fast two-inch XP2230 phototube, thus reducing the rate per tube to 5 MHz. The base is modified for high current and low gain using a strongly tapered divider chain. This type of base has been used successfully at counting rates of up to 50 MHz.[19]

A second beam counter, shown in Figure 1 as H1, is identical to T1 and is placed in the beam downstream of the neutron detectors behind a thick iron hadron absorber. The use of this counter in coincidence with the T1 beam counter would eliminate spurious triggers caused by hadronic contamination of the beam. (See Appendix 4 for a detailed discussion of hadronic contamination.) Based on discussions with the SMC group[21] now running in the SPS M2 beam area, it is expected that muons scattering in the target will be deflected at very small angles. So requiring such a coincidence, effectively an angle cut, will throw out only a few percent of valid spallation events.

In front of each detector is placed a thin 7 mm plastic scintillator (sl-s8, see Figure 1). These detectors are used to differentiate charged particles such as protons and pions from the neutral gammas and neutrons which are unlikely to scatter inside the thin plastic.

In addition, plastic scintillators are placed above and below each detector and are operated in coincidence to veto cosmic muons.

Several large plastic scintillators, T2, are placed upstream of the neutron detectors and are used to veto muons in the beam halo which could fire the TOF detectors.

4 The experiment

The layout of our experiment is similar to a recent CERN PS experiment [22] in which neutrons and pions were measured following anti-protons’ stopping in a target. Another group, E665 at Fermi–lab [23], recently measured neutrons following deep–inelastic scattering by 470 GeV muons. However, the latter experiment selected muons with large energy transfer (ν ≥ 20 GeV) and measured neutrons in a small energy range 1 to 10 MeV (limiting the usefulness of this result for underground detectors).

Our experiment will run with 10 cm x 10 cm targets: we will study thin targets 5 gcm⁻² and thick targets 50 gcm⁻² consisting of either Graphite, Silicon, Copper or Lead. Three neutron detectors will be placed 1.5 meters from the target, three at 3.0 meters, and two at 4.5 meters as shown in Figure 1. The different distances allow us to cover a wider range of energies than at a single distance
coincidence with the ADC gate and TDC start. The multi-hit TDC OCR Output beam halo veto, T2, and the muon veto scintillators are run in anti-

enough delay to account for the slowest and fastest particles. The

stop for the TDC is generated by the muon beam counter, T1, with

signals. The discriminator also starts a CAMAC multi-hit TDC. The

light is used to discriminate between neutron-like and gamma—like

the third digitizes only the pulse tail. The ratio of delayed to prompt
digitizes the full analog signal, one digitizes only the pulse rise, and

discriminator which provides gates for 3 CAMAC ADCS. One ADC

Analog signals from each of the counters N1 to N8 go to a low—level

DAQ and electronics

The experiment requires modest space and equipment and could be

run in either a single–user or parasitic mode.

5 DAQ and electronics

Analog signals from each of the counters N1 to N8 go to a low-level
discriminator which provides gates for 3 CAMAC ADCs. One ADC
digitizes the full analog signal, one digitizes only the pulse rise, and
and the third digitizes only the pulse tail. The ratio of delayed to prompt
light is used to discriminate between neutron–like and gamma–like
signals. The discriminator also starts a CAMAC multi-hit TDC. The
stop for the TDC is generated by the muon beam counter, T1, with
enough delay to account for the slowest and fastest particles. The
beam halo veto, T2, and the muon veto scintillators are run in anti-

coincidence with the ADC gate and TDC start. The multi-hit TDC
allows us to identify and reject multiple muons (see Appendix 2). The CAMAC crate is read out via an IBM PC whenever a LAM is present on the TDC. For each event we record the charge in 3 ADCs, the time in the TDC and the status of a CAMAC register for the charged particle counters s1 to s8. Based on studies of the background from radioactivity and cosmic radiation we expect the trigger rate from all eight detectors above a threshold of 2 MeV to be about 200 Hz. At this trigger rate our DAQ exhibits a dead time of about 5%. Based on this estimate, we will write approximately 50 MB of data per day which will be archived to tape once per week during the scheduled M2 beam maintenance period.

6 Analysis

Neutral particles are tagged by their failure to deposit energy in the thin scintillators s1 to s8. Neutrons and gammas are then separated using pulse shape discrimination. The time of flight is corrected to the muon-target vertex and time is converted to energy for the candidate particle. (For a detailed discussion of energy resolution, reconstruction efficiency and background see Appendices 1-4). The neutron yield, energy spectrum, and angular distribution are thus obtained.

7 Results from a test of a prototype neutron counter using an AmBe neutron source

We have developed and tested a prototype neutron PSD/TOF detector complete with a thin charged-particle detector (s1–s8 in Figure 1) and muon veto scintillators above and below. Two 5-inch Philips XP4512 PMTs are coupled to a cylindrical pyrex vessel containing Bicron 501A scintillator. A schematic of the readout is shown in Figure 4. Neutrons are provided by an AmBe source placed 1 m from the detector. A plastic scintillator, T1, is placed near the neutron source to detect 4.4 MeV gamma rays produced by the source in coincidence with the neutrons. A neutron recoil in the TOF detector starts the TDC and the 4.4 MeV gamma stops it. The prompt, delayed, and full charge of each pulse is measured by three FERA 4300B charge ADCs. The ratio of delayed to prompt light distinguishes neutrons from gammas [25]. Figures 5 and 6 illustrate the excellent neutron/gamma separation achieved. A $^{60}$Co gamma-ray source is used initially to calibrate the gamma flight time. With a 1.0
MeV (electron equivalent) energy threshold, pulse shape discrimination rejects 98% of gammas while accepting 92% of neutrons (see Figure 8). The separation improves at higher energies. The energy spectrum of neutrons, reconstructed from TOF (detected in coincidence with the 4.4 MeV gamma rays) is shown in Figure 7. The spectrum ends around 6 MeV, as expected because of energy shared with the 4.4 MeV gamma ray. The charged-particle detector, s1, is placed between the AmBe source and the TOF detector. An ionizing particle traversing s1 will deposit at least 1.5 MeV in the counter. Setting a threshold in s1 of 0.5 MeV, we found that of all neutron-like events detected in the TOF counter, only 1% also caused the charged-particle detector to fire. Similarly, only 0.1% of neutron-like events in the TOF detector were accompanied by a top-bottom muon coincidence hit. This indicates that the charged-particle vetos will have a negligible effect on the neutron detection efficiency.

8 Monte Carlo simulation of detector efficiency

The neutron detection efficiency was Monte-Carlo modeled using the GEANT-GCALOR [26] package. Neutrons were generated with energies from 2 to 1000 MeV. The efficiency for neutrons entering the detector is shown in Figure 9 as a function of both energy threshold and neutron energy. Our simulations agree with the calculations of D. Polster et al. [22] for a similar detector. The integrated efficiency is about 30% at a 2.5 MeV neutron energy threshold. Included in the simulation is the fact that PSD begins to diminish at high energies due to the escape of energetic recoil protons. This has the effect of causing some high-energy neutrons to be misidentified as gammas and reduces the detection efficiency for 1 GeV neutrons from 10 to about 8%.

9 Requirements

For this experiment we require the following CERN resources:

- A high energy muon beam, around 100 GeV, at an intensity of a few $x10^7$ muons per spill.
- Hadronic contamination of the beam, intrinsic or from upstream users, below a few times $10^{-5}$ hadrons per muon.
• Five weeks to run in either single-user or parasitic mode (target changes can be made during weekly beam shutdown).

• Assistance from the survey staff to position our target and beam counter precisely in the beam.

• 10 m (L) x 5 m (W) x 3 m (H) of space in the beam, and an area to place a standard NIM rack and a personal computer.

• Computing accounts on the CERN Unix cluster for members of the collaboration, to allow e-mail and remote access.

• A CERN LAN connection for our DAQ and analysis computers.

We will provide the following equipment:

• All Detectors, vetos, liquid scintillator, etc.

• NIM and CAMAC electronics, a DAQ computer, and an analysis workstation.

• Target material

• Hardware for positioning the detectors and targets.

• Computing power for the data analysis (our group has 6 IBM RS6000 workstations at Caltech).

Our requested schedule is as follows:

• one week with thick targets, C, Si, 50 g cm\(^{-2}\).

• two weeks with thin targets, C, Si, 5 g cm\(^{-2}\).

• one week with no target (background run).

• one week with high Z targets, Cu, Pb, 50 g cm\(^{-2}\).

• (Total of 5 weeks beam time).
10 Acknowledgements

We thank D. Hilscher and H. Schellman for providing us with information about their experiments, H. Newman for assisting us in contacting the CERN SPS, and L. Gatignon and A. Schopper for information on the muon beam and SPS opportunities. We appreciate the technical assistance of J. Hansen in repairing and assembling a number of plastic scintillation detectors, and gratefully acknowledge the help of two Caltech undergraduates, Xinh Huynh and Patrick Spradlin in the construction and testing of the neutron detectors. M. Ericson and J. Delorme contributed to the theoretical investigation and will continue to participate in the interpretation of the experiment.
Appendix 1: Energy Resolution

Neutron energy in this experiment is reconstructed by measuring the neutron time of flight from its production site in the target to the TOF detector in which it scatters. Accordingly, the energy resolution is a function of the photo-multiplier tube timing response and the neutron flight path distance. This produces a different characteristic resolution for each of the three target–detector distances used in this experiment, 1.5, 3.0, and 4.5 meters. The TOF detectors are read out by 5-inch Philips XP4512 tubes with 1.1 nsec RMS time jitter, and the muon beam counter is read out by 2-inch XP2230 tubes with 1.5 nsec timing. The finite target thickness (at most 20 cm) and detector size contribute to uncertainties in the neutron production and detection point, giving a final flight time uncertainty of about 2 nsec (1 $\sigma$). This resolution was verified in measurements made with a prototype detector (see Figure 8). The uncertainty in the time of flight becomes larger for very low-energy neutrons, but this effect is offset by a decreasing sensitivity of the reconstructed energy to the flight time in this range.

For purposes of the energy resolution, the maximum measurable energy for a given detector distance will be defined as the highest energy, or shortest flight time, that can be resolved at the one $\sigma$ level from a $\gamma$-ray. These energies are tabulated below for each of the three detector positions. The second table displays the energy resolution (defined as the $E - \sigma$ to $E + \sigma$ distance) in per cent for a number of energies.

<table>
<thead>
<tr>
<th>Target–Detector Distance [cm]</th>
<th>Maximum Energy Resolvable [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 cm</td>
<td>400 MeV</td>
</tr>
<tr>
<td>300 cm</td>
<td>750 MeV</td>
</tr>
<tr>
<td>450 cm</td>
<td>1100 MeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Neutron Energy in [MeV]</th>
<th>Resolution at 150 cm</th>
<th>Resolution at 300 cm</th>
<th>Resolution at 450 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>20 %</td>
<td>10 %</td>
<td>5 %</td>
</tr>
<tr>
<td>30</td>
<td>40 %</td>
<td>20 %</td>
<td>13 %</td>
</tr>
<tr>
<td>50</td>
<td>56 %</td>
<td>26 %</td>
<td>18 %</td>
</tr>
<tr>
<td>100</td>
<td>90 %</td>
<td>40 %</td>
<td>27 %</td>
</tr>
<tr>
<td>300</td>
<td>290 %</td>
<td>91 %</td>
<td>56 %</td>
</tr>
<tr>
<td>500</td>
<td></td>
<td>140 %</td>
<td>89 %</td>
</tr>
</tbody>
</table>
Appendix 2: 
Reconstructing Energy from a High-Rate Muon Beam

The measurement of neutrons following muon-nucleon deep inelastic scattering will be done at a very high-intensity muon beam: $4 \cdot 10^7 \mu$ per 2.4 sec spill, or $1.7 \cdot 10^7 \mu$ per second during the spill. This means that muons will be arriving at the rate of one every 60 nsec on average. This could lead to confusion if a second muon were to appear while a neutron produced by an earlier muon was still in transit to the TOF detectors. In this case an unambiguous reconstruction of the neutron energy would be impossible, and the event would necessarily be thrown out.

A neutron scattering in the time-of-flight detector has an equal probability of losing any amount of energy up to its full kinetic energy. The energy deposited in the TOF detector defines the longest possible flight time for the neutron and thus defines how far back in time one must look to identify the muon which produced it. For an event to be reconstructable it is necessary that only one muon lie in this time interval. At the SPS beam, muons arrive according to poisson statistics at an average rate of one per 60 nsec. Thus the probability of seeing one muon followed by no muons for 1 nsec is given by $P = \left(\frac{1}{60}\right)^0 \cdot e^{-\frac{1}{60}} / 0!$, or 98.35%. Similarly, the probability that two muons are spaced by at least $m$ nsec is given by $(0.9835)^m$. So, for example, an energy deposit of 5 MeV in a TOF counter at 150 cm from the target would require that only one muon be present in the preceding 43 nsec. The likelihood of this is $(0.9835)^{43}$, or 49%. But any neutron with an energy greater than 5 MeV could have made this deposit, so in general, the reconstruction probability for a neutron of energy $E$ is the integrated average of all energy deposit efficiencies up to energy $E$. In the case of a 5 MeV neutron in the detector at 150 cm, this gives 36%. So the final detection efficiency for a 5 MeV neutron would be the product of the reconstruction probability (36%) and the Monte-Carlo modeled interaction probability (55% - see Proposal Fig. 9), or 20%.

The table below displays reconstruction efficiencies for various neutron kinetic energies for each of the three detector distances used, 1.5, 3.0, and 4.5 meters. This table illustrates the fraction of detected neutrons accepted, the remainder thrown out because of parent muon ambiguity.

<table>
<thead>
<tr>
<th>Detector Distance (m)</th>
<th>Neutron Energy (MeV)</th>
<th>Detection Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>5</td>
<td>36%</td>
</tr>
<tr>
<td>3.0</td>
<td>5</td>
<td>20%</td>
</tr>
<tr>
<td>4.5</td>
<td>5</td>
<td>15%</td>
</tr>
</tbody>
</table>

The table extends to higher energies as well, as the reconstruction probability increases. However, the interaction probability decreases with increasing energy, leading to a reduction in the overall detection efficiency.
<table>
<thead>
<tr>
<th>Neutron Energy (MeV)</th>
<th>Reconstruction Efficiency for Distance: 150 cm</th>
<th>Reconstruction Efficiency for Distance: 300 cm</th>
<th>Reconstruction Efficiency for Distance: 450 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18 %</td>
<td>3 %</td>
<td>0.6 %</td>
</tr>
<tr>
<td>5</td>
<td>36 %</td>
<td>14 %</td>
<td>6 %</td>
</tr>
<tr>
<td>10</td>
<td>47 %</td>
<td>23 %</td>
<td>12 %</td>
</tr>
<tr>
<td>50</td>
<td>71 %</td>
<td>52 %</td>
<td>39 %</td>
</tr>
<tr>
<td>100</td>
<td>79 %</td>
<td>64 %</td>
<td>53 %</td>
</tr>
<tr>
<td>200</td>
<td>86 %</td>
<td>75 %</td>
<td>66 %</td>
</tr>
<tr>
<td>500</td>
<td>94 %</td>
<td>86 %</td>
<td>80 %</td>
</tr>
<tr>
<td>1000</td>
<td>96 %</td>
<td>92 %</td>
<td>88 %</td>
</tr>
</tbody>
</table>
Appendix 3: Uncorrelated Background

Neutron–like events in the TOF counters uncorrelated in time with the muon beam may accidently occur near a muon beam trigger and thus be misidentified as beam–related neutrons. These neutron–like events could be produced by hadrons, PSD–misidentified gammas, or muons from cosmic ray showers, or by PSD–misidentified gammas from natural radioactivities in the detector or tube glass, laboratory walls, etc. It is difficult to estimate what the rates will be at the CERN SPS location, but some guidance comes from measurements done at Caltech with a full–size prototype detector measuring 20 cm dia. x 20 cm L.

Data was taken with the prototype detector filled with Bicron 501A liquid scintillator in a ground–level laboratory at Caltech, i.e. there was no overburden to shield the cosmic ray flux. The detector was calibrated using a $^{232}$Th $\gamma$ source and an AmBe neutron source. Background data was then taken and a neutron PSD cut applied. The neutron–like background rate was found to be 0.03 Hz (of a total 5 Hz) above a 4 MeV electron–equivalent energy threshold and 0.2 Hz (of 120 Hz) above 0.8 MeV. These events will be counted as background if they occur within a consistent flight time of a beam muon. They will of course be subject to the same reconstruction cuts as the true signal (see Appendix 2), but as a first approximation, we can define background events as those occurring within 50 nsec of a beam muon. In this case we have, for a 0.8 MeV threshold, $1.7 \cdot 10^7 \mu/sec \cdot 0.22\text{neutrons/sec} \cdot 50 \cdot 10^{-9} \text{sec} = 0.187\text{events/sec}$ during a 2.4 sec spill repeated every 14.4 sec. This gives 2700 events per detector per day for a 0.8 MeV threshold. For a 4 MeV threshold, this rate drops to 340 events per detector per day. The following table summarizes the expected signal and accidental background rates for the various detector distances and thin/thick target runs. The close detectors are assumed to operate with a 1 MeV threshold and the far detectors with a higher (such as 4 MeV) threshold. Note also that the “accidental” neutron rate will be measured with the beam both on and off resulting in an extra factor of seven in statistics.

<table>
<thead>
<tr>
<th></th>
<th>Events per day at 150 cm</th>
<th>Events per day at 300 cm</th>
<th>Events per day at 450 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin Target</td>
<td>signal: 12,000</td>
<td>3000</td>
<td>1300</td>
</tr>
<tr>
<td></td>
<td>background: 2700</td>
<td>340</td>
<td>340</td>
</tr>
<tr>
<td>Thick Target</td>
<td>signal: 120,000</td>
<td>30,000</td>
<td>13,000</td>
</tr>
<tr>
<td></td>
<td>background: 2700</td>
<td>340</td>
<td>340</td>
</tr>
</tbody>
</table>
Appendix 4: Correlated Backgrounds

Events in the neutron TOF counters associated with the muon beam but not with muon-target interactions comprise the correlated background of this measurement. These events could come from the following sources:

- Neutrons, π's, and γ's produced by the muon beam in the plastic scintillator beam counter, T1.

- Hadronic contamination of the muon beam, either through direct detection or through secondary interactions.

- Off-beam, or halo muons, either through direct detection or through secondary interactions.

In the first case the beam counter, T1, acts as a production target with a $\rho x$ path length of about $2 g cm^{-2}$. This results in a neutron production rate of about half of that from the thin target and a twentieth of that from the thick target. The scintillator, T1, is also kept far upstream (6 m) of the target to reduce the solid angle acceptance. In the worst case, the TOF counter N8 is about 10.4 m from T1, resulting in a correlated background rate of about 10% of the thin target signal rate. This background will be measured during the no-target run.

In the second case it is possible that hadrons present in the beam, from either intrinsic contamination or upstream users, could interact in the target (or T1) and produce neutrons which would appear to have come from muons. In addition, these contaminating hadrons could elastically scatter into a TOF detector and appear to be reaction products. This process is dangerous even for low contamination levels because of the small muon–nucleon inelastic scattering cross section. The cross section for the muon inelastic scattering process is about $5 \cdot 10^{-5}$ barns. If we take the $\pi N$ or $p N$ total cross section, about $30 mb$, as an approximation for the above background processes, we see that a contamination level of $10^{-3}$ hadrons / muon would result in a 1:1 signal to background. The SPS beam has an intrinsic contamination level of about $10^{-6}$ which presents no problems. We must be wary, however, of upstream users to make sure the induced contamination remains below several times $10^{-5}$ which would
introduce a systematic error of several percent. Since this background originates in the target, it cannot be measured in the no-target run. However, this background can be eliminated if necessary by the coincident operation of a downstream beam counter (see counter H1 in Figure 1). Counter H1 is identical to beam counter T1 except that it is placed downstream behind a thick iron hadron absorber. Hadron contaminants that fire the upstream T1 counter will be absorbed in the iron (or scattered away by the target) and thus fail to fire the downstream counter, marking them as invalid events. A small fraction of valid muon spallation events will result in muon scattering angles large enough to miss the downstream counter and will be rejected by this requirement. Discussions with the SMC group[21], however, have informed us that only about 1% of scattered muons are deflected by more than a beam diameter over tens of meters.

The third source of background comes from halo muons. A few percent of the muon beam intensity lies outside the beam core and extends to about 2 meters radius. These halo muons could strike a TOF detector and appear to be beam products. The estimated rate of halo muons striking any one TOF detector is about 3000 per spill. This requires the addition of a large-area halo veto, comprising several plastic scintillators for a total area of about 30 cm x 300 cm, to keep all the TOF detectors in shadow. The firing rate of such a veto would be about 40 kHz during a spill, and the rate of real coincidences between the veto and a TOF detector about 15 kHz. The veto would need disable the TDC start only for a few nsec since a neutron in transit from the target at that time could still subsequently interact and be successfully reconstructed despite the halo's firing. Thus the dead time introduced by such a veto would be 0.02%.

In addition, halo muons could inelastically scatter in the halo veto or other structural materials and produce neutrons that could be mistaken for those produced in the target. The largest production comes from halo muons interacting in the three-meter-wide concrete platform running the length of the beam pipe 1.3 meters below it. Integrating the production yield along the platform with the solid angle to the neutron detectors, we calculate that the background from the platform will be of the same order as the signal for the thin-target runs, and about a factor of ten below the signal for the thick-target runs. However, these neutrons can be eliminated by placing muon counters upstream to tag halo muons entering the platform and issuing a veto for 100 nsec. The platform area to be covered is about 20 cm high x 3 m wide, resulting in a veto firing rate of about 25 kHz. The dead time introduced by such a veto would be only 0.3%. Moreover, large breaks in the concrete platform exist at a few
locations in the M2 experimental hall, and the experiment could be set up in such an area. All halo-associated backgrounds will be measured in the no-target run.
Appendix 5:
Coexistence with the Spin Muon Collaboration

The experiment, as described, is self contained and capable of operating in single-user mode in the SPS M2 area. On the other hand, the experiment is also well suited for operation in parasitic mode behind the current main user, the Spin Muon Collaboration. In fact for operation behind SMC a number of beam systems described here become redundant. Discussions with members of SMC have proved very useful in developing a plan to incorporate SMC systems into this experiment.

SMC operates a number of large-area beam halo counters ideal for covering our neutron detectors as well as background-neutron production sites in the concrete platforms (see Appendix 4). N. DeBotton of SMC has kindly offered to aid us in configuring these veto signals for use with our data acquisition.

SMC also operates a downstream hadron veto consisting of an iron absorber followed by a segmented plastic scintillator. N. DeBotton has again offered that this apparatus could be repositioned and incorporated into our data stream.

Finally, SMC hodoscope H6 could also be incorporated in place of our segmented beam counter, T1. This hodoscope is positioned in the beam upstream of our target and could be used to provide the TDC stop signal for our time-of-flight measurement. A. Staude of SMC has offered his help in incorporating signals from this apparatus.
11 References

Figure 1: A schematic view from above of the detector layout illustrating neutron detector and plastic scintillator placement relative to the beam.

N1-N8: Neutron TOF detectors
8" diam. x 8" length active volume
s1-s8: Charged particle ID counters
8" x 8" plastic scintillator
T1: Segmented Beam counter
6" x 6" x 1" plastic scintillator
T2: Beam Halo vetos
1/4" plastic scintillator
30 cm x 3 m
H1: Segmented downstream beam counter
with iron hadron absorber
Figure 2: The neutron detector.

Pyrex Vessel Containing
Bicron BC501 Scintillator

8" 8"

Philips XP4512 (5"")
Figure 3: Kinetic energy versus time of flight at 1.5 m.
Figure 4: Readout schematic for one detector module. The AmBe source was employed for test runs undertaken at Caltech.
Figure 5: Ratio of delayed ADC/prompt ADC x 1000, showing neutron - gamma separation with PSD.
Figure 6: Scatter plot of delayed VS prompt ADC, showing neutron - gamma separation.
AmBe Source spectrum from TOF
Threshold = 1 MeV electron equivalent

Figure 7: Energy spectrum of neutrons from an AmBe source reconstructed via TOF.
Figure 8: TDC distribution with AmBe source, illustrating timing resolution and gamma rejection from pulse shape discrimination.
Neutron Detection Efficiency
GEANT/GCALOR Monte Carlo
Requiring stopped proton

Figure 9: Monte Carlo simulation of the neutron detection efficiency as a function of neutron energy and threshold. Neutrons are assumed to be detected only if recoil protons ionize heavily and stop in the scintillator producing delayed light and thus making PSD possible.