SEARCH FOR THE DOUBLE BETA DECAY OF Nd^{150}
 USING A MAGNETIC SPECTROMETER-DETECTOR

MASTER

Abstract

by

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A large aperture, low resolution magnetic spectrometer-detector was designed and constructed to search for the double beta decay of Nd^{150} . The spectrometer-detector was operated for ~ 750 hours in the low background environment of a salt mine, 2000 feet below ground level. Lower limits were set on the two neutrino and no neutrino decay modes of

$$\tau_{\beta\beta, 2\nu} > 5 \times 10^{18} \text{ years}$$

$$\tau_{\beta\beta, 0\nu} > 7 \times 10^{18} \text{ years.}$$

An interpretation of these results in terms of the character of the electron neutrino and lepton conservation is made.

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TABLE OF CONTENTS

ABSTRACT	ii
LIST OF TABLES	iv
LIST OF FIGURES	v
ACKNOWLEDGEMENTS	vi
INTRODUCTION	1
I THE SPECTROMETER-DETECTOR	5
II DATA COLLECTION SYSTEM	9
III SYSTEM OPERATION	11
IV DATA ANALYSIS	13
V PRESENTATION OF RESULTS	15
VI DISCUSSION OF BACKGROUND	18
VII DISCUSSION OF RESULTS	21
VIII POSSIBLE IMPROVEMENTS TO THIS EXPERIMENT	24
APPENDIX A DETAILS OF THE DATA ANALYSIS PROGRAMS	25
APPENDIX B DETAILS OF EFFICIENCY CALCULATION	27
APPENDIX C MEASUREMENT OF SOURCE CONTAMINATION	32
FOOTNOTES	37
TABLES	39
FIGURES	45

LIST OF TABLES

Table 1	Summary of Some Recent Double Beta Decay Experiments	39
Table 2	Summary of Data From Source Run Configuration Runs	40
Table 3	Summary of Data From Source Background Configuration Runs	41
Table 4	Summary of Data From General Background Configuration Runs	42
Table 5	Spectrometer-Detector Efficiencies for Several Magnetic Field Values	43
Table 6	Observed Count Rates for β - γ Coincidence Experiment	44
Table 7	$\epsilon_{\text{det}}^{\gamma}$ $\epsilon_{\text{geom}}^{\gamma}$ For Several γ Ray Energies	44

LIST OF FIGURES

Figure 1	End View of Spectrometer	45
Figure 2	Rough Field Map of Spectrometer Interior, Values in gauss	46
Figure 3	Picture of Spectrometer Side View	47
Figure 4	Picture of Spectrometer End View	48
Figure 5	Picture of Spectrometer Interior View	49
Figure 6	Picture of Source Bag Frame	50
Figure 7	Electronic System	51
Figure 8	Photomultiplier Dropping Chain	52
Figure 9	Gate Enable Generator	53
Figure 10	View of Electronics Room in Experimental House in Morton Salt Mine	54
Figure 11	Typical Data Traces	55
Figure 12	Typical Noise Traces	55
Figure 13	Background Pulse Height Spectrum for Right Bank of Detectors	56
Figure 14	Background Pulse Height Spectrum for Left Bank of Detectors	57
Figure 15	Observed Source Run Sum Spectrum in 297.5 Hours .	58
Figure 16	Observed Source Background Sum Spectrum in 233.8 Hours	59
Figure 17	Observed General Background Sum Spectrum in 213.8 Hours	60
Figure 18	Single Electron Spectra for Decay $Nd^{150} \rightarrow Sm^{150} + 2e^-$.	61
Figure 19	Electron Energy Sum Spectra for the Decay $Nd^{150} \rightarrow Sm^{150} + 2e^-$	62
Figure 20	Observed Net Sum Spectrum for the Decay $Nd^{150} \rightarrow Sm^{150} + 2e^- + 2\gamma$	63

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INTRODUCTION

Double beta decay, the simultaneous emission of two beta particles and possibly two neutrinos from the same nucleus, has been sought experimentally over the last twenty-two years.¹⁻⁸ The experimental techniques employed fall into three categories:

1. The detection of two electrons in coincidence by counters surrounding a sample of the material.
2. The detection in a spark chamber or emulsion of two electron tracks coming from a common point within a source.
3. The detection of the daughter element by studying its abundance in sources of the parent with a mass spectrometer.

The third method, which determines only the decay rate, seems to have successfully yielded half lives for the decay $\text{Te}^{130} \rightarrow \text{Xe}^{130}$ and $\text{Se}^{82} \rightarrow \text{Kr}^{82}$ and to a lesser extent for the decay $\text{Te}^{128} \rightarrow \text{Xe}^{128}$ in the work of Kirsten et al.,^{6,7} and that of Gerling et al.⁸ While methods one and two are sensitive to both the half life and the energy distribution of the electrons, no application of these methods has yet allowed the unambiguous detection of two electrons from a double beta decay candidate.

Before the discovery of parity non-conservation in weak interactions, interest in double beta decay came from the relation between the character of the neutrino and the predicted decay rate.^{9,10}

If the neutrino were a Dirac particle, the decay occurred with the emission of two β -particles and two neutrinos (or anti-neutrinos) while if the neutrino were a Majorana particle, the decay proceeded without the emission of neutrinos. Recent conjectures in weak interaction theory allow that both types of decay might occur.

Based upon an excess of Xe^{128} detected in one of Kirsten's earlier experiments⁶ and also an experiment of Takaoka and Ogata⁵ and Kirsten's well accepted result for Te^{130} , Pontecorvo¹¹ has suggested that neutrinoless double beta decay could be a first order effect of a super weak interaction ($\Delta Q = \pm 2$, $\Delta S = 0$) rather than a second order effect of the usual weak interaction ($\Delta Q = \pm 1$, $\Delta S = 0$). He compared this to the super weak interaction proposed by Wolfenstein¹⁴ ($\Delta Q = 0$, $\Delta S = \pm 2$) which causes a slight violation of CP conservation in K_L^0 decay. Meanwhile, Primakoff and Rosen¹² have suggested that neutrinoless double beta decay was indeed a second order process of the weak interaction and have presented a Hamiltonian that accounts for lepton non-conserving double beta decay and for the CP non-conservation observed in K_L^0 decay at the same time.¹³ Searching for the neutrinoless decay mode is then seen as a sensitive test of the principle of lepton conservation. However, since these arguments are all based on an excess of Xe^{128} that can not be related directly to double beta decay alone and was not observed in a similar experiment on another rock sample, the best way to answer the problem of lepton conservation is to attempt to measure the energy spectra of the electrons off a double beta decay source.

The no neutrino decay mode is easiest to identify experimentally. Here the two electrons share the available energy and the signature of this mode is seen in the spectrum of the sum of the electron energies. All of the events in this spectrum will be concentrated at the transition energy. The two neutrino mode has a continuous spectrum of electron sum energies terminating at the same energy, but heavily favoring the lower energy end. The present experiment is designed specifically to observe the two neutrino mode but is also sensitive to the neutrinoless mode.

All counter experiments to detect double beta decay suffer from two different types of problems. First, a multiple scattering of γ -rays, and electrons formed in one detector, being driven through the source to appear in the other, make large contributions to the observed coincidence rate. Secondly, if contamination from Bi^{214} , a member of the Ra decay chain, exists in the source, double beta decay can be simulated by a beta decay, followed immediately by an internal conversion deexcitation in the daughter nucleus. To overcome the first problem a large aperture, low resolution double beta magnetic spectrometer was constructed that:

- (a) allowed no electron to pass from one bank of detectors to the other, and
- (b) used lead shielding between detectors to attenuate source associated γ -rays.

The experiment was operated in a low background environment in a salt mine. Source contamination was investigated in an experiment

designed to look specifically for β - γ coincidences coming from the Nd^{150} source.

Table 1 summarizes the experimental and theoretical situation for several double beta decay candidate nuclides.

Two experiments have been performed searching for the double beta decay of Nd^{150} . The experiment of Cowan et al.² was sensitive only to the neutrinoless decay mode while East's³ experiment was designed to observe both.

I. THE SPECTROMETER-DETECTOR

The spectrometer-detector is shown in end view in Figure 1. It consists of a large, cylindrical aluminum vacuum chamber, one meter in diameter and 1.9 meters long. The vacuum chamber is wrapped with about 1800 turns of 1/4" diameter aluminum wire, placed in ten layers. The layers are separated with sheets of 5-mil mylar and successive turns are spaced with tygon tubing. The ends of each layer of wire are accessible at the surface of the solenoid. The solenoid maintains a field of about 150 gauss over about 60% of the volume of the spectrometer. Figure 2 shows a rough field map of the interior of the spectrometer. A vacuum pump maintains a pressure in the range 5-20 microns of Hg. and the spectrometer reaches an equilibrium temperature around 22°C, for a current of 15 amperes.

Inside the vacuum chamber is a framework that serves to support the detector holders in position and provide the necessary baffling. The baffles, B, are two sheets of 1/8" thick aluminum that run the length of the spectrometer and along with the detectors, S_{left} and S_{right}, divide the active volume into two wedge shaped spaces.

The axially directed magnetic field allows electrons to spiral clockwise or counterclockwise in the spectrometer. The first benefit of this design is that the spectrometer may be run in the normal, data collecting mode, where the electrons spiral from the source to the detectors, and in the field reversed, background mode

with the source associated electrons spiralling into the baffles, B. Secondly, the detectors have been successfully isolated so that an electron formed in one bank of scintillators cannot leave that detector, make its way through the source and be counted in the other bank. Typical electron trajectories are shown as dashed lines in Figure 1 for the data collecting mode.

Each bank of detectors is made up of three sheets of pilot "B" plastic scintillator 43 cm x 55 cm x 1/4". Each sheet is viewed by two EMI 6097S low noise, 2 inch photomultiplier tubes and held in place in an aluminum detector holder. The photomultiplier tubes are spaced 4" back from the scintillators and the tubes and light pipes are wrapped with 4 layers of netic and conetic magnetic shield foils. The shielding allowed a change in gain of less than 5% for the four tubes situated nearest the middle of the spectrometer, when the magnetic field was turned on. The two tubes on the end of each detector bank suffered gain changes up to 20% and for this reason were hooked up so that their high voltage could be adjusted independent of the other four tubes in the bank. Their gain was then adjusted relative to the other tubes in the bank each time the system calibration was checked. The photomultiplier tube bases and the high voltage distribution network, which were inside the vacuum chamber, were potted in RTV-602, a clear silicone potting compound. The phototube prongs and bases were coated with Dow Corning S compound, a silicone gel. The potting compound and gel were used primarily to provide insulation against corona and discharges while the spectrometer was in operation.

The energy calibration and uniformity of response of the detectors were checked by observing the 0.973 MeV internal conversion electron from a small Bi^{207} source. The pulse height remained constant within about $\pm 6\%$ as the electron source was moved to various positions on the scintillator, not directly in front of either phototube. The energy resolution (HWHM), averaged over the several source positions, was found to be 25%.

The sources were prepared from Nd_2O_3 enriched to 92.5% Nd^{150} , obtained from Oak Ridge National Laboratory on loan. Spectrographic analysis of the Nd_2O_3 indicated a chemical purity of 98.5%, with trace amounts of Ca, Mg, La, Pr and Sm present.

The Nd^{150} sources consist of five 5 cm x 30 cm, 1-mil thick mylar bags, each containing about 4.9 grams of Nd_2O_3 . The Nd_2O_3 was formed into a paste and spread uniformly throughout the mylar bags to a thickness of 33 mg cm^{-2} . The bags were then clamped into an aluminum frame for support. The five sources contained (20.6 ± 0.1) grams of Nd^{150} . The sources were placed along the axis of the spectrometer. $1/2"$ of aluminum and $1/4"$ of lead were placed between the sides of the source frames and each detector bank to shield against multiple γ -ray scattering.

The spectrometer-detector was operated in a steel shack, constructed in the Fairport mine of the Morton Salt Company. There, the low energy γ -ray intensity is reduced by a factor of 20 from its ground level value and the cosmic ray induced event rate is a factor of 4×10^4 lower than at ground level.³ The low energy back-

ground spectrum from the right and left banks are shown in Figures 13 and 14.

Two 25,000 BTU air conditioners were placed to blow cold air directly on the spectrometer and the spectrometer room remained at a temperature of 16°C for the duration of the runs. Since the experiment was unattended for most of its operation, a series of relays protected the spectrometer and its associated equipment against operation under severe conditions caused by interruption of electrical power to the experimental site.

Side, end and internal pictures of the spectrometer are shown in Figures 3, 4 and 5 while Figure 6 shows one of the five source bag frames.

II. DATA COLLECTION SYSTEM

A block diagram of the electronic system is shown in Figure 7. The high voltage supplied to each bank was divided into two branches: one taking high voltage to the four photomultiplier tubes in the middle of the bank, while the other branch supplied voltage to the two end tubes. The two end tubes were most affected by changing the direction of the magnetic field and their output could then be adjusted into balance with the mid bank tubes after each field direction change. The photomultiplier tube dropping chain, is shown in Figure 8. The resistance R_1 is used to balance the output of the tubes to a common value for each bank. Output signals were available from the anode and the last dynode.

The outputs of the six tubes in each bank were ganged together, passed through a low noise preamplifier and an A-8 double delay line linear amplifier. The signal was then divided into two parts. The first part was fed to a zero crossover discriminator, and then to a coincidence circuit where coincidences were sought with similar pulses from the other bank of detectors. If two pulses were coincident within a resolving time, τ_R , of 50 nsec., a pulse was sent to a camera trigger circuit similar in design to the one used by F. Dix.¹⁷ The trigger circuit supplied signals to flash lights in the camera data box, to trigger the oscilloscope, to increment the coincidence scaler and to advance the camera to the next frame.

The second part of the amplified pulse was delayed (10 μ sec for the left bank, 16 μ sec for the right), passed through a linear gate, ganged with the pulses coming from the other bank and displayed on the oscilloscope screen. Left and right channel and coincidence counts were monitored on three scalars.

The oscilloscope horizontal output was used to generate an enable pulse for each of the linear gates in the display circuitry. Figure 9 shows a schematic diagram of this gate enable pulse generator. A triangular shaped pulse, varying from 0 to about 7.5 volts for the duration of the oscilloscope sweep is impressed on the base of Q_1 . Q_1 and Q_2 make up a Schmidt trigger circuit giving an output when the voltage at the base of Q_1 exceeds the values set by resistor, R. Q_3 and Q_4 make up an astable univibrator whose output is limited to a 4 volt high 2 μ second duration pulse. The pulse width is determined by the value of C and the resistance to ground at the base of Q_4 . The result is a pulse that can be adjusted to occur in time from ~ 1 μ second after the oscilloscope trace begins until the trace resets itself.

Whenever two pulses appear in the two channels within the resolving time and with energies greater than ~ 250 keV, the pulses were displayed on the oscilloscope screen and a picture was taken. The data collection system was then dead for ~ 0.3 seconds while the camera advanced the film one frame.

Figure 10 shows a photograph of the electronics room in the experimental house.

III. SYSTEM OPERATION

A data run consisted of several calibration frames followed by ~ 1800 frames of data recorded on Kodak linograph ortho film. Previous to and after the completion of each run the high voltage, amplifier gain, system pressure, spectrometer current magnitude and direction, left and right bank singles rates, and coincidence efficiency were checked and recorded. Although substantial changes in any of these readings occurred rarely, an occurrence was used as a good cause to delete that run from analysis. The chief offender was loss of coincidence efficiency due most probably to long stabilization times for the tube type amplifiers when the system was restarted after power shutdowns.

The calibration of the detection system was checked at least every month, at times allowed by system shutdowns. The Bi source was placed in front of each photomultiplier tube and the 0.973 MeV electron peak position checked with the magnetic field going in each direction and turned off. The high voltage of the end tubes relative to that of the central tubes in each bank was determined in that way. Finally the source was placed in the middle of each sheet of plastic and the response of each sheet was checked and balanced to the others. The results were the calibration constants for each bank for the next series of runs.

The runs were grouped, a series of normal data mode runs followed by a series of background mode runs, with non source associ-

ated background runs interspersed when system pressure was lost due to a power shutdown. For the non source background runs, the spectrometer was connected up to give no net field inside and the sources were removed.

During the course of the experimental runs the detection system was disassembled three times for major structural revisions and shut down several times for minor repairs to the high voltage system and for replacement of photomultiplier tubes. After each instance, the spectrometer-detector performed as well after the adjustments as before the problem appeared.

The vacuum pump brought the spectrometer to within a factor of 10 of its operating pressure in about an hour, and took about a day to stabilize at its ultimate pressure. The spectrometer required approximately one day to come to thermal equilibrium after the magnet current was turned on. Finally, the photomultiplier tubes were noisy for about one week after they had been exposed to light. These "time constants" demanded a minimum system down time period after every power shutdown or alteration that was made on the spectrometer.

IV. DATA ANALYSIS

The film was projected on a Recordak film scanner and measurements of the heights of the pulses from the left and right banks were made on an arbitrarily ruled projection screen. Figure 11 (a and b) show two typical data traces selected from run 02230. Figure 11a shows a low energy event ($\sim 1/4$ MeV in each channel), while 11b depicts the deposit of ~ 3 MeV in the left bank and ~ 1 MeV in the right.

A number of system triggers occurred because of electronic noise picked up by the detectors. Figure 12 (a and b) shows the two distinctly different types of noise that occurred.

12a shows a pulse train composed of several spiked pulses. These were observed to happen when the air conditioner compressors turned on and off and at other times that could be associated with the operation of heavy equipment by mine personnel. The "triangular" shaped pulses that appear in the both channels in Figure 12b are associated with the regulation of the magnet power supply and come from a connection between the end terminals of the solenoid that had momentarily worked loose. Both of these types of triggers were easily recognized by the people scanning the film and eliminated from the data record.

The pulse heights from the calibration frames and the data frames were then punched onto computer cards for analysis by an IBM 1800 computer. (Details of the analysis programs are in Appendix A.)

The calibration frames were used to generate a least squares linear fit to determine the energy calibration constants for that particular data run. This method had the advantage that it cancelled out any idiosyncrasies that might exist in any film reader-recordak combination. The raw pulse height data were stored on magnetic tape, as well as on the cards. The pulse heights were then converted to energies and this information was stored on another magnetic tape. In this final form, the data could be plotted as left and right bank and sum energy spectra for the three classes of data runs. The sum spectra are shown for the source run, source background and general background runs in Figures 15, 16 and 17.

V. PRESENTATION OF RESULTS

Since the half life for double beta decay is very long compared to the experimental observation time, the rate of occurrence of events is taken as constant and is given by:

$$\frac{\Delta N}{\Delta t} = \frac{N}{\tau}$$

where N is the number of Nd^{150} atoms present and τ is the mean life of the decay. The observed half life is computed from the formula:

$$\tau_{1/2} = \frac{0.69N\epsilon}{R}$$

where R is the experimentally determined counting rate and ϵ is the efficiency of the spectrometer-detector for observing double beta decay. Evaluating N for 24.1 grams of Nd_2O_3 and expressing R in hr^{-1} gives:

$$\tau_{1/2} = \frac{6.85 \times 10^{18} \epsilon}{R} \text{ years.}$$

Tables 2, 3, and 4 summarize respectively the runs observed in the source run, source background and general background operating modes of the spectrometer. Figure 18 shows the theoretically expected single electron spectra for the two neutrino and no neutrino decay

modes and Figure 19 shows the expected electron sum energy spectra for the two modes, calculated by Rosen and Primakoff.¹⁶

The experimentally determined differential count rate sum spectrum is shown in Figure 20. The solid curve is the theoretically predicted spectrum for a half life of the two neutrino mode of $\tau_{\frac{1}{2}, 2\nu} = 5 \times 10^{18}$ yrs. The net count rate corresponding to this graph for a deposit of more than 250 keV in either bank of detectors is:

$$R_{\text{obs}} = (0.2 \pm 0.6) \text{hr}^{-1},$$

where the error quoted is associated with statistical fluctuations only. An upper limit on the observed count rate is estimated by the integral of the likelihood function up to this rate being equal to 0.9 as:

$$R_{\text{obs}} = 0.24 \text{ hr}^{-1}.$$

Taking the efficiency for observing the two neutrino mode as 16% (See Appendix B, Details of Efficiency Calculation) the half life can then be estimated as:

$$\tau_{\frac{1}{2}, 2\nu} \gtrsim 5 \times 10^{18} \text{ yrs.}$$

The count rate observed between 3 and 4 MeV can be used to estimate a lower limit for the no neutrino decay mode. The

observed rate is

$$R_{\text{obs}} = (0.05 \pm 0.07) \text{ hr}^{-1}.$$

Using the same criterion as in the two neutrino case, an upper limit on this count rate can be set at the 90% confidence level to be:

$$R_{\text{obs}} = 0.074 \text{ hr}^{-1}.$$

A lower limit for the no neutrino decay mode can then be set, using the efficiency calculated for this mode in Appendix B of 7%, of:

$$\tau_{\frac{1}{2}, 0\nu} \gtrsim 7 \times 10^{18} \text{ years}.$$

Sample correlation coefficients were calculated for each run and for all the runs in each operating mode of the spectrometer-detector. For both decay modes these are expected to be slightly negative, as a high energy event in one detector would be associated with a low energy event in the other. This would also be true for multiple scatterings of γ -rays.

VI DISCUSSION OF BACKGROUND

The calculations described in Appendix C set an upper limit on the half life for the two neutrino decay mode observable by this experiment on this source of:

$$\tau_{\frac{1}{2}, 2\nu} = 6 \times 10^{18} \text{ yrs.}$$

A previous experiment on this source³ also yielded a positive result for the half life for the two neutrino mode of:

$$\tau_{\frac{1}{2}, 2\nu} \sim 3 \times 10^{17} \text{ yrs.}$$

The present experiment was designed with two points in mind:

- i) to cut down non source associated background due to multiple scattering of γ -rays and electrons detected in one detector making their way to the other, and
- ii) to make this detector much less sensitive to source associated background than the previous one.

If the major source of background is due to Bi^{214} contamination, and allowance is made for the same type of interactions in East's experiment as in Appendix C, the rate of detection of false events in his detector would be

$$R_E = 46.2 \times 10^{-2} (\lambda N),$$

where (λN) is the contaminant activity, measured in Appendix C compared to the present detection system rate of:

$$R_P = 2.1 \times 10^{-2} (\lambda N).$$

The difference is due to a larger double beta detection efficiency, in East's apparatus a significantly ($\sim$ a factor of 75) larger efficiency for seeing source associated γ -rays, and a larger amount of source. Thus, for the same contamination activity the present experiment is about a factor of 22 less sensitive to the effects of source contamination. This would imply that the half life measurable by the experiment should be limited by East's half life multiplied by this factor or about:

$$7 \times 10^{18} \text{ yrs},$$

which is consistent with the results of Appendix C.

The introduction of the source, source bags and source frames into the spectrometer-detector results in an increase in the coincidence rate of:

$$(15.8 \pm 0.6) \text{ hr}^{-1}.$$

Since this effect shows up symmetrically (i.e., in both the source

run and source background modes) it is most probably due to γ -rays coming again from deexcitations in member nuclei of the radium decay chain contaminating the aluminum used to construct the detector frames. The observed increase is consistent with an increase in the single channel count rates observed when the frames were inserted into the spectrometer-detector. Any electrons that might also be produced with these γ -rays would be absorbed in the frame holders themselves and not contribute to the two neutrino mode detection rate.

VII DISCUSSION OF RESULTS

Since the measured lower limit for the two neutrino mode half life closely approximates the upper limit set on the measurable half life by source contamination, this experiment does not provide conclusive evidence for this decay mode. The consistency of this experiment to that of East also substantiates this result. The problem of source contamination does not effect the no neutrino decay mode as there is not enough energy available ($Q = 3.2$ MeV) to a significant number of electrons. To get the total energy available, the beta decay electron must have an energy near the endpoint energy. As most of the electrons have considerably less energy, this occurrence is not too probable. In fact, the results of contamination contribute electrons with energies around or less than 1 MeV.

Nonetheless, a lower limit on the half lives of the two decay modes is set by this experiment, and these results can be used to gain some information on the weak interaction. Lee and Wu¹⁰ point out that a definite relationship exists between the concepts of a non zero neutrino mass, a departure from strict "two component" neutrino coupling and the possibility of lepton non conservation. If one is assumed to be true, then the other two automatically follow. The experimental results can be interpreted in the following ways:

1) Neutrino mass.

If we allow only that the neutrino mass be non zero and insist upon the artificial premises that the

neutrino still be 100% polarized and that lepton conservation not hold, then an upper limit for the neutrino mass can be calculated, using an expression derived by Grueling and Whitten:²⁰

$$M_\nu \lesssim [1.5 \times 10^{-5} \left(\frac{\tau_{\beta, 2\nu}}{\tau_{\beta, 0\nu}} \right)^{1/2}] M_e$$

$$= 3 \times 10^{-3} M_e.$$

This is about a factor of 15 larger than the most recent experimental result.²¹

ii) Lepton conservation and the two component neutrino.

Primakoff and Rosen¹² have put forth a Hamiltonian for a zero mass neutrino whose lepton weak current is given by:

$$L_\lambda = \psi_e^\dagger \gamma_4 \gamma_\lambda [(1 + \gamma_5) + \eta(1 - \gamma_5)] \psi_\nu,$$

where ψ_ν describes a Majorana neutrino and the coefficient η governs a small mixture of the opposite helicity projection operator. They then derived an expression relating the no neutrino half life to the real parameter η :

$$\tau_{\beta, 0\nu} \approx \frac{5 \times 10^{13.9}}{\eta^2}.$$

Solving this expression for η and inserting the no neutrino decay

mode half life determined by this experiment yields:

$$\eta \lesssim 9 \times 10^{-3},$$

which is about a factor of 9 larger than the result from the work of Kirsten.⁷ While this method for parameterization of lepton non conservation is not unique, all others lead to a similar result. Primakoff also calculated the expected half life on the assumption that an $N^*(1236)$ nucleon resonance, which can undergo double beta decay directly, was included in a nucleus with a probability of about 1%. While this leads to a more restrictive limit on η , it is based on another supposition whose validity is also open to question. By mixing a small amount of the opposite helicity state term

$$(1 - \gamma_5) \psi_\nu$$

into the lepton weak current, Primakoff's Hamiltonian also allows a deviation from two component neutrino coupling. The intermediate state neutrino is then not 100% longitudinally polarized and can be emitted by one hadron along with an electron and be reabsorbed by another hadron as another electron is emitted. The coefficient η then also characterizes the exactness of the two component neutrino coupling.

VIII POSSIBLE IMPROVEMENTS TO THIS EXPERIMENT

There are two areas where this experiment might be improved sufficiently to allow conclusive results regarding the matter of double beta decay. Clearly, the first lies in the matter of source contamination. The apparatus as it stands has determined the two neutrino half life to the limit set by this problem. To eliminate it would reduce bettering the half life limit to a matter of observation time. This then raises the next question, that of long term stability. The present experiment suffered grievously from including the photomultiplier tubes inside the vacuum chamber. Two disadvantages resulted from this. First, the most prevalent reason for system shutdown came from the development of electrical discharges inside the vacuum can. Each occurrence demanded that the system be disassembled to the point where the corona or arcing occurred and then repaired. If the tubes could be moved outside the spectrometer this problem would cease to exist. The second problem created by including the tubes inside the detector was one of temperature. The single channel discriminator levels were set so that they cut off just above the thermionic noise produced in the tubes while the field was on. With the tubes outside the chamber, this is no longer a problem and the energy discriminators could be run down and the detection efficiency of the apparatus be increased by as much as 50%. Furthermore, the spectrometer-detector could be run at a higher magnetic field value, also increasing the detection efficiency, by about 5%.

APPENDIX A. DETAILS OF THE DATA ANALYSIS PROGRAMS

The data for each run consisted of about 100 pairs of pulse heights used to make a relative calibration of each run and about 1500 pairs of pulse heights of the observed data. The actual analysis of each run had to be broken down into several steps as storage space in the 1800 was limited. The data, punched on computer cards, was read by the program DIRIT and written on the data tape in two blocks. The first contained the run number, time and total counts observed and the second the several pairs of pulse height information. The calibration frames were used by the program CALFC to generate a least squares linear fit to the energy calibration for each bank. The program TRANS took the raw data from the data tape and the calibration constants calculated by CALFC and generated a second magnetic tape, the reduced tape. TRANS wrote several blocks on the reduced tape. The first contained the run number, time, number of data frames and calibration constants for that run. The data were written as energy pulse height pairs in blocks of 250 pairs each, until all pairs were written on the reduced tape. The two tapes allowed quick access to the data and also eliminated considerable effort in the event a change in calibration constants was thought necessary. Each run was then analyzed by another program, COROL. This program set lower and upper level discriminators on the

heights from each bank and on the sum height, calculated a correlation coefficient and plotted histograms of the left bank, right bank, and sum spectra observed during each run. After all the runs were listed on the reduced tape a final analysis was made by the program SPANL. In addition to the features contained in COROL, SPANL grouped the runs into the three categories determined by the operational mode of the spectrometer-detector and calculated observed count rates for the nine different spectra between 0 and 5 MeV. The data were then treated by several less ambitious programs which produced the final analyzed results. NET determined the source run minus source background differential sum and bank spectra. WTSUM calculated the weighted averages and standard deviations of the individual runs for the spectrometer-detector's three modes. MAXL evaluated the integral of the likelihood function to determine the upper limits on the net count rates. SDEFF calculated the efficiency of the detector by a Monte Carlo method (see Appendix B). Finally, several minor programs were used to do basic "bookkeeping", that is keeping track of locations of the individual runs on the two tapes and providing access to the information at the beginning of each run.

APPENDIX B. DETAILS OF EFFICIENCY CALCULATION

The most important factor affecting the efficiency of the spectrometer-detector for seeing double beta decay is a geometrical one; the determination of the aperture of the detectors at a position of decay within the source. It is difficult to estimate this number analytically not only because of the energy and angular distributions of the electrons but also due to the fact that the electrons leave the decay point going in directions oriented randomly to the direction defined by the magnetic field. Clearly a decay by decay detailed calculation using a "Monte Carlo" method is best suited to determine the efficiency. The calculation was done on the Chi Corporation Univac 1108 computer using a table of random numbers supplied as part of the soft ware.

A decay point (x, y, z) was selected randomly within the source strip and a coordinate system erected there with its x-axis pointing parallel to the axis of the spectrometer. The kinetic energies E_1 and E_2 , in units of $m_e c^2$ of the two electrons are selected between 0 and the transition energy, E_0 , according to the energy distributions given by B1 for the two neutrino mode and B2 for the no neutrino mode subject to the constraint that their sum must be less than or equal, in the case of the two neutrino mode, or equal, for the no neutrino mode, to the transition energy.

$$f(E_1, E_2, E_0)_{2\nu} = [E_0 - (E_1 + E_2)]^5 (E_1 + 1)^2 (E_2 + 1)^2 \quad (B1)$$

$$f(E_1, E_2, E_0)_{0\nu} = (E_1 + 1)^2 (E_2 + 1)^2 (E_1^2 + 2E_1 + E_2^2 + 2E_2 + \frac{2(E_1^2 + 2E_1)(E_2^2 + 2E_2)}{(E_1 + 1)(E_2 + 1)}) \quad (B2)$$

The directions, specified by the polar and azimuthal angles (θ_1, ϕ_1) and (θ_2, ϕ_2) , of the two electrons were selected at random subject to the constraint that the angle, α , between them given by:

$$\cos \alpha = \sin \theta_1 \sin \theta_2 (\cos \phi_1 \cos \phi_2 + \sin \phi_1 \sin \phi_2) + \cos \theta_1 \cos \theta_2 \quad (B3)$$

be distributed according to the angular distributions given by B4 for the two neutrino case and B5 for the no neutrino case.

$$g(E_1, E_2, \cos \alpha)_{2\nu} = 1 - \frac{(E_1^2 + 2E_1)^{1/2} (E_2^2 + 2E_2)^{1/2}}{(E_1 + 1)(E_2 + 1)} \cos \alpha \quad (B4)$$

$$g(E_1, E_2, \cos \alpha)_{0\nu} = 1 - (E_1^2 + 2E_1 + E_2^2 + 2E_2 + 2(E_1 + 1)(E_2 + 1)) \times$$

$$\frac{(E_1^2 + 2E_1)^{1/2} (E_2^2 + 2E_2)^{1/2}}{(E_1^2 + 2E_1 + E_2^2 + 2E_2)(E_1 + 1)(E_2 + 1) + 2(E_1^2 + 2E_1)(E_2^2 + 2E_2)} \cos \alpha. \quad (B5)$$

The energy and angular distributions used are those of Rosen and

Primakoff.^{15,16} If the electrons emerged from the same side of the source, which was indicated by $\cos\theta_1$ and $\cos\theta_2$ having the same sign, the fail register was incremented by one and the process started over.

The next step was to determine if electron 1 would reach one of the detector banks. The energy lost by the electron traversing the source was determined by taking the range-energy relationship of Katz and Penfold¹⁹ given by:

$$R_0 = 412 E^{(1.27-0.095\ln E)} \quad (B6)$$

and differentiating it to determine the energy loss per unit absorber thickness:

$$\frac{\Delta E}{\Delta R} = \frac{E^{-(0.27-0.095\ln E)}}{412(1.27-0.19\ln E)} \quad (B7)$$

The energy of the particle was degraded by this multiplied by the path length of travel through the source. If the resultant energy was less than zero, the fail register was again incremented by one and the process restarted. If the event survived this test, the angle, γ_1 , of the particles direction to the x-axis was determined from:

$$\cos\gamma_1 = \sin\theta_1 \cos\phi_1, \quad (B8)$$

and the component of the particle's momentum perpendicular to the field direction was determined. That fixed the radius of the particles trajectory and the angular frequency of its motion in the magnetic field. For each set of these values there are two possible tracks the electron might follow, depending upon the values of the angles, (θ_1, ϕ_1) . This is true since the surface of the detector will lie on a chord of the circle, described in end view by the electron, and either the larger or smaller path along the circumference may be traversed depending on the angles ϕ_1 and θ_1 . If the larger path is traversed the diameter of the circle is checked against the radius of the spectrometer. If the diameter is larger the fail register is incremented and the process restarted. If the smaller path is followed, the length of the chord is checked against the radius of the spectrometer and if the chord is larger the fail register is incremented. In either case, if the event passes the test, the time to go from the source to the detector can be determined, and from this, the distance traveled along the axis of the spectrometer can also be calculated. This is then checked to see if the particle will go out the ends of the spectrometer before it hits a detector. If it does, the fail register is incremented and the process restarted. If the event remains, the chord of the circle is checked against the distance from the decay point to the detector. If it is smaller, the fail register is incremented by one and the process restarted. Passing this test means that electron one has arrived at a detector. At this point the energy resolution

of the plastic scintillator is introduced by distributing the energy randomly about its original energy weighted by a normal distribution function centered at the original energy with a standard deviation determined by the average half width at half maximum of the 0.973 MeV monoenergetic electron from Bi^{207} used to calibrate the detectors. Electron 2 was then subjected to a series of tests similar to those for electron 1.

Electrons one and two passing all the tests meant that the decay was accepted and the succeed register was incremented by one. This process was repeated until the required number of events were generated. These events were then subjected to discriminators to reproduce the actual experimental conditions. A summary of the results is shown in Table 5 for three magnetic field values 100, 150 and 200 gauss, and for the two neutrino and no neutrino modes of decay. This allows a comparison to see the effect a non uniform magnetic field would have on the results. The effect of including or not including the angular distribution and the energy lost in the source are also tabulated. The efficiencies for a magnetic field of 150 gauss were used for the calculations. The values determined should be thought of as an approximation to the actual efficiency of the spectrometer-detector.

APPENDIX C. MEASUREMENT OF SOURCE CONTAMINATION

Since the possibility of contamination in the Nd_2O_3 source existed, an experiment was designed to look for the presence of Bi^{214} by detecting electrons and gamma rays in coincidence coming from a thin slab of the source. The contamination simulates double beta decay by the ordinary beta decay of Bi^{214} to an excited state of Po^{214} followed immediately by an internal conversion de-excitation in Po^{214} or by two cascade γ -rays producing internal conversion electrons. Clearly, if the slab of source is sandwiched between an electron detector (a piece of Pilot "B" scintillator (16" x 16" x 1/8")) and a gamma ray detector (a 4" high x 5" diameter NaI(Tl) crystal) and coincidences sought between them, a reasonably sensitive determination of the contaminant activity can be made. The experiment was also run at the Morton Salt Mine facility with an added shielding factor supplied by an iron house with walls 6 inches thick surrounding both detectors. Consideration of the Po^{214} energy level diagram¹⁸ shows that the 0.6 MeV γ -ray accompanies most of the decay electrons and thus gives a specific signature that can be used to identify the existence of Bi^{214} .

Three types of runs were made:

- i) a run lasting 41.4 hours with the source in a bag held between the detectors,
- ii) a run lasting 18.5 hours with only the bag between the detectors, and

iii) a run lasting 41.6 hours with nothing between the detectors.

Discriminators were set to accept electrons with energies greater than 100 keV and gamma rays with energies greater than 500 keV. The latter value was selected so that gamma ray counting was done in the photopeak of the 0.609 MeV gamma and for all the higher energy gammas also. Table 6 summarizes the results of the three runs

The count rate expected can be expressed as

$$R_{\beta\gamma} = (\lambda N) \cdot p_2 \cdot e_{\text{geom}}^{\gamma} \cdot e_{\text{det}}^{\gamma} \cdot e_{\text{geom}}^{\beta} \cdot e_{\text{det}}^{\beta} \quad (C1)$$

where (λN) is the activity of the contaminant, p_2 is the percentage of Bi^{214} decays leading to two or more outgoing particles. (70%) , e_{det}^{γ} is the detection efficiency of the crystal for seeing a point source placed at the center of its face, e_{geom}^{γ} is an area weighted average measured over the entire face of the crystal. e_{geom}^{β} is the chance that an electron will leave the source heading towards the plastic ($= \frac{1}{2}$) and e_{det}^{β} is the probability that the electron will be detected by the plastic (taken as 1). The product $e_{\text{det}}^{\gamma} \cdot e_{\text{geom}}^{\gamma}$ is tabulated in Table 7 for several gamma ray energies. The detection system was calibrated, the gamma detection efficiencies determined, and the system timing aligned using a Bi^{207} source that gave a .973 MeV internal conversion electron in coincidence with other gamma rays. When the above expression is evaluated, the relationship between observed count rate and contaminant activity is

$$R = 0.023 (\lambda N) \quad (C2)$$

An estimate that about 1/2 the beta decay electrons do not make it out of the source with an energy above the discriminator value is included in the above calculation. The observed count rate, from Table 6, is:

$$R = (0.0 \pm 0.3) \text{hr}^{-1}.$$

If the same criterion is applied to this rate as used before, that the upper limit be given by the value up to which the integral of the likelihood function is equal to 0.9, the limit becomes:

$$R = 0.22 \text{ hr}^{-1}.$$

The source activity corresponding to this is:

$$(\lambda N) \simeq 10 \text{ hr}^{-1}.$$

To convert this activity to a rate in the spectrometer-detector, allowance is made for three types of events:

- i) That internal conversion indeed take place and two electrons come off from the source.
- ii) A single electron comes off from the source coincident with a gamma that converts in the scintil-

lator in the other bank.

- iii) An electron comes off from the source coincident with a gamma which converts in the source to produce another electron.

Other schemes to produce a count in each bank like two cascade gammas or multiple scattering of a single γ are at least an order of magnitude smaller than the ones listed, and also symmetric in that they contribute in the source run and source background operational modes of the spectrometer-detector.

An estimate of the contribution of effect (i) is quite easy and can be made by consulting tables of intensities of internal conversion electrons. This multiplied by the efficiency for seeing double beta decay yields:

$$R_1 = 5.6 \times 10^{-2} \epsilon(\lambda N). \quad (C3)$$

Effect (iii) is estimated by looking at the attenuation coefficients for a gamma to pass through 1/2 the source thickness and multiplying that by the efficiency for detecting double beta decay to get:

$$R_3 = 3.4 \times 10^{-2} \epsilon(\lambda N). \quad (C4)$$

Effect (ii) is not as easy. This is found as the chance the gamma will enter the solid angle of the detector, traverse 1/2 inch of aluminum, 1/4 inch of lead and be detected in about 16 inches of

plastic scintillator multiplied by the efficiency of detecting the electron in the other detector (=55%)

$$R_2 = 0.16 \times 10^{-2} \text{ (AN)} \quad (C5)$$

This corresponds to a nonsymmetric background rate of:

$$R = 2.1 \times 10^{-2} \text{ (AN)}, \quad (C6)$$

in the spectrometer-detector and an upper limit on the half life that can be observed for this source by this experiment of:

$$\tau_{1/2v} = 6 \times 10^{18} \text{ years,}$$

where the fact that this experiment uses 18 grams of Nd_2O_3 and the main experiment uses 24 grams has been accounted for.

FOOTNOTES

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Decay	Observational Method	HALF LIFE				Reference
		Theoretical [*] 2v (yrs)	0v (yrs)	Experimental 2v (yrs)	0v (yrs)	
$\text{Nd}^{150} \rightarrow \text{Sm}^{150}$	Scintillator - source Sandwich	$8 \times 10^{20 \pm 2}$	$2 \times 10^{15 \pm 2}$	$> 3 \times 10^{17}$	$> 5 \times 10^{18}$	L. V. East ³
	Large aperture - low resolution spectrometer-detector			$> 5 \times 10^{18}$	$> 7 \times 10^{18}$	Present work
$\text{Ca}^{48} \rightarrow \text{Sc}^{48}$	Streamer chamber	$1 \times 10^{21 \pm 2}$	$3 \times 10^{15 \pm 2}$	$> 4 \times 10^{19}$	$> 2 \times 10^{21}$	Barden et al. ⁴
$\text{Te}^{130} \rightarrow \text{Xe}^{130}$	Mass spectrograph	$8 \times 10^{21 \pm 2}$	$8 \times 10^{15 \pm 2}$	$(2 \pm 1) \times 10^{21}$		Kirsten et al. ⁶
	"			$(3.0 \pm 0.4) \times 10^{20}$		Gerling et al. ⁸
	"			$(8.2 \pm 0.6) \times 10^{20}$		Takaoka and Ogata ⁵
$\text{Se}^{82} \rightarrow \text{Kr}^{82}$	"	$2 \times 10^{21 \pm 2}$	$1 \times 10^{16 \pm 2}$	$(6 \pm 2) \times 10^{19}$		Kirsten et al. ⁷
$\text{Te}^{128} \rightarrow \text{Xe}^{128}$	"	$8 \times 10^{25 \pm 2}$	$2 \times 10^{18 \pm 2}$	$(3 \pm 3) \times 10^{22}$		Kirsten et al. ⁶
	"			$> 2 \times 10^{23}$		Kirsten et al. ⁷
	"			$> 8 \times 10^{20}$		Gerling et al. ⁸
	"			$\sim 3 \times 10^{22}$		Takaoka and Ogata ⁵

^{*}After Rosen and Primakoff¹⁶

TABLE 1 SUMMARY OF SOME RECENT DOUBLE BETA DECAY EXPERIMENTS

RUN NUMBER	FRAMES RECORDED	FRAMES ACCEPTED	RUN* TIME	RATE $E_s > 0.5 \text{ MeV}$	CORRELATION COEFFICIENT	RATE $3.0 \text{ MeV} < E_s < 4.0 \text{ MeV}$
3079	1655	1028	1381.9 min	$(0.74 \pm 0.02) \text{ min}^{-1}$	-0.05	$(0.027 \pm 0.004) \text{ min}^{-1}$
3129	1667	1345	1451.7	(0.92 ± 0.03)	-0.11	(0.042 ± 0.005)
8189	1156	712	955.6	(0.74 ± 0.03)	-0.17	(0.017 ± 0.004)
8199	935	926	1175.8	(0.78 ± 0.03)	-0.17	(0.008 ± 0.003)
10019	1223	1193	1193.2	(0.99 ± 0.03)	-0.08	(0.018 ± 0.004)
10159	200	190	199.0	(0.95 ± 0.07)	-0.20	(0.015 ± 0.009)
10169	1097	1065	1143.6	(0.93 ± 0.03)	-0.24	(0.010 ± 0.003)
11039	1891	1253	1572.2	(0.98 ± 0.03)	-0.39	(0.025 ± 0.004)
01120	1367	969	1048.2	(0.93 ± 0.03)	-0.26	(0.016 ± 0.004)
01130	1501	911	1129.7	(0.80 ± 0.03)	-0.65	(0.034 ± 0.005)
01150	1501	1220	1191.7	(1.02 ± 0.03)	-0.45	(0.016 ± 0.004)
02120	1784	1253	1340.1	(0.93 ± 0.03)	-0.15	(0.004 ± 0.002)
02130	1757	1331	1479.2	(0.89 ± 0.02)	-0.20	(0.005 ± 0.002)
03090	1490	1089	1117.7	(0.97 ± 0.03)	-0.60	(0.009 ± 0.003)
03180	1559	1393	1485.4	(0.93 ± 0.02)	-0.32	(0.007 ± 0.002)
	20783	15878	17855.0 min	$(0.891 \pm 0.007) \text{ min}^{-1}$	-0.30	$(0.0109 \pm 0.0008) \text{ min}^{-1}$
			297.58 hrs	$(53.4 \pm 0.4) \text{ hr}^{-1}$		$(0.66 \pm 0.05) \text{ hr}^{-1}$

*Adjusted for system dead time

TABLE 2 SUMMARY OF DATA FROM SOURCE RUN CONFIGURATION RUNS

RUN NUMBER	FRAMES RECORDED	FRAMES ACCEPTED	RUN* TIME	RATE $E_g > 0.5 \text{ MeV}$	CORRELATION COEFFICIENT	RATE $3.0 \text{ MeV} < E_g < 4.0 \text{ MeV}$
03059	1334	853	1066.6min	$(0.80 \pm 0.03) \text{ min}^{-1}$	-0.06	$(0.025 \pm 0.005) \text{ min}^{-1}$
03109	1687	1175	1277.6	(0.91 ± 0.03)	-0.10	(0.037 ± 0.005)
10269	1397	909	1072.2	(0.84 ± 0.03)	-0.28	(0.013 ± 0.003)
11059	1336	805	878.6	(0.91 ± 0.03)	-0.28	(0.010 ± 0.002)
01110	1636	1224	1363.9	(0.89 ± 0.03)	-0.21	(0.010 ± 0.003)
02100	1826	828	1020.9	(0.80 ± 0.03)	-0.18	(0.014 ± 0.004)
02170	1877	1380	1393.6	(0.98 ± 0.03)	-0.11	(0.008 ± 0.002)
02180	1980	1614	1669.0	(0.96 ± 0.02)	-0.21	(0.010 ± 0.002)
02190	1995	1554	1548.9	(1.00 ± 0.03)	-0.25	(0.008 ± 0.002)
03120	543	437	444.0	(0.98 ± 0.05)	-0.17	(0.002 ± 0.002)
03140	1632	1089	1275.9	(0.85 ± 0.03)	-0.05	(0.013 ± 0.003)
02090	1440	767	1015.0	(0.75 ± 0.03)	-0.06	(0.008 ± 0.003)
<hr/>						
	18683	12635	14026.2min	$(0.887 \pm 0.008) \text{ min}^{-1}$	-0.19	$(0.0100 \pm 0.0008) \text{ min}^{-1}$
			233.8hrs	$(53.2 \pm 0.5) \text{ hr}^{-1}$		$(0.60 \pm 0.05) \text{ hr}^{-1}$

*Adjusted for System Dead Time

TABLE 3 SUMMARY OF DATA FROM SOURCE BACKGROUND CONFIGURATION RUNS

RUN NUMBER	FRAMES RECORDED	FRAMES ACCEPTED	RUN [*] TIME	RATE $E_s > 0.5 \text{ MeV}$	CORRELATION COEFFICIENT	RATE $3.0 \leq E_s \leq 4.0$
10139	1779	1130	1539.1min	$(0.73 \pm 0.02)\text{min}^{-1}$	-0.19	$(0.007 \pm 0.002)\text{min}^{-1}$
11159	1183	755	1689.4	(0.45 ± 0.02)	-0.10	(0.008 ± 0.002)
12039	830	530	749.4	(0.70 ± 0.03)	-0.15	(0.011 ± 0.004)
01200	1471	808	1121.8	(0.72 ± 0.03)	-0.21	(0.017 ± 0.003)
02060	1833	785	1401.8	(0.56 ± 0.02)	-0.18	(0.008 ± 0.002)
02110	1760	967	1317.2	(0.73 ± 0.02)	-0.25	(0.005 ± 0.002)
03130	1496	1132	1591.7	(0.71 ± 0.02)	-0.24	(0.004 ± 0.002)
03200	1362	934	1528.4	(0.61 ± 0.02)	-0.25	(0.003 ± 0.001)
03230	1440	869	1092.0	(0.79 ± 0.03)	-0.16	(0.005 ± 0.002)
03310	938	792	1372.8	(0.58 ± 0.02)	-0.38	(0.007 ± 0.002)
<hr/>						
	14092	8702	13403.6min	$(0.626 \pm 0.007)\text{min}^{-1}$	-0.19	$(0.0060 \pm 0.0007)\text{min}^{-1}$
			223.4hrs.	$(37.6 \pm 0.4)\text{hr}^{-1}$		$(0.36 \pm 0.04)\text{hr}^{-1}$

*Adjusted for System Dead Time.

TABLE 4 SUMMARY OF DATA FROM GENERAL BACKGROUND CONFIGURATION RUNS

Magnetic Field	100 gauss		150 gauss		200 gauss	
	2v	0v	2v	0v	2v	0v
Conditions						
No angular distribution No energy loss in source No energy discrimination	0.14	0.014	0.18	0.05	0.21	0.07
Angular distribution No energy loss in source No energy discrimination	0.20	0.017	0.29	0.07	0.33	0.10
Angular distribution Energy loss in source No energy discrimination	0.17	0.017	0.24	0.07	0.28	0.11
Angular distribution, Energy loss in source, and $E_d > \frac{1}{2} \text{ MeV}$ $E_s > \frac{1}{2} \text{ MeV}$	0.10	0.016	0.16	0.07	0.18	0.11
$E_d > \frac{1}{2} \text{ MeV}$ $E_s > 1 \text{ MeV}$	0.06	0.016	0.12	0.07	0.14	0.11
$E_d > \frac{1}{2} \text{ MeV}$ $E_s > 2 \text{ MeV}$	0.01	0.016	0.01	0.07	0.02	0.11
$E_d > \frac{1}{2} \text{ MeV}$ $E_s > 3 \text{ MeV}$		0.014		0.06		0.10
$E_d > \frac{1}{2} \text{ MeV}$ $E_s > 1 \text{ MeV}$	0.03	0.014	0.06	0.06	0.07	0.10

TABLE 5 SPECTROMETER DETECTOR EFFICIENCIES FOR SEVERAL MAGNETIC FIELD VALUES

Table 6 Observed Count Rates for β - γ Coincidence Experiment

Run Configuration	Run Duration	Coincidence Counts	Coincidence Rate
Source + bag	41.43 hrs.	45	$(1.08 \pm 0.18) \text{ hr}^{-1}$
Bag	18.50 hrs.	20	$(1.08 \pm 0.21) \text{ hr}^{-1}$
Nothing	41.60 hrs.	22	$(0.53 \pm 0.11) \text{ hr}^{-1}$

Table 7 $e_{\text{det}}^{\gamma} e_{\text{geom}}^{\gamma}$ For Several γ Ray Energies

γ - ray Energy	$e_{\text{det}}^{\gamma} e_{\text{geom}}^{\gamma}$
0.5	0.131
1.0	0.036
2.0	0.035

END VIEW OF SPECTROMETER

Figure 1 Gary R. Smith

Figure 2. Rough Field Map of Spectrometer Interior, Values in gauss

Figure 3. Picture of Spectrometer Side View

Figure 4. Picture of Spectrometer End View

Figure 5
Picture of Spectrometer Interior View

Figure 6
Picture of Source Bag Frame

Figure 8. Photomultiplier Dropping Chain

-53-

GATE ENABLE GENERATOR.

Figure 9

Figure 10.

View of Electronics Room in Experimental
House Located in Morton Salt Mine

Figure 11a

Figure 11b

Typical Data Traces

Figure 12a

Figure 12b

Typical Noise Traces

Figure 13

Figure 14

Figure 15

Figure 16

Figure 17

Figure 18 Single Electron Spectra for Decay $\text{Nd}^{150} \rightarrow \text{Sm}^{150} + 2e^-$

Figure 19 Electron Energy Sum Spectra for
the Decay $\text{Nd}^{150} \rightarrow \text{Sm}^{150} + 2e^-$

Figure 20