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PROGRESS REPORT

ON

RESEARCH IN NUCLEAR PHYSICS

August 1, 1994 - June 30, 1995

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DISCLAIMER

PREFACE

The progress on Grant No. DE-FG05-87ER40314 from August 1, 1994 to June 30, 1995, is summarized in this report. Our activities for the past year were focussed on the rare electron capture studies, using experimental facilities at Tennessee Technological University (TTU) and Montana State University (M_TSU).

Two undergraduate students, both majoring in physics, are currently working on the project. They are Brian Faircloth and Predrag Miočinović. Both have assumed roles of significant responsibility.

Gloria Julian has continued as the secretary and bookkeeper for the project. We appreciate her efficient, accurate service and incredible self-control. We would also like to thank Elizabeth Walker, our equipment technician, for cheerfully assisting us in our home laboratory and helping us keep track of our equipment.

Special thanks are due the scientists and support personnel at M_TSU for their assistance and hospitality, without which much of this work would not have been possible.

Finally, we would like to remind the reader that the unpublished work described in this report is preliminary and should not be quoted in the literature without prior approval.

R. L. Kozub

M. M. Hindi

Search for Massive Neutrinos in the Recoil Spectrum of ^{37}Cl following Electron Capture Decay of ^{37}Ar

M. M. Hindi, R. L. Kozub, S. J. Robinson, A. Altgilbers,† B. Faircloth,† P. Miocinovic,† R. Avci,‡ Lin Zhu,‡ and G. J. Lapeyre‡

We continue to develop our experiment to search for massive neutrinos in the recoil spectra of ^{37}Cl following the electron capture (EC) decay of ^{37}Ar.[1],[2] Several changes (most of which were proposed and presented in last year's progress report[1]) were made: (1) a PC-based multi parameter data acquisition system was implemented, (2) a two-dimensional position sensitive microchannel plate detector (PSD) was assembled and used, (3) a procedure for obtaining the ^{37}Ar source from neutron-irradiated ^{40}Ca was developed, and (4) a graphite substrate was used instead of the gold-plated Si substrate. The PC-based data acquisition system and the PSD are described elsewhere in this report. Here we describe items (3) and (4) and present some of the recoil measurements conducted with the new system.

Source preparation

In our previous recoil measurements the ^{37}Ar was produced from the ^{36}Ar(n,γ)^{37}Ar reaction. Since it was nearly impossible for us to separate the ^{37}Ar from the ^{36}Ar, the monolayers of gas which were adsorbed on the cold surface in those measurements had only about 0.01% ^{37}Ar. This year we developed a procedure to produce the ^{37}Ar via the ^{40}Ca(n,α)^{37}Ar reaction, which should allow us, in principle, to obtain a much higher concentration of ^{37}Ar on the surface.

Pure Ca metal (99.99% elemental purity), in the form of crystalline dendritic pieces, ampouled under argon to prevent oxidation, was purchased from Johnson Matthey, Alfa Aesar. We initially encapsulated about 0.5 g of the Ca metal in a single quartz tube. The Ca was outgased by heating it while pumping down the quartz tube with a turbo-molecular pump. The quartz tube was sealed with a H_2/O_2 torch when the pressure dropped below 10^{-6} torr. Before sending the Ca metal for irradiation we tested the procedure for releasing the trapped ^{37}Ar from the Ca metal using an unirradiated sample. The quartz tube was heated to a temperature of 950 °C in an electric oven for five minutes (the melting point of Ca is 840 °C, that of quartz is 1700 °C). It was found that at this temperature the Ca metal reacted chemically with the inner surface of the quartz tube (SiO_2) and that

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[1]R. L. Kozub and M. M. Hindi, *Progress Report on Research in Nuclear Physics, 1993-1994* (DOE/ER/40314-8), 10 (1994).

[2]L. Zhu, *et al.*, J. Vac. Sci. Technol. A **12**, 2037 (1994).

upon cooling the bonded compound cracked the quartz tube. To solve this problem, the quartz tube containing the Ca sample was itself sealed inside another evacuated quartz tube. A couple of tests with this arrangement showed that while the inner tube broke as usual after heating, the outside tube remained intact. Therefore we prepared several such doubly encapsulated Ca samples and sent one of them for irradiation at Brookhaven National Laboratory's High Flux Beam Reactor (HFBR). (Unfortunately, the HFBR was shutdown for several months and we did not get the irradiated sample back until the end of October, 1994. We attempted to get the irradiation done at several other reactors, but the cost was either prohibitive or the reactor would not irradiate pure Ca metal.)

The Ca was irradiated for one week at an in-core position, producing about 20 mCi of ^{37}Ar. The Ca was melted as described above and the ampoule later introduced into a vacuum chamber which was baked at 150 °C for 12 hours and then pumped down to 10^{-8} torr. The ampoule was then broken mechanically with a piston attached to a linear feedthrough. The gas was leaked into the main chamber (which has a base pressure of 10^{-10} torr) via a precision leak valve. The gas was adsorbed on a graphite substrate (described below) cooled down to 16 K. From the Auger-electron count rate from a monolayer of adsorbed gas we deduce that the fraction of ^{37}Ar on the surface was about 0.1%. This constitutes a ten-fold increase in the surface concentration of ^{37}Ar, compared to the surface concentration obtained previously with ^{37}Ar produced via the ^{36}Ar(n,γ)^{37}Ar reaction.

Nevertheless, the ^{37}Ar fraction on the surface is still small and needs further boosting. Since the chemical composition of the contaminants is now different from Ar, we should be able to chemically purify the ^{37}Ar gas by using a system of getters and cold traps in the chamber where the ampoule is broken. We are planning to do this in the next set of measurements this summer (1995).

Graphite substrate

Another change which we've made in the experimental setup is the use of a graphite substrate to adsorb the Ar on, instead of the gold-coated Si substrate which was used before. We had three concerns about the gold substrate: (1) The gold surface was not atomically flat, (2) the high nuclear charge results in a substantial amount of backscattering of the Cl Auger electrons, and (3) the electron density at the surface is high and extends to a distance on the order of the atomic (in this case gold) radius, thus possibly contributing to the neutralization of the ^{37}Cl ions. To overcome the above problems we used a high grade pyrolitic graphite (HPG) of 12×10 mm^2 area and 2 mm thickness as a substrate. The fresh cleaved HPG was examined by using a scanning tunneling microscope (STM) in air; this revealed an atomically flat surface. The HPG was cleaved again from both sides just before being put inside the Ultra High Vacuum (UHV) chamber.

To maintain good thermal contact between the graphite substrate and the cold finger a

new mounting bridge which connects the HPG to the cold finger was designed. The bridge was machined with ultrahigh purity (99.999%) copper to increase the thermal conductivity at low temperature. (At 20 K, copper with 99.999% purity is 10 times more thermally conductive than one with 99.9% purity.) Sapphire plates, which have both high thermal conductivity and high electrical resistance at 20 K, were inserted between the HPG and the copper bridge to allow the substrate to be electrically isolated, so that the sample could be biased, if it was so desired, while maintaining good thermal contact with the copper.

Tests showed that the new system could be cooled down to 16 K, and that Ar readily adsorbs onto the graphite at that temperature. Auger spectroscopy showed no measurable contamination of the substrate at 16 K.

Recoil spectra from ^{37}Ar adsorbed on graphite

Figure 1 compares the retarding field spectrum from 1 Langmuir (1L)[3] of ^{37}Ar on the new graphite substrate, to that from 1L $^{36/37}$Ar on gold which was obtained previously. The number of counts at each retarding voltage V represents the yield of ions with energy $E > qeV$, where q is the charge state of the ion. The solid curve shows a Monte Carlo simulation of the retarding field spectrum expected from the decay of isolated ^{37}Ar atoms. The Monte Carlo simulation gives a charge state distribution of 9.1% for $q = 1$, 18.8% for $q = 2$, 48.7% for $q = 3$, 17.7% for $q = 4$, and 5.1% for $q = 5$. These numbers are in reasonable agreement with the measured charge state distribution of ^{37}Cl following the EC decay of gaseous ^{37}Ar. If the recoil ions have the single energy of 9.6 eV (as they almost do in the Monte Carlo simulation) then at a retarding voltage of 10 V the yield would be zero; for a retarding voltage between 4.8 V and 10 V only $q = 1$ ions would contribute to the yield; for a retarding voltage between 3.2 V and 4.8 V both $q = 1$ and $q = 2$ ions would contribute to the yield, and so on. This explains the location and height of the "kinks" in the simulated retarding field spectrum.

From the analysis of the retarding field spectrum of ^{36,37}Ar adsorbed on the gold substrate (Fig. 1) we have obtained[2] a yield of ~53% for $q = 1$, ~21% for $q = 2$, and ~27% for $q \geq 3$. We have interpreted[2] the excess yield of charge one, (compared to what one would expect from the Monte Carlo simulation) as being due mostly to charge exchange between the multiply charged ^{37}Cl and the neighboring ^{36}Ar (and possibly the gold substrate). The new retarding field spectrum obtained from ^{37}Ar produced via the ^{40}Ca(n,α)^{37}Ar reaction and adsorbed on the new graphite substrate (Fig. 1, solid squares) shows a substantially different charge state distribution for the recoiling ions. While we have not analyzed this spectrum quantitatively yet, it is clear from the figure that the yield of charge state one is much smaller than that of the higher charge states, and is closer to the simulation than

[3]One Langmuir is the exposure of a surface to 10^{-6} torr·s and represents one monolayer for a sticking coefficient of one.

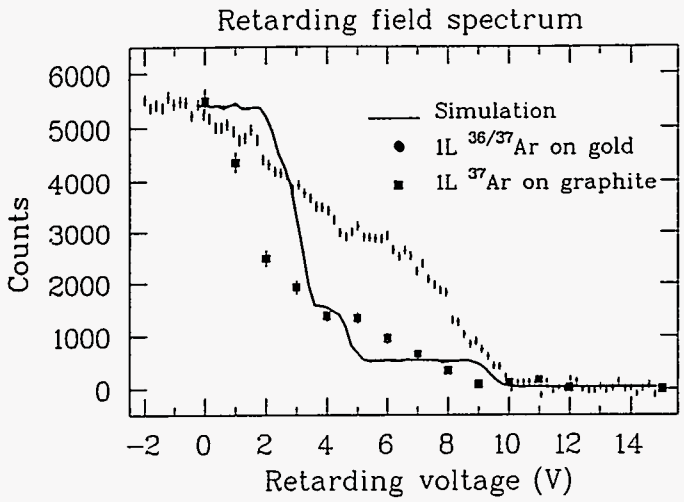

Figure 1: Retarding field spectra of ^{37}Cl ions after EC decay of ^{37}Ar in the gaseous state (solid line), part of a ^{36,37}Ar admixture frozen on a gold substrate (solid circles), and ^{37}Ar frozen on a graphite substrate (solid squares).

that of the $^{36/37}$Ar admixture on gold. We had hoped that the smaller amount of charge exchange on the graphite substrate would result in a narrower energy distribution for the recoils and hence in a more sensitive search of heavy neutrino admixture. However, as indicated below, this did not turn out to be the case.

Figure 2(a) shows a time-of-flight spectrum for ^{37}Cl recoils from 1L ^{37}Ar adsorbed on the graphite substrate. This spectrum is compared to spectra obtained from 5L ^{37}Ar on graphite (Fig. 2(b)) and 6L ^{37}Ar on top of 2L ^{40}Ar adsorbed on the graphite (Fig. 2(c)). Figure 3 shows the same spectra, transformed to an energy distribution, after subtracting accidental coincidence counts. As Figs. 2(a) and 3(a) show, the recoils from 1L ^{37}Ar on graphite are shifted down in energy by about 2 eV, and have a more substantial low energy tail, than those from multilayers on graphite, and multilayers on top of a 2L ^{40}Ar buffer. These measurements indicate that adsorbing the ^{37}Ar straight onto the graphite would not give spectra suitable for heavy neutrino searches. From a surface science point of view, however, the demonstrated sensitivity of the charge and energy distributions of the recoils to the substrate indicates that these spectra might be useful in studying surface properties.

The energy spectrum from 5L ^{37}Ar on graphite (Fig. 3(b)) resembles that from 6L ^{37}Ar on 2L ^{40}Ar (Fig. 3(c)). These spectra also have approximately the same centroid and width as a spectrum obtained from multilayers of ^{36,37}Ar on gold. This similarity indicates that the spectra for these multilayers are dominated by the effect of the interaction of the recoils

with neighboring atoms, and that the effect of the substrate is diminished considerably. This qualitative finding is in agreement with the model calculation carried out last year,[4] which indicated that if the Cl ions were separated from the graphite substrate by a few atomic diameters, the probability of charge exchange with the graphite would drop to negligible levels.

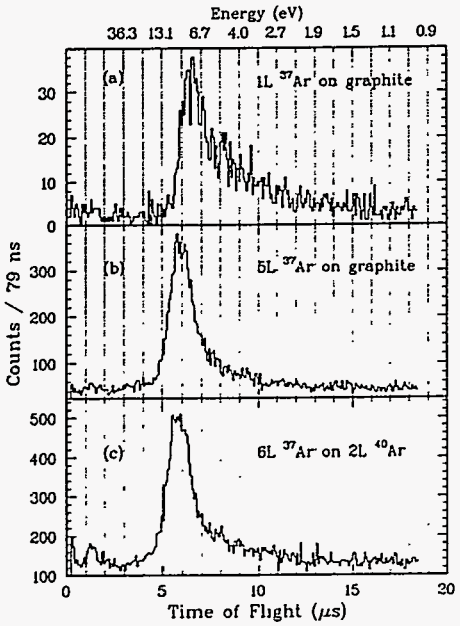

Figure 2: Time of flight spectra of ^{37}Cl ions after EC decay of ^{37}Ar from (a) 1L adsorbed on graphite, (b) 5L adsorbed on graphite, and (c) 6L on top of 2L ^{40}Ar adsorbed on graphite.

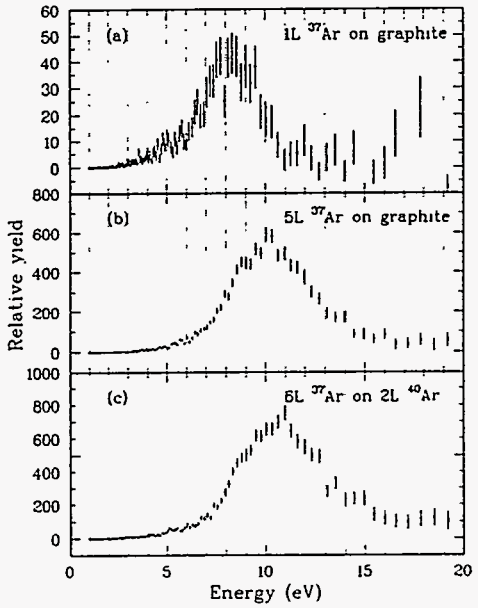

Figure 3: Same spectra as in Fig. 2, converted to energy scale, after subtracting accidental coincidences.

Future Developments

The work conducted so far leads to the following recipe for performing a search for a massive neutrino in the recoil spectrum of ^{37}Cl: (1) Use graphite for the cold substrate. It is easy to cleave the graphite to produce an atomically flat surface. (2) Adsorb 2 - 5 layers of high purity ^{40}Ar on top of the graphite. These layers would then also be atomically flat, and should serve to isolate the ^{37}Cl recoils from the substrate. (3) Adsorb a fraction of a monoloayer of ^{37}Ar produced via the ^{40}Ca(n,α)^{37}Ar reaction, after cleaning, on top of the ^{40}Ar. (4) Conduct time-of-flight measurements in coincidence with K x rays. As explained in last year's report,[1] detecting x rays will select ^{37}Cl ions which end up with

[4] R. L. Kozub and M. M. Hindi, *Progress Report on Research in Nuclear Physics, 1993-1994*, (DOE/ER/40314-8), 18 (1994).

charge +1 after the atomic cascade. Since the first ionization potential of Ar is higher than that of Cl, no charge exchange can take place between the Cl and the Ar bedding.

We are currently working on designing a gas cleaning system, and should be able to implement it and test it this summer. We have very recently obtained funds for the purchase of an ultrahigh-vacuum-compatible germanium x ray detector. We are close to selecting such a detector, but the proposed delivery time (3–4 months) will not enable us to perform the desired recoil measurements this summer (1995). We are also currently working on a molecular dynamics simulation to investigate the fate of Cl ions which recoil into the Ar bedding. With these final improvements we should be able, hopefully by the end of next summer (1996), to set reasonable limits on the mixing of heavy neutrinos with the electron neutrino.

Probability of Double Auger Decay of a K Hole in ^{37}Cl following Electron Capture Decay of ^{37}Ar

M. M. Hindi, R. L. Kozub, S. J. Robinson, A. Altgilbers,[†] B. Faircloth,[†] R. Avci,[‡] Lin Zhu,[‡] and G. J. Lapeyre[‡]

An inner shell vacancy in a light atom is usually filled by an Auger transition – a nonradiative process in which one higher shell electron fills the vacancy and another electron is ejected with an energy equal to the transition energy. In a certain fraction of the Auger decays, however, another electron is shaken off, with the *two* electrons sharing the transition energy. This process is known as double Auger decay. In the independent (i.e., single) particle model of the atom double Auger decay is forbidden; its occurrence, therefore, is due to many-body correlations in the wavefunction. Although evidence for the process was first reported 30 years ago,[1] most measurements to date, like the first one, deduce the probability of double Auger decay only indirectly, from the charge distribution of photoionized atoms, after correcting for multiple ionization produced in the photo process itself; there are very few measurements of the energy distribution of the ejected electrons and no coincidence measurements of the two emitted electrons nor of the angular correlation between them, although a theoretical calculation of these exists.[2]

In last year's progress report[3] we presented the first measurement of the energy distribution of electrons emitted in the double Auger decay of the K hole left in ^{37}Cl after the K electron capture (EC) decay of ^{37}Ar. Here we present new measurements on the absolute probability of double Auger decay in ^{37}Cl.

The apparatus which we use for the study of the recoil spectra of the ^{37}Cl ions[4] can be used to study electron-electron coincidences, by configuring all the microchannel-plate detectors (MCP's) for electron detection. For the work described here, 10 L of ^{37}Ar gas was adsorbed on a graphite substrate at 16 K. Three MCP detectors, one of which was position sensitive (PSD),[4] were placed at $-60°$, $0°$, and $60°$, from the normal to the substrate, at a distance of 6 cm from it. Each detector had three screens, each with 90% transmission, in front of it. The first and last screens were grounded, while the middle screen could be negatively or positively biased. By applying a negative bias V, one can allow only electrons with energy $E \geq eV$ to enter the detector. The data acquisition system allowed the recording of double coincidences between any pair of detectors as well

[†]TTU student.

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[1]T. A. Carlson and M. O. Krause, Phys. Rev. Lett. **14**, 390 (1965).

[2]M. Ya. Amusia, I. S. Lee and V. A. Kilin, Phys. Rev. A **45**, 4576 (1992).

[3]R. L. Kozub and M. M. Hindi, *Progress Report on Research in Nuclear Physics, 1993–1994* (DOE/ER/40314-8), 13 (1994).

[4]See contribution elsewhere in this report.

as triple coincidences between all three detectors. For each coincidence event the time between the start detector and the stop detector was recorded, as well as the position signals in the PSD detector when it registered a signal.

The relative intensities of the normal Auger transitions of a Cl K hole are 84.4% for KLL, 15.1% for KLM and 0.5% for KMM. The energy of the Auger electron involved is about 2400 eV, 2600 eV, and 2800 eV, respectively. For the KLL and KLM transitions the K Auger electron is followed by two and one, respectively, LMM Auger electrons with an energy of about 170 eV. Thus if a screen bias is set at -250 V only K Auger electrons can enter that detector, while if a screen bias is set at -100 V both K and L Auger electrons can be detected. (Since all of the measurements presented here were conducted with negative screen biases, we will just give the magnitude of the bias from now on.) Figure 1(a) shows a (shifted) time spectrum of coincidence counts between a start detector with a screen bias of 100 V and a stop detector with a screen bias of 250 V. The peak corresponds to coincidences between the (slow) LMM electrons detected in the start MCP and the (fast) KLL or KLM electrons detected in the stop MCP. Figure 1(b) shows a coincidence spectrum with the biases on the two MCPs swapped, and now, as expected, the peak is shifted to later times because the fast K electron is detected in the start MCP and the slow L electron is detected in the stop MCP. When both detectors have screens biased at 100 V (thus allowing each to detect both K and L Augers) one observes (Fig. 1(c)) both the early (L_{start}-K_{stop}) peak and the late (K_{start}-L_{stop}) peaks, as well as a "prompt" peak due to coincidences between the two LMM Augers electrons which follow the KLL transition. (The K-L and L-K peaks do not have the same area because there is a larger attenuation, by the gas multilayers, of L electrons heading to the start detector, which is at 60° to the normal of the sample, than of L electrons heading to the stop detector, which is along the normal to the sample. Such an attenuation is not suffered by the much more energetic K electrons.)

Figure 1(d) shows a coincidence spectrum with both screen biased at 250 V, thus preventing LMM Auger electrons from entering either detector. One would not expect to see electron-electron coincidences from a normal Auger decay with these biases. The coincidences we do see, therefore, are (one) evidence of the double Auger decay of the K hole. In this process the two electrons share the total available energy of about 2200 eV, and it is possible for the two electrons to have more than 250 eV each. The time spread reflected in the spectrum shown in Fig. 1(d) is consistent with that expected from two electrons sharing 2200 eV of energy (the shortest time corresponds to starting on a 250-eV electron and stopping on a 1950-eV electron and the longest time to starting on a 1950-eV electron and stopping on a 250-eV electron.) To insure that the observed coincidences are not between a K Auger electron and an x ray or a UV photon from a subsequent atomic transition, we have conducted coincidence measurements with one of the detectors configured for electrons and the other for positive ions, but with a screen voltage of +40 V, so that only photons could enter the detector. The number of coincidences observed in this mode was less than 1% of that observed in Fig. 1(d).

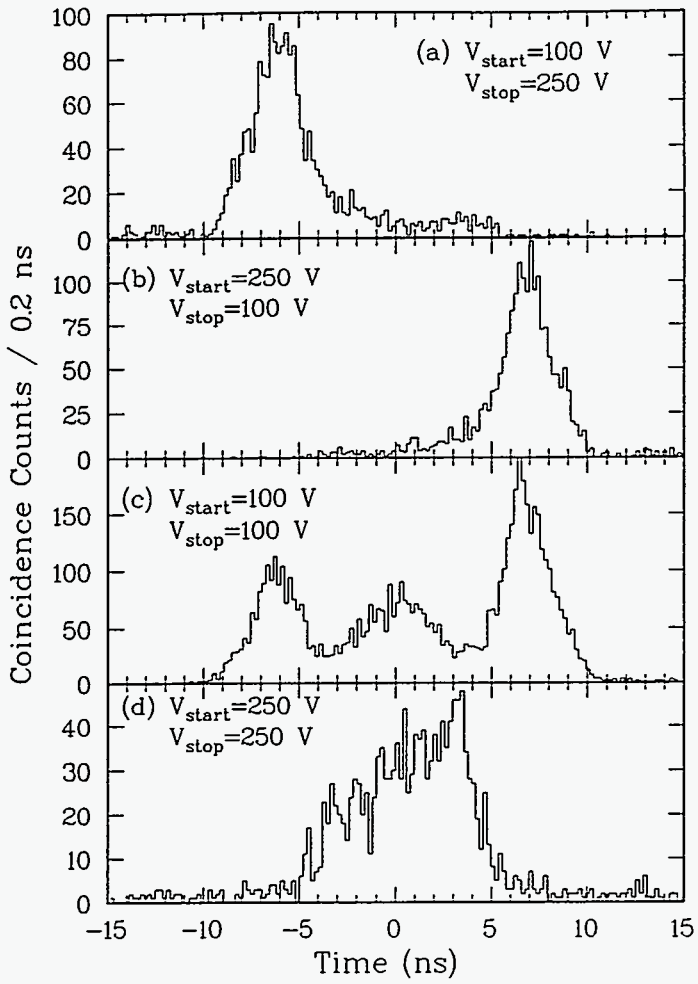

Figure 1: Time coincidence spectra between two MCP detectors with screen biases of (a) $V_{\text{start}} = 100$ V, $V_{\text{stop}} = 250$ V, (b) $V_{\text{start}} = 250$ V, $V_{\text{stop}} = 100$ V, (c) $V_{\text{start}} = 100$ V, $V_{\text{stop}} = 100$ V, and (d) $V_{\text{start}} = 250$ V, $V_{\text{stop}} = 250$ V. The spectra show coincidences between (a) L(start) and K(stop) Auger electrons, (b) K(start) and L(stop) electrons, (c) L(start)-K(stop), L(start)-L(stop), and K(start) and L(stop) electrons, and (d) the two double Auger K electrons.

From the ratio of coincidence counts between the two double Auger electrons to the coincidence counts between K and L electrons we deduce that the double Auger probability (per K Auger transition), with both electrons having an energy greater than 250 eV is between 12% and 15%. The limits arise from the possible range of values in the ratio of detection efficiency for the LMM Auger electron ($E \approx 170$ eV), to that of $\approx$ 250-eV electrons.

The dependence of the double Auger decay probability on the energy distribution of the two emitted electrons was measured by collecting coincidence spectra similar to that shown in Fig. 1(d), but with one of the screen voltages held at 1100 V and the other scanned from 250 V to 1100 V. Figure 2 shows the measured absolute double Auger probabilities. A

data point at a retarding voltage V_1 has contribution from double Auger pairs with one of them having kinetic energy from eV_1 to 1100 eV, and the other having the left over energy (from $2200 - eV_1$ eV to 1100 eV). The probability at the 250-1100 V point is $(5.4 \pm 0.4)\%$; this point has contribution from double Auger electrons with energy from 250 eV to 1100 eV, and hence the measured probability should be about half of that obtained with the 250-250 V screen biases, which has contribution of electrons with energy from 250 eV to 1950 eV.

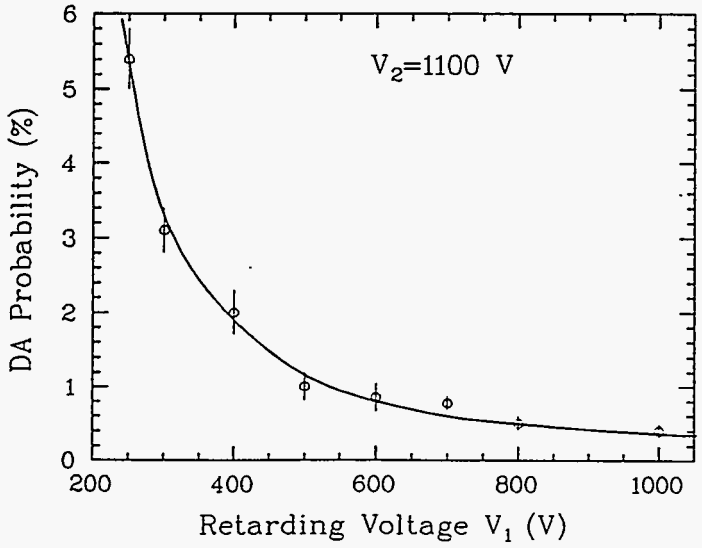

Figure 2: Double Auger probability as a function of the (absolute) retarding voltage on one of the screens. The screen on the other detector had a bias of $V_2 = 1100$ V.

The shape of the energy distribution from the new measurement (^{37}Ar on graphite) is in substantial agreement with that measured last year (^{36,37}Ar on gold).[3] This agreement bolsters our claim that the observed coincidences are due to double Auger electrons, rather than between secondary electrons generated from the interaction of a K Auger electron with the substrate, since one would expect the number of secondaries generated on gold to be substantially different from that generated on carbon.

Another estimate of the double Auger decay probability was obtained from the ratio of the L-K coincidence yield to that of L-L coincidence yield (Fig. 1(c)). In the absence of double Auger decay this ratio is expected to be $(2f_{KLL} + f_{KLM})/f_{KLL} = 2.19$, where f_{KLL} and f_{KLM} are, respectively, the KLL and KLM fractions of the K Augers. The measured ratio was 1.66 ± 0.07. If double Auger decay happens, the filling of the three L vacancies produced by the double Auger process will create three LMM Auger electrons. In addition, the energy distribution of the double Auger electrons (as predicted theoretically and measured in this work, Fig. 2), is strongly skewed to the asymmetric energy

partitioning, with one electron having most of the energy. Thus in double Auger decay one has, most of the time, four slow electrons and one fast electron. There are six different ways of getting a slow-slow coincidence from these four electrons (which contributes to the L-L peak), and four ways of getting a slow-fast coincidence (which contributes to the L-K peak). Assuming the double Auger probability per K Auger decay to be P_{DA}, the measured ratio of the slow-fast (K-L) peak to the slow-slow (L-L) peak should then be $(1.84 + 4P_{\mathrm{DA}})/(0.84 + 6P_{\mathrm{DA}})$. Equating this ratio to our measured value of 1.66 ± 0.07 gives $P_{\mathrm{DA}} = (8 \pm 3)\%$, which is somewhat lower, though not inconsistent with, the range of 12% to 15% obtained above.

Another evidence for our observation of the double Auger process comes from triple coincidences between three of the four slow electrons which accompany the process. All three detectors had a screen bias of 100 V. For triple coincidences the times between the $-60°$ (Left) and $0°$ (PSD) detectors, and between the $-60°$ (Left) and $+60°$ (Right) detectors were recorded. Figure 3 shows a density plot of the number of triple coincidence events as a function of the Left-PSD time (x axis) and Left-Right time (y axis). Figure 4 is a schematic diagram explaining the origin of the triple coincidence counts observed in Fig. 3. Unfortunately, the Right MCP worked for only a very short time before it developed a short, so we were unable to obtain good statistics on triple coincidences. However it is clear from Fig. 3 that there are counts (about six) corresponding to three $\sim$ 170-eV coincident electrons. As Fig. 3 shows, there are essentially no accidental counts in the triple coincidence spectrum and it is very unlikely that three electrons of that energy can be coincident with each other from a source other than the double Auger decay of the K hole.

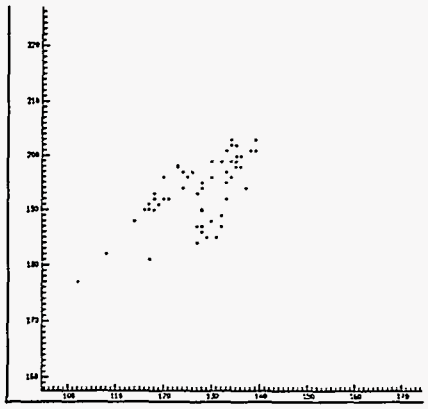

Figure 3: Density plot of triple coincidence counts as a function of the Left-PSD time (x axis) and Left-Right time (y axis).

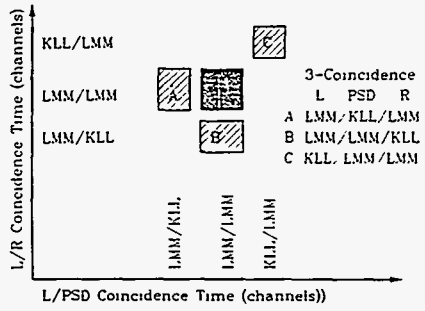

Figure 4: Schematic diagram of the triple coincidence spectrum. The solid region is where LMM-LMM-LMM triple coincidences are expected.

We have attempted to examine the angular correlation between the two double Auger electrons by looking at the number of coincidence counts versus position in the PSD. The angular variation over the PSD amounts to only 23.5°; over this relatively small range the theoretical angular distribution is predicted to change by $\approx 10\%$. We did not have sufficient statistics in the coincidence counts to examine a variation in the angular correlation at that level.

A paper on our results is being prepared. Future work should examine the angular correlation of the double Auger electrons and the subshell distribution of the three vacancies which are produced. This would require at least two energy-selective detectors, to determine precisely the total energy of the two double Auger electrons. We do not currently have such detectors, but a proposal will be submitted by our Montana State colleagues to acquire such a system.

A PC-based Multiparameter Data Acquisition System

M. M. Hindi

In order to support the experiments on massive neutrino search and double Auger decay which we are conducting at Montana State University, we acquired a new PC-based multiparameter data acquisition system. A major effort was spent on writing the acquisition software and debugging it here at Tennessee Tech before the system was shipped to Montana. We list here the hardware components of the system and give a brief description of the main features of the software we developed.

The newly acquired hardware components of the system are the following:

- A DELL model 466V/XPS Desktop Computer System, featuring a 66 MHz Intel 486 microprocessor, 16 MB of RAM, a 256 Kb cache, a 450 MB IDE hard drive, and a double speed CD-ROM drive. (price: $3,000)
- An ISA SCSI Controller ADAPTEC 1540 card, for communication between the PC and the 8 mm SCSI tape drive, listed below. (price: $237)
- A KineticSystems model 2927-Z1A, 16-bit IBM-PC interface with DMA for communication between the PC and the CAMAC crate controller. (price with cable: $1,523)
- A KineticSystems model 3922-Z1B parallel bus CAMAC crate controller. (price $2,475)

In addition to the above newly purchased components, the hardware system also had a 2.2 GB 8-mm Exabyte tape subsystem, from Transition Technologies, Inc., ($3,500), a CAMAC crate, and the usual assortment of CAMAC modules. A schematic of the hardware components is shown in figure 1.

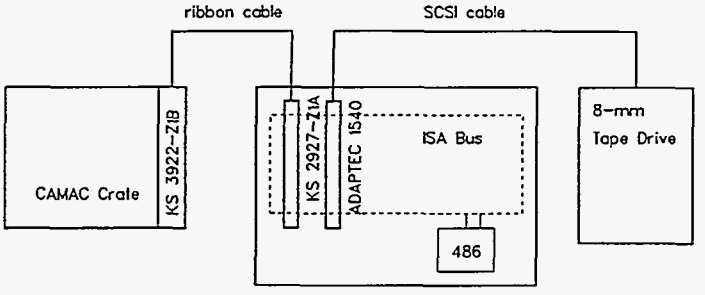

Figure 1: Schematic diagram of the PC-based data acquisition system.

The DOS-based main data acquisition software was written locally in the C language and compiled using Borland's C++ 3.1 compiler. Communication with the KineticSystems 2927 interface, which controls the transfer of data from the crate controller to the CPU (and optionally directly to memory, via Direct Memory Access) was done via in-line assembly code. Real-time communication with the tape subsystem via the ADAPTEC 1540 SCSI controller was done using an object library of C-callable routines, EXBLIB-RT, purchased from Data Strategies International, Inc., (price: $450) and linked with the main program. The program has a graphical, menu-driven interface and offers the following features:

- Event by event data acquisition and recording with the following features:
  - Up to 256 16-bit words per event can be read from the CAMAC crate and written, event by event, to the hard drive or to the 8-mm tape. The number of parameters per event could be easily extended beyond 256. The tape buffers are written in the L002 format used by Oak Ridge National Lab's HHIRF. This format allows the tapes to be replayed using ORNL's Upack and Vaxpack replay and analysis packages.
  - The CAMAC commands to be executed on each run start, each event, and each run stop, are read from an ASCII file. The event triggers are based on the enabled look-at-me (LAM) signals listed in this file. Two versions of the program exist, one which polls the 2927 interface for the occurrence of the LAM and another which books an interrupt upon the occurrence of a LAM.
  - The measured data acquisition speed is about 66 k words per second (about 15 μs per word). This could in principle be boosted to about 800 k words per second (about 1.3 μs per word) with the use of Direct Memory Access, which the 2927 board supports; we have not made use of the DMA transfer capability yet. The current rate is quite adequate for our coincidence measurements.
  - CAMAC commands can be entered interactively. Tape control can also be entered interactively. Like all other features in the program, these are available via easily accessible drop down menus and pop-up forms.
- Histogram definition and event sorting:
  - From 1–100% of the acquired events can be sorted on line into one- or two-dimensional histograms.
  - Currently 64 one-dimensional and 32 two-dimensional histograms are allowed, but the number can be easily extended. The program allocates memory below the 640 Kb "barrier" to as many histograms as possible, and allocates EMS memory to the remaining histograms. In principle all of the 16 MB of RAM above the 1 MB mark could be made available for histograms.
  - A condition can be associated with each histogram. A condition is a logical AND of gates on the parameters. (In a coincidence experiment, for example, the

condition associated with a coincidence spectrum (histogram) could be a logical AND of a gate set on the time (or TAC) parameter and a gate set on the energy parameter.) The histograms, conditions and gates can be specified interactively via menus and then saved to an ASCII file, or read from an ASCII file. The gates can be changed dynamically. One- or two-dimensional ("banana") gates can be specified.

- The following histogram display and manipulation features are available:
  - Simultaneous display of up to eight one-dimensional spectra and four two-dimensional spectra. The one-dimensional spectra can be displayed stacked or overlayed. The counts can be displayed on a linear or logarithmic scale, and the channel ranges to be displayed can be specified with a mouse-controlled cursor or typed in for precise selection.
  - The histogram display can be live (i.e. the spectrum is updated dynamically as counts come in), or static (updated only upon user request).
  - Peak areas, centroids and widths can be obtained interactively.
  - Dynamic projection onto either axis can be made from the two-dimensional histograms.
  - The on line spectra can be saved to a file. The currently available file formats are the .spk and .his formats used in ORNL's software packages.

We have been using the new data acquisition package for the past 12 months and have found it to be reasonably stable and easy to use. It has been quite adequate for acquiring and monitoring the status of data at the low – moderate rates which we encounter in our measurements. A replay version of the program which is capable of replaying the event data from either tape or hard disk was also written.

It is perhaps worth also mentioning here that in addition to the DOS operating system, we have also installed *Linux* on our new PC. *Linux* is a freely available and increasingly popular Unix clone. We have managed to port the Oak Ridge scanning and spectrum display programs to it and do most of our data analysis on it.

Our system was duplicated recently by our colleague Dr. Steven Robinson. His system uses a Pentium processor with a PCI bus. We would be happy to offer the software we wrote to anyone who wishes to acquire it.

A Two-Dimensional Position-Sensitive Microchannel Plate Detector

M. M. Hindi, R. L. Kozub, A. Altgilbers,† B. Faircloth,† R. Avci,‡ and Lin Zhu‡

For the Auger electron-recoil ion coincidence measurements (described elsewhere in this report), it is desirable to have the ion detector close to the source to achieve high coincidence efficiency. In order to maintain knowledge of the flight distance, however, a two-dimensional position sensitive detector is required. This year we have acquired, assembled and successfully operated such a position-sensitive microchannel plate (MCP) detector.

Two image-quality microchannel plates, 25 mm in diameter, and a 100 kΩ resistive anode encoder (RAE) were purchased from Quantar, Inc. The RAE design is similar to that of Augustyniak *et al.*[1], and consists of a uniform resistive surface with resistivity r, bounded by four circular arcs of radius of curvature a and resistance per unit length $R_L = r/a$, as shown in Fig. 1. The RAE is large enough to inscribe the MCP area within the arcs. The design is based on the Gear theorem, which states that a uniform current

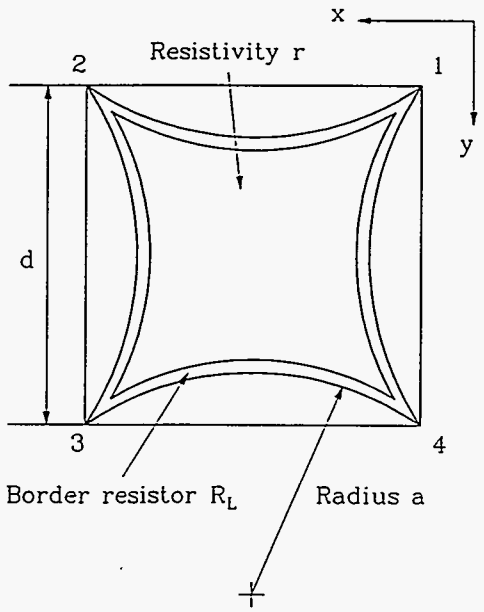

Figure 1: Geometry of the resistive anode encoder. Electrical connections are made at the four corners.

flow in an infinite sheet having resistivity r is unaffected by a circular hole of radius a if the hole is bordered by a line resistor of value $R_L = r/a$. In this design the currents I_a flowing

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[1]W. M. Augustyniak and H. P. Pie, IEEE Trans. Nucl. Sci. NS 19, 196 (1972).

to the four corners would be inversely proportional to the resistance (and therefore the distance) from the point (x, y) at which the charge cloud Q strikes the surface. Explicitly, for the geometry shown in Fig. 1, the coordinates (x, y) are related to the currents by

$$x = d\frac{I_2 + I_3}{I_1 + I_2 + I_3 + I_4}, \qquad y = d\frac{I_3 + I_4}{I_1 + I_2 + I_3 + I_4}.$$

The housing assembly, which was made up of 37 pieces of Ta, Al, and Teflon, was designed at Montana State University by Lin Zhu, and machined professionally. Figure 2 shows a simplified cross section of the assembly. The four corners of the RAE were connected to charge sensitive preamplifiers, the outputs of which were shaped by linear amplifiers. The amplified pulses were digitized by Analog to Digital Converters (ADC's) interfaced to a PC-based data acquisition system via a CAMAC crate, and the position signals were computed by the software on an event by event basis. The timing pulse was extracted capacitively from the rear side of the second MCP.

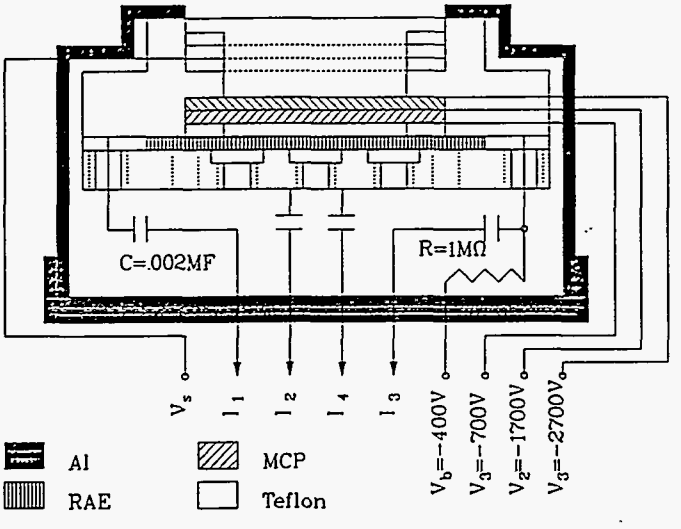

Figure 2: Cross section diagram of the home-assembled MCP-RAE detector, biased for positive ion detection.

The spatial resolution of the RAE was checked by putting a copper mask with an array of holes of diameter 0.2 mm in front of it. The best resolution we were able to achieve was better than the 1/100 specified by Quantar, Inc. Figure 3 shows an image of the mask produced by a beam of electrons. To monitor the stability and linearity of the signals during the long coincidence runs we installed 3x3 Ta wires, with a diameter of 0.35 mm each, in front of the screen closest to the MCP's. Figure 4 shows the image produced by the recoiling ^{37}Cl ions, collected during one of our runs (see contribution elsewhere in this

report). The image of the Ta wires is very clear. (The wires were stretched by hand and the slight bends in the image actually reflect the bends in the wires.) It should be noted that the image is *not* a geometrical shadow, – the source of ions was too extended and too close to the detector to produce a shadow – but rather a focusing effect of the electric field lines which guide the ions, whose energy is very small (about 10 eV) compared to that gained from the field (2700 eV), away from the wires. A similar image was not observed when detecting Auger electrons in the MCP. One can also see in Fig. 4 a partial image of the screen mesh just behind the Ta wires. The criss-crossing lines of the mesh were 200 μm apart and 20 μ in diameter. This image illustrates the successful operation of this detector.

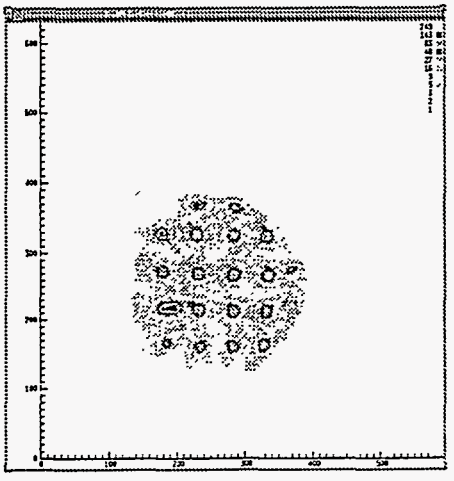

Figure 3: Image produced in the RAE by an electron beam of a copper screen with an array of 0.2-mm holes in it.

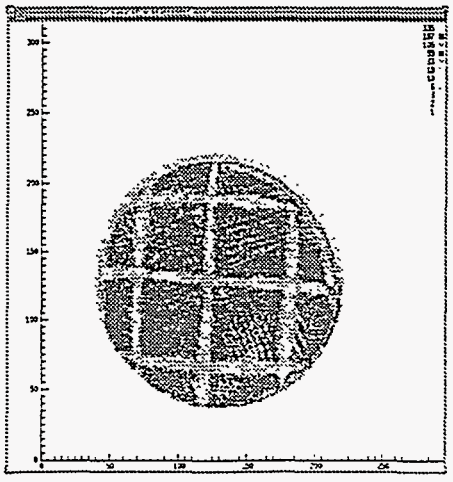

Figure 4: Image produced in the RAE by recoiling ^{37}Cl ions, with $\approx$ 10 eV energy. The 3x3 lines are Ta wires 0.35-mm in diameter, about 2 mm in front of the microchannel plates.

PUBLICATIONS

(August 1, 1994 - June 30, 1995)

Journal articles:

1. "β^+ decay and cosmic-ray half-lives of ^{143}Pm and ^{144}Pm," M. M. Hindi, A. E. Champagne, M. T. F. da Cruz, R.-M. Larimer, K. T. Lesko, E. B. Norman, and B. Sur, *Phys. Rev. C* **50**, 728-732 (1994).

2. "Search for a 17 keV Neutrino Using a ^{14}C-Doped Germanium Detector," F. E. Weitfeldt, E.B. Norman, Y. Chan, M. T. F. da Cruz, A. García, E. E. Haller, W.L. Hansen, M. M. Hindi, G. Kenchian, R.-M. Larimer, K. T. Lesko, P. N. Luke, R. G. Stokstad, B. Sur, and I. Žlimen, Phys. Rev. C (in press, 1995).

3. "Absolute Intensity of Internal Bremsstrahlung from the EC Decay of ^{125}I," M. M. Hindi, R.L. Kozub, and S. J. Robinson, Phys. Rev. C (submitted, 1995).

Conference Contributions

1. "Radio-isotope Yields from 1.85-GeV Protons on Mo and 18.5- and 5.0-GeV Protons on Te," D. W. Bardayan, M. M. Hindi, M. T. F. Da Cruz, Y. D. Chan, A. Garcia, R. M. Larimer, K. T. Lesko, E. B. Norman, D. F. Rossi, R. G. Stokstad, F. E. Weitfeldt, I. Zlimen, and A. F. Barghouty, submitted to the 24th International Cosmic Ray Conference, Roma, Italy, August 28-September 8, 1995.

2. "Kinematical Probes of Neutrino Mass," The N1 Working Group: E. Adelberger, D. Ahluwalia, D. Caldwell, P. Cushman, M. Diwan, L. Durand, J. Engel, G. Gelmini, R. Gibbs, M. Hindi, B. Kayser, R. Kozub, D. Lalanne, R. Lanou, J. Laplanche, W. Palmer, R. Peccei, A. Piepke, H. Robertson, S. Rolli, G. Segre, A. Sonnenschein, and C. Sutton, Proceedings of the Snowmass 94 Conference (in press).

Abstracts

1. "The Auger Relaxation of ^{37}Cl Following Electron Capture Decay of ^{37}Ar," L. Zhu, R. Avci, G. J. Lapeyre, M. M. Hindi, R. L. Kozub, and S. J. Robinson, 41st National Symposium of the American Vacuum Society, Denver, Colorado, 318 (1994).

2. "Electron Capture Q Value of ^{179}Ta," M. M. Hindi, B. O. Faircloth, R. L. Kozub, K. R. Czerwinski, R.-M. Larimer, K. T. Lesko, E. B. Norman, and B. Sur, submitted for the Fall DNP/APS Meeting, Bloomington, Indiana, 1995.

Abstracts (cont.)

3. "Determination of Weak Transition Intensities in ^{144}Nd," S. J. Robinson, A. Altgilbers, M. M. Hindi, E. B. Norman, and R.-M. Larimer, submitted for the Fall DNP/APS Meeting, Bloomington, Indiana, 1995.

TTU PERSONNEL
(August 1, 1994 - June 30, 1995)

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DOE = Department of Energy
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TTU = Tennessee Technological University

APPENDIX