DOE/ER/40389--62

DE90 002565

Experimental Investigations in Particle Physics at Intermediate Energies

Performance Report

for December 1st, 1988 to December 31st, 1989

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October 31, 1989

Prepared for
The U.S. Department of Energy
(Division of High Energy and Nuclear Physics)
Under Contract No. DE-FG02-88ER-40389

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Abstract

The major emphasis of this project continues to be on fundamental symmetries and parameters of the Standard Model. The primary project is BNL E791, a search for the decay $K_L^0 \to \mu e$, which would violate the rule of separate lepton number conservation. The technique uses a drift-chamber spectrometer, with particle identification, picking out candidate decays from 2-particle triggers by measuring the two-particle invariant mass m, and the collinearity angle Θ_c. For reconstructed $K_L^0 \to \pi^+\pi^-$ decays the rms resolution in m was ~ 1.4 MeV/c^2, and in Θ_c it was ~ 0.3 mrad; these values match the design specifications. All the data from the 1988 run of E971 have been analyzed for $K_L^0 \to \mu e$, $K_L^0 \to \mu\mu$, and $K_L^0 \to ee$ events, and the results submitted for publication. We find an upper limit from the 1988 data for the branching fraction for $K_L^0 \to \mu e$ of 2.2×10^{-10} (90% C.L.) and a limit of 3.1×10^{-10} (90% C.L.) for $K_L^0 \to ee$. We also measured the branching fraction for $K_L^0 \to \mu\mu$ to be $(5.8 \pm 0.6 \pm 0.4) \times 10^{-9}$, with a sample of 87 events. Our limits are the best reported. The limit on the decay $K_L^0 \to \mu e$ places a lower limit on the mass of a new particle mediating such decays of 50 TeV. We have learned much about dealing with low-level backgrounds; we are confident that we can reject all backgrounds to $K_L^0 \to \mu e$ at the 10^{-11} level.

The 1989 run was completed in May 1989, and all the 2,900 data tapes have been run through the first pass of the analysis, by using two computing centers: the BNL center and the Cornell Supercomputer facility. We expect to increase the sensitivity by a substantial factor over that for the 1988 run.

The LCD project at LAMPF (measurement of $\nu - e$ elastic scattering) has continued, with an allocation of $1.4M in funds for FY90. A new fast ten-inch photomultiplier has been developed (by Burle Industries) which meets the needs of the detector, and will undoubtedly have many other applications. A subsidiary project, on neutrino oscillations and known as LSND, has been proposed as a smaller-scale prototype of LCD that would also have physics results. This project is still under discussion.

The other neutrino work at Los Alamos, E764, will result in a final publication. Calculations are being completed of the neutrino flux, necessary for the measurement of the $\nu_\mu\, {}^{12}C$ inclusive cross sections. These will be the best measurements of ν-nuclear scattering. The measurement of the cross section for the exclusive reaction $\nu_\mu\, {}^{12}C \to \mu^-\, {}^{12}N$ is unique.

We have continued to participate in planning for experiments at CEBAF, particularly the 'Hall C' effort.

In a new development, Dr. Martoff is establishing a facility for fabrication of superconducting detectors of nuclear radiation; the equipment has been funded and is partly installed. Planned uses include searching for 'Dark Matter.'

In summary, the objectives for this year have been met.

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1 Introduction

We have continued to work on the structure of fundamental interactions, particularly on their basic symmetries and conservation laws. Our primary emphasis in the last year has been on the rare K_L^0 decay experiment at Brookhaven National Laboratory. The experiment is intended to look for lepton non-conservation, which is an assumption of the Standard Model without any theoretical basis. This work is in collaboration with six other institutions [1]. Good progress has been made on this work: a report [5] on data collected in our first run (May 1987) has been published, two papers on the 1988 run have been submitted for publication (preprints are submitted with this report) [14,15], and analysis of the 1989 data is well underway.

We continue to devote some effort to the Los Alamos 'Large Cherenkov Detector' (LCD – E1015) [3], which is proceeding well. A new proposal (LSND – LAMPF E1173) on neutrino oscillations, using LCD technology, is being developed. In the case of other neutrino work at LAMPF (E764), a final paper (on $\nu - C$ interactions) is in preparation. A related publication on the passage of electrons through aluminum [10] has been submitted for publication.

A proposal to the DOE University Research Instrumentation program was funded and work has begun on this project [17]. The aim of the project is to fabricate nuclear radiation detectors of much higher sensitivity than existing types. The detectors will use superconducting tunnel junctions, and the technique is expected to have many applications, including the search for Dark Matter.

Details of the work on rare kaon decays are given in section 2, of the work on LCD, LSND and E764 in section 3. Reference to work on rare pion decay, muon capture and participation in planning for CEBAF is in section 4. The detector development effort led by Prof. Martoff is described in section 5. An outline of effort and funds expended is in section 6. Finally, publications resulting from the work are listed in section 6.1 and reports in section 6.2. A representative list of talks on the rare kaon work (by all members of the collaboration) is given in section 6.3 and talks on other topics in section 6.4.

2 Progress on BNL E791: Rare K_L^0 decays

The main goal of this project (E791) is to test the idea of separate lepton-number conservation to a new level of sensitivity. This is motivated by fresh consideration of the possibility that separate lepton number is not exactly conserved, as a result of attempts to develop more satisfactory theories than the Standard Model (SM). The branching fraction for $K_L^0 \rightarrow \mu e$ is a critical test of such theories. Other goals proposed were a search for the decay $K_L^0 \rightarrow ee$, the CP-violating decay $K_L^\circ \rightarrow \pi^\circ ee$, a precise branching fraction for the decay $K_L^0 \rightarrow \mu\mu$, and the CP-violating polarization in $K_L^0 \rightarrow \mu\mu$.

Details of the physics goals and the design of the experiment are given in the original proposal [2]. In this section, we outline our progress to date, and give current results.

In May 1987, we had a shakedown run (4 weeks); a first publication resulted [5]. For the 1988 run, we completed the remainder of the spectrometer, except for the ability to measure muon polarization. The 1989 run began with studies of ways to improve the sensitivity (thicker target, smaller production angle, improved trigger electronics) and then settled into steady data-taking in a slightly improved mode. Details are given in the following sections.

2.1 1988 Run

Results from the Spring 1988 run were submitted, in August, for publication in Physical Review Letters. One paper [14] gives upper limits for the branching fractions for $K_L^0 \rightarrow \mu e$ and $K_L^0 \rightarrow ee$ decays, while another [15] gives a measurement of the branching fraction for $K_L^0 \rightarrow \mu\mu$. The limit for $K_L^0 \rightarrow \mu e$ is 2.2×10^{-10} and for $K_L^0 \rightarrow ee$ it is 3.1×10^{-10}, both at 90% C. L. These are currently the lowest limits on these processes.

The measured branching fraction for $K_L^0 \rightarrow \mu\mu$ is $(5.8 \pm 0.6 \pm 0.4) \times 10^{-9}$, where the errors are statistical and systematic, respectively. This result is based on the observation of 87 events. Using this value and current measurements for $K_L^0 \rightarrow \gamma\gamma$ the ratio $B(K_L^0 \rightarrow \mu\mu)/B(K_L^0 \rightarrow \gamma\gamma) = 1.01 \pm 0.13 \times 10^{-5}$. Rather basic theoretical considerations predict that this ratio should be greater than 1.20×10^{-5}. The experimental value is 1.5 standard deviations below this bound. The discrepancy between the measured value and the bound is well within reasonable statistical fluctuations. Nevertheless, the observation of a value of $B(K_L^0 \rightarrow \mu\mu)$ at, if not below, the low end of its permitted range has interesting implications. The group did very thorough and redundant checking of the input values to the branching fraction to be as certain as possible of their accuracy.

2.2 1989 Run

In the 1988 data no candidate $K_L^0 \to \mu e$ events survived reasonable cuts on track quality, particle identification, mass and collinearity. Even relaxing individual cuts introduced little background, so that it was reasonable to expect that a much larger data sample would still be background free, after reasonable cuts. Our efforts were therefore directed at taking more data in 1989 in a reliable and efficient manner and at trying to increase the data rate by increasing the kaon flux. Reasonable improvements in particle identification were also sought.

The data acquisition and on-line monitoring software was further improved for efficient long term operation. Problems with automatic switching between tape drives were solved, although we were later occasionally plagued by low-quality tapes. For this run all eight 3081/E on-line computers were installed and operating. In this condition it was possible to take data with 4 to 5 $\times 10^{12}$ protons/pulse on target and have virtually no dead time. At this rate it was not necessary to implement the level 2 trigger, which was found to have an inefficiency of $\sim 20\%$. The beam rate was set by optimizing the rate of K_L^0 decay events that could be reconstructed from the drift chamber data.

Several new modules were built and installed in the level 1 trigger logic by Temple. A principal objective was to give more flexibility and speed to the definition of a cluster in the finger scintillator hodoscope associated with the Pb glass detector.

Some modifications of the trigger logic were then made. The computer controlled access to the trigger was made more comprehensive so that anyone on the shift could quickly and reliably shift between various complex trigger requirements. At the beginning of the run a major effort was made to tighten the timing resolution of the 372 trigger counters in the level 0 trigger. An improvement from 20 ns to 14 ns was achieved.

No major changes were made to the muon hodoscope and the Cherenkov counters, both Temple responsibilities. Time measurements in both systems were improved by installing new TDC's with least counts of 220 psec instead of the previous 2.5 nsec. The muon hodoscope was also moved a few inches upstream to place it nearly in contact with the iron absorber. Study of the previous data had suggested the possibility of a background caused by particles at wide angles that might hit the inner edge of the hodoscope without passing through the iron.

An inadvertent displacement of the Cherenkov counters was caused by the pressure of a Helium bag placed in the beam between the two counters. Study of the data has identified the exact set of runs affected and determined the effect on the counter efficiency. About 25% of the data runs, in the earlier part of the run, were affected. The counter efficiency was reduced from 96% to 88% during those runs. The overall average efficiency is estimated to be 93%.

The pressure in the decay region was about 40 microns in the 1988 run. The low pumping speed of the vacuum connections used for normal pumping was such that it was impossible to substantially improve on this value. Therefore the Temple group removed the retractable regenerator assembly we had installed in the vacuum tank. Its purpose had been to provide a contollable and well located source of regenerated K_S^0's, but the excellent operation of the equipment and the ready identification of CP-violating $K_L^0 \to \pi^+\pi^-$ decays had made it superfluous. The port through which it was installed was therefore used to make a low impedance connection to a high speed turbo pump. The pressure at the pump mouth was then 15μ. Systematic studies of the dependence of rate on pressure were made during the runs, but have not yet been analyzed. At most a small effect is anticipated.

In 1988 the angle of the secondary beam from the incident proton beam was 2.75°. It was hoped that the K_L^0 flux per proton could be increased by working at a smaller angle, since neutron interactions did not seem a limiting factor at 2.75°. A low intensity run at 1.875° showed, however, that the increase in K_L^0 intensity was less than expected and was counterbalanced by a decrease in the event reconstruction efficiency, due to increased rates in the drift chambers. Some of the short-fall in intensity is due to reabsorption and scattering in the Cu target. This target had been made slightly larger in cross-section this year to match more closely the size and drifts of the incident proton beam. It is also possible that extrapolations from the sparse existing data overestimated the kaon production cross section. An attempt to understand the yield by going back to the thinner target at the end of the run was made impossible by extremely high radiation levels at the target station. The effort to run at smaller angles was abandoned before the radiation levels at the target prevented final adjustments. Data was taken at 2.75° as before.

The AGS continued to run at 24 GeV primary energy in 1989. This energy results in approximately 1/3 reduction in kaon flux. The AGS management argued that this factor is compensated by shorter cycle time, better machine reliability and a longer operating period due to lower power costs.

The E791 group observed already in 1988 that there was considerable fine structure in the AGS beam that drastically reduced the effective duty cycle. This year a microcomputer was set up to Fourier-analyze the beam spill and send the results back to the AGS operators. Strong components were found at various multiples of 60Hz all the way up to 1440Hz. The operators were able to reduce some of the worst of this structure, but there are still large effects that the AGS should try to eliminate.

Data acquisition ceased at the end of May. Approximately 3,500 data tapes (of which 2,900 were physics data tapes), each containing about 90,000 events, were accumulated. All of the physics data tapes have been put through a first pass of analysis. This pass does track and vertex reconstruction. Events are retained if they have a satisfactory geometric reconstruction and then are consistent in reconstructed mass and angle with a two-body decay of the K_L^0 consistent with the identification of the decay particles by the muon hodoscope and Cherenkov counters. Acceptance criteria are quite loose at this stage. The rapid processing of the first pass was made possible by using the Cornell supercomputer in addition to the BNL 3090.

In preparation for the second analysis pass, studies of the muon hodoscope counters and Cherenkov counters have determined the new timing parameters for each counter throughout the run. Further refinement of the numbers may be desirable as the analysis proceeds.

A major effort was made to re-measure the magnetic field just before the 1989 run. Improved magnetic shields had been installed on the first magnet (96D40) to reduce the field at the first drift chamber. (Additional coils were desirable for the 96D40, because it was being run with coils designed only for its original vertical gap. The coils did not arrive in time to be installed before the measurement had to begin.) In addition we believed that the experience gained from the first measurement would give us data of higher consistency and quality in a re-measurement. The large extent of the total magnetic field makes a measurement at the 0.1% level extremely difficult with available appartus. The next stage of data analysis will rely on the magnetic field map which is being produced from the raw field measurements.

Efforts were also made to increase the speed and accuracy of the software which reconstructs particle momenta from the drift chamber data. It is estimated that about 100 hours of CPU time will be needed for kinematic fitting of the second pass data. Preliminary study indicates that there will be over 200 $K_L^0 \to \mu\mu$ events in this data.

2.3 Conclusions and Results

We have met the objectives for the current period: to make the best measurement on $K_L^0 \to \mu e$, improve limits on $K_L^0 \to ee$ and make a more precise measurement of the $K_L^0 \to \mu\mu$ branching fraction. We have published results from data taken in 1988 [14,15] and have made our experience and current results available to the community (see section 6.3 and references [7,8,16,9]). Data taken in 1989 but not yet analysed may triple our sensistivity. Since other experiments, notably at Fermilab, have much better sensitivity for $K_L^0 \to \pi^0 ee$, we have stopped work on that decay.

Here we discuss some of the implications of the results from the 1988 run: the best limit on $K_L^0 \to \mu e$, and on $K_L^0 \to ee$ and the most precise measurement of the $K_L^0 \to \mu\mu$ branching fraction. Since other experiments, notably E731 at Fermilab and E845 at BNL, have much better sensitivity, we have stopped further work on $K_L^0 \to \pi^0 ee$. As noted above, the analysis of the 1989 data is in progress; we expect about 200 $K_L^0 \to \mu\mu$ events, and appropriate sensitivities for $K_L^0 \to \mu e$ and $K_L^0 \to ee$.

2.3.1 $K_L^0 \to \mu e$ branching fraction

The present reported values of $B(K_L^0 \to \mu e)$, from the recent round of experiments, are:

BNL E791: $\leq 2.2 \times 10^{-10}$ (90 % CL), 1988 data.[14]

BNL E780: $\leq 1.9 \times 10^{-9}$ (90 % CL), 1988 data. [37]

KEK: $\leq 4.3 \times 10^{-10}$ (90 % CL), 1989 data. [38]

We expect our 1989 data to give a limit of about half our limit above, if it is of the same quality as our 1988 data.

We can compare $K_L^0 \to \mu e$ to other rare processes in terms of sensitivity to new physics, showing that our $K_L^0 \to \mu e$ search is probing physics at scales near 100 TeV. We compare with two approaches: that of Cahn and Harari [39], referred to here as C&H, who proposed a 'horizontal interaction' mediated by a new boson, and suppressed by its high mass; and with the 'effective Lagrangian' approach of Buchmuller and Wyler [40], which establishes a scale of a new interaction, rather than a particle mass. The results of the models of C&H and B&W are given in table 1, which gives the lower limits using recent data [14,41,42,43,44].

2.3.2 $K_L^0 \to \mu\mu$ and $K_L^0 \to ee$ branching fractions

The decay $K_L^0 \to \mu\mu$ is the well-known GIM-suppressed flavor-changing neutral current decay. The previous accepted value of $B(K_L^0 \to \mu\mu)$ was $(9.5^{+2.4}_{-1.5}) \times 10^{-9}$ [46]. Recent values are:

BNL E791: $(5.8 \pm 0.6(\mathrm{stat}) \pm 0.4(\mathrm{syst})) \times 10^{-10}$ [15]

KEK: $(8.4 \pm 1.1(\mathrm{stat.\ only,\ no\ syst.})) \times 10^{-10}$ [38]

Theoretical investigations [45] have been made of the contribution to the $K_L^0 \to \mu\mu$ rate by the intermediate process $K_L^0 \to \gamma\gamma$. If this absorptive part of the amplitude for this decay were the only contribution, the branching ratio would be expected to be $B(K_L^0 \to \mu\mu) \approx 1.20 \times 10^{-5} \times B(K_L^0 \to \gamma\gamma)$. (This is often referred to as the 'unitarity limit.') After an experiment reported a value (later superseded by the measurements cited in ref. [46]) significantly below this, increased theoretical activity emphasized that other processes could decrease this branching ratio very little.

The calculations of the GIM mechanism, which suppress the decay in the quark model, have been extended to the six-quark Standard Model in several analyses.[48] As a result, the deviation from rate predicted from the $K_L^0 \to \gamma\gamma$ intermediate state can be used to constrain SM parameters in some models. For example, the model of Shrock and Voloshin gives (for large m_t) the 'structure-dependent' contribution to the branching fraction as $B_{SD} \approx 3.6 \times 10^{-11} (\mathrm{GeV/c^2})^{-4} (Re(V_{ts}^* V_{td}))^2 m_t^4$.

The difference between our result for $B(K_L^0 \to \mu\mu)$ and the value predicted from the observed $K_L^0 \to \gamma\gamma$ rate is $(-1 \pm 0.7) \times 10^{-9}$. If $B_{SD} \leq 10^{-9}$ as implied by this result, and $m_t \sim 100$ GeV/c^2, this would place a limit of $\sim 5 \times 10^{-4}$ on $\mathrm{Re}(V_{ts}^* V_{td})$, compared with possible ranges up to 1.4×10^{-3} in the SM, and greater if there are more than three families. Other models give smaller predictions, so that the constraint of $B(K_L^0 \to \mu\mu)$ is less useful.

The prediction from $K_L^0 \to \gamma\gamma$ for $B(K_L^0 \to ee)$ is 2.5×10^{-12}. A measured rate significantly higher than this might indicate new physics. The present published values of $B(K_L^0 \to ee)$ are:

BNL E791: $\leq 3.1 \times 10^{-10}$ (90 % CL).[14]

BNL E780: $\leq 1.2 \times 10^{-9}$ (90 % CL). [37]

KEK: $\leq 5.6 \times 10^{-10}$ (90 % CL).[38]

Process	current value	C&H bound (TeV)	B&W bound (Tev)
$K_L^0 \to \mu e$	$< 2.2 \times 10^{-10}$ [a]	55	115
$K^+ \to \pi^+ \mu^+ e^-$	$< 2 \times 10^{-10}$	40	43
$\mu N \to e N$	$< 4.6 \times 10^{-12}$ [b]	190	340
$\mu^+ \to e^+ e^+ e^-$	$< 1 \times 10^{-12}$	80	186
$\mu \to e\gamma$	$< 1.7 \times 10^{-11}$	20	–
Δm_K	3.5×10^{-6} eV	400	1000

[a] This expt., 1988 data
[b] Conversion on Ti/Capture

Table 1: Comparison of mass bounds on new interactions obtained by simple dimensional arguments with bounds calculated following Cahn and Harari (C&H) and Buchmuller and Wyler (B&W). The bounds from B&W are bounds on the *scale* Λ of a new interaction, rather than on the mass of a mediating particle.

3 Neutrino interactions at LAMPF

3.1 Neutrino-electron scattering – LCD (E1015)

The LCD proposal [3] is to make a precise measurement of the neutrino-electron scattering cross-section at LAMPF. Using a beam-stop neutrino source and a water-Čerenkov detector, the relative total crossections for elastic $\nu_\mu e$, $\nu_e e$, and $\overline{\nu_\mu} e$ scattering will be measured with sufficient precision to fix $sin^2\theta_W$ to less than 1%. This bears on the consistency of the parameters of the Standard Model, and is complementary to other measurements, of the Z^0 mass for example. The recent increase in the likely mass of the top quark ($m_t > 77$ GeV/c^2) has made LCD more important, by increasing the size of the ($\approx 7\%$) radiative corrections to which LCD is sensitive.

The project has passed through several phases. It was reviewed by a DOE-appointed panel chaired by B. Barish, which made a favorable recommendation. Engineering studies indicate the feasibility of constructing the device at the site, and a financial review found that the estimated budget is reasonable. The development of suitable photomultipliers is proceeding into production. Tests of a several examples of one manufacturer's tube (Burle Industries) have been carried out, and several other manufacturers have developed prototypes in response to our specifications. The U.S.-Canadian Sudbury Neutrino Observatory project is likely to adopt the Burle PMT that was developed for LCD.

Our particular responsibility is currently to develop plans for calibration of the detector during operation, and to study the possibility of using drift tubes as a cosmic-ray veto.

3.2 Neutrino oscillations – LSND

This is a proposal to search for neutrino oscillations using a smaller-scale prototype of LCD and an existing neutrino area that is equipped with a cosmic-ray veto shield. Its intent is to use LCD technology in a physics experiment, both as a development tool for the LCD project and to improve limits on neutrino oscillations by an order of magnitude over existing results. The LCD technology to be used consists of several elements: large PMT's immersed in a Cherenkov medium (with the addition of some scintillator but using both types of light), the data acquisition electronics, and similar reconstruction algorithms.

A detailed description is being submitted with our Continuation Application.

3.3 Neutrino interactions – E764

Final calculations on the difficult question of the neutrino flux have been completed, allowing absolute values of ν cross sections to be given (with a 15% systematic uncertainty). These are the $\nu_\mu C$ inclusive scattering total cross section and the unique measurement of the exclusive reaction $\nu_\mu \, ^{12}C \rightarrow \mu^- \, ^{12}N$. The values will be compared with calculations based, for example, on the approach of Walecka [49]. This comparison should result in better understanding of nuclei and their interaction with the well-understood ν probe.

A detailed description covering all aspects of the experiment, including the ν oscillation limits, is being written for submission to Physical Review.

Experimental work done on radiative processes occurring during the passage of electrons through a multi-layered Aluminum Scintillator sandwich has been written up and submitted for publication in Nuclear Instruments and Methods. The work is currently available as an internal report[10].

It is expected that Sunyana Dhatta will complete a thesis on $\nu_\mu^{12}C$ inclusive cross sections shortly.

4 CEBAF and Other Work

We have continued to maintain an interest in CEBAF, with Prof. Martoff as our representative. He participated in the preparation of the "Hall C Design Report" and in the May 23-24 1989 meeting of the STAR (Symmetric Toroidal Array) spectrometer collaboration and design group. Our primary interests are in the measurement of parity violation in electron scattering (from protons and helium), and in the possibility of doing kaon physics using production of ϕ mesons as a source of kaons.

Previous work at LAMPF has resulted in a previously un-reported publication on $\pi^0 \rightarrow 3\gamma$ and $\pi^0 \rightarrow 4\gamma$ [6].

Prof. Martoff reported on his muon capture work at the XXIIIrd Yamada Conference [11] and the Asilomar APS-DNP meeting [36], and has submitted some results on fast proton emission following muon capture for publication [19]. Other reports by Prof. Martoff include a talk at the Montreal Symposium on Weak and Electromagnetic Interactions in Nuclei [12] and a calculation relating to cold fusion [13].

5 New Detector Technologies and Dark Matter Search

Prof. Martoff has initiated an effort to develop extremely sensitive detectors for nuclear radiation, and to use these in a variety of ways. For example, an approach to particle identification for 'Dark Matter' is described in an accompanying report [18]. The major part of the effort will be to construct working, full-scale detectors, as described in the sections that follow.

5.1 Superconducting Detectors (University Research Instrumentation Program)

This year we proposed a facility for fabricating superconducting detectors for nuclear radiations, using techniques that have been validated on a small scale. This equipment proposal was funded by the DOE University Research Instrumentation program ($250,000) and by matching funds from Temple ($200,000). The full proposal has been submitted as a Temple report [17]; a summary of the physics issues to be studied and of the technology is given in this section. Prof. Martoff will be the leader of this effort, and has applied for independent operating funds.

The characteristics of the proposed devices would permit sensitive searches for heavy neutral exotic particles of cosmic origin (these are candidates to explain the missing mass, or "dark matter", also referred to as WIMPs, or weakly interacting massive particles [50]). Coherent elastic scattering of terrestrial neutrinos [51] from the detector nuclei could also be measured for the first time. This process is interesting because of its likely importance in supernova energy transport and its potential sensitivity to anomalous semileptonic neutral weak interactions. Again the possibility of measurements with a variety of nuclides differing in nuclear spin and isospin is important in constraining possible anomalous interactions, or searching for dark matter particles with certain specific interactions with hadrons.

Non-conservation of lepton number and nonzero neutrino masses are related violations of Standard Model symmetries. These effects can be sought in a wide variety of experiments, ranging from Kaon decay measurements at GeV energies, to searches for neutrinoless double beta decay and distortions of beta decay spectral endpoints and IB spectra in the KeV to MeV energy range.

In the low energy experiments, the sensitivity depends strongly on detector resolution. The monochromatic sum energy line from neutrinoless double beta decay must be distinguished from a continuum due to primordial and cosmogenic radionuclides, neutron interactions, etc. The beta spectra and IB spectra are perturbed by nonzero neutrino mass only within a few eV of the kinematic endpoint. The aim of the superconducting detector research is to construct detectors or detector arrays large enough and with enough resolution to improve the already stringent limits available from the low energy experiments.

Aside from the question of energy resolution, it is advantageous to be able to conduct certain experiments with a variety of nuclides. Nuclear structure uncertainties make double beta decay lifetime measurements in a single nuclide difficult to interpret in terms of a bound on neutrino mass. Several elements with isotopes in which double beta decay is energetically allowed are superconductors (Zn, Zr, Mo, Ru, Cd, Sn), and could therefore potentially be made into high resolution source/detectors by our technique. To set useful limits, the total instrumented mass must contain tens to hundreds of grams isotope, and must have quite low intrinsic radioactivity.

Certain other expected properties of the proposed detectors would make some fundamental experiments possible, or improve the attainable limits in such experiments. Even for energy depositions of a few KeV, the theoretical energy resolution of ideal superconductive detectors would be of the order of one per cent. The performance will be dominated not by the statistics of the $\sim 10^6$ quasiparticles produced, but by noise in the electronics and the fluctuations in the energy trapped in lattice defects produced by the radiation primaries. The signal size per unit deposited energy should remain rather constant for both low- and high-LET radiation (e.g. X-ray absorption by Compton scattering and neutral particle elastic scattering from detector atoms, producing fast atom recoils). This characteristic is being checked in calibration experiments with neutron elastic scattering planned on the Ohio University Van de Graaff neutron facility in collaboration with J. Rapaport.

Greatly improved energy resolution in practical nuclear radiation detectors would also have wide applicability in technical applications, like radiochemical analysis and environmental monitoring. Interferences of radiations in mixtures of activities would be reduced. Sensitivity to low levels of specific monochromatic radiations would be improved.

5.2 Brief description of facility

The equipment being installed is a complete facility for fabricating and evaluating cryogenic radiation detectors. The fabrication facilities include two state-of-the-art deposition systems, a high vacuum sputtering system (HVSS) and a high vacuum electron beam evaporation system (HVEBS). These two provide the necessary flexibility to prepare and deposit the wide variety of films expected to be needed for the detector development. This equipment also permits production of many superconducting alloys, intermetallic compounds and even oxide systems. The test facility consists of a cryostat commercially built to our specifications, as well as a data acquisition system capable of evaluating the DC and pulse electrical characteristics of the detectors produced. A modular clean enclosure is being built to house the deposition equipment, initially operating at Class 10,000 conditions, with a curtained area around the deposition equipment providing laminar flow and Class 100 conditions. The allowed particulate density in the non-curtained areas of the enclosure will be improved as required and funds for such improvements will be obtained separately. Other equipment such as laminar flow benches and lithographic equipment will be obtained as donations from local industries. Contact has been established with several large device development and fabrication industries in the tri-state area.

Initially detectors will be produced with an array of junctions on a thin, low residual resistivity Nb substrate. Using an array of junctions permits study of barrier thickness and junction size variation without changing samples in the cryostat.

5.3 Industrial Collaboration

We expect that close collaborations with industry will be important in the proposed research, e.g. to produce state of the art GaAs devices for test as radiation detectors. Collaborations between industry and the Temple Center for Materials Research (CMR) have been established, mainly in the area of superconducting device development. The industrial participants include General Electric's Astrospace Division and Electro-Science Laboratories, Inc. The Temple CMR staff also has a joint research effort with the Naval Air Development Center in Warminster.

The Ben Franklin Partnership Program of the Commonwealth of Pennslyvania provides state funds as partial support of the existing University- Industry joint projects. It is likely that such state funding would also become available for joint efforts directly focussed on the research proposed in this document, providing further leveraging of the Federal funds. A detailed proposal has been prepared with the Kurt J. Lesker Company (Clairton, Pennsylvania) to develop a high-yield process for fabrication of trilayer tunnel junctions, requesting $34,878 from the Ben Franklin fund and committing $189,428 in company resources [4].

5.4 Conclusion

The clean room and some equipment will be installed during the current period, and students will gain some experience in cryogenics, as well as test probe construction. The equipment will add to the developing sophisticated thin film and device fabrication facility at Temple. This facility will permit a significant extension of on-campus nuclear and particle physics research, while also benefitting from expertise and facilities in solid state physics and thin film technology existing in other Temple University research groups, such as the Center for Materials Research. The increase in on-campus activity will increase our involvement with the department's graduate program and lead to more students electing to train in the nuclear physics area. The industrial collaborations will enrich the experience of graduate students involved in the research, and perhaps lead to commercialization of some superconducting electronic devices.

6 Investigators' Time and budget

The investigators spent the expected time on the contract. K. McFarlane spent one-third time during the academic year 88-89 and two summer months working on the project. In addition, K. McFarlane has a leave for the academic year 89-90 and is devoting full time to the project, with half salary from Temple and half from DOE. V.L. Highland worked on the project full time for two summer months and had one-third released time during the academic year. L.B. Auerbach's involvement was slightly reduced: one-third time during the academic year, and *one* summer month.

In September 1988, C.J. Martoff joined the Physics Department at Temple as a Visiting Associate Professor. He has worked (about one-sixth time during the academic year and one month in the summer) on the LCD and CEBAF parts of this project, while preparing an independent proposal. He has now been appointed to a tenure-track position and has submitted independent proposals.

We have been fortunate in attracting excellent Post-Doctoral Research Investigators. P. Buchholz worked on the project for the full 13 months, while M.B. Sivertz left us in June, 1989 to work at U.C. San Diego. We are being joined by S. Kettell (Ph.D. from Yale on muonium work at Los Alamos) and C. Guss (Ph.D. from Northwestern on σ_{tot} for $p\bar{p}$ at 1.8 TeV, at Fermilab); their resumes are attached to our continuation request.

G. Daniel has played an important role as Senior Research Technician; he is University supported. Students working on the project included John Belz.

Domestic and foreign travel was close to what was planned.

A detailed financial report will be filed at the appropriate time.

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versity). Added after submission: J. Konigsberg, W. Slater, P. Rubin, (UCLA); D.M. Lee, C. Milner, H. Ziock (LANL); K. Arisaka, J. Urheim, P. Knibbe (U of Pennsylvania); K. Lang, S. Axelrod, J. Margulies, (Stanford); P. Buchholz, M. Sivertz (Temple U); and R. Welsh, M. Eckhause, R. Winter, C. Kenney, M. Chapman, J. Ginkel, R. Whyley, P. Guss, D. Joyce, J.R. Kane (College of Wm. and Mary), Proposal to AGS: Study of Very Rare K Decays. Submitted January 1984, approved by BNL as E791, June 1984.

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6.1 Publications

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6.3 Invited Talks on E791

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[22] "Preliminary Results and Status of BNL E791: Study of Very Rare K_L^0 Decays", presented by K. McFarlane, Temple University, at the XXIIIrd Rencontres de Moriond, March 6th-13th, 1988.

[23] "A Search for the Very Rare Decay $K_L^0 \rightarrow \mu e$: in the Brookhaven National Laboratory Alternating Gradient Synchrotron Experiment 791", presented by C. Milner, Los Alamos National Laboratory, at the Spring meeting of the APS, Baltimore, Maryland, April 20, 1988.

[24] "A Search for $K_L^o \rightarrow \mu e$: Analysis and Results", presented by P. Melese, University of California at Los Angeles, at the Spring meeting of the APS, Baltimore, Maryland, April 20, 1988.

[25] "Preliminary Results from E-791 Rare Kaon Decay Experiment", to be presented by M. Sivertz, Temple University, at the Snowmass Conference, June 27-July 15, 1988.

[26] "Preliminary Results From a Search for Rare K_L^0 Decays : BNL Experiment 791", presented by K. Lang, Stanford University, at the BNL Workshop on Rare K Decays and CP Violation, August 25-27, 1988. (No proceedings.)

[27] "Recent Results from BNL E791: Study of Very Rare K_L^0 Decays", to be presented by P. Buchholz, Temple University, at the IX. European Symposium on Antiproton - Proton Interactions and Fundamental Symmetries, Mainz, Germany, September 5-10, 1988.

[28] "Experimental Perspectives on the Physics of Kaon Decays", to be presented by R. Cousins, University of California at Los Angeles, at the meeting of the Division of Nuclear Physics, Santa Fe, New Mexico, October 13-15, 1988.

[29] "Rare K_L^0 Decays at High Intensities: The BNL E791 Experience", presented by K. McFarlane, Temple University, at the Snowmass 1988 Summer Study, June 30, 1988.

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6.4 Other Talks

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