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THE LBL/UCSB 76Ge DOUBLE BETA DECAY EXPERIMENT: FIRST RESULTS

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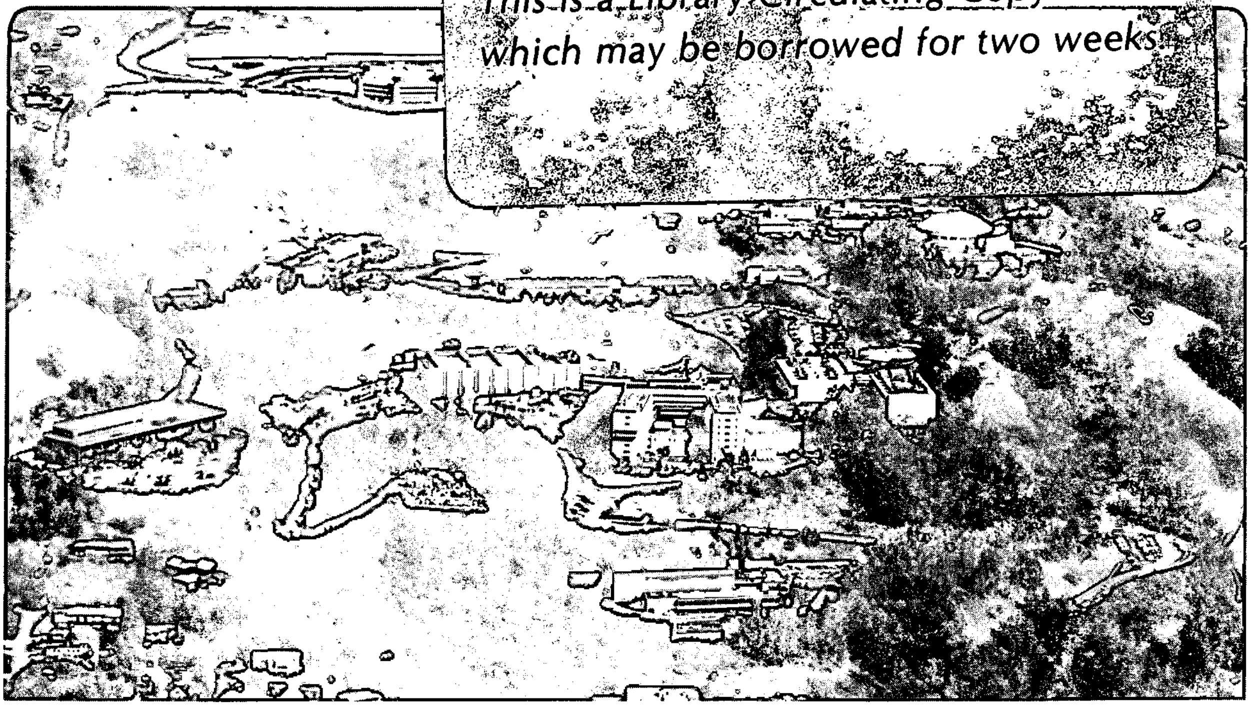

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THE LBL/UCSB ^{76}GE DOUBLE BETA DECAY EXPERIMENT: FIRST RESULTS

LBL-18043

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Abstract

A paper given at the IEEE Nuclear Science Symposium last year presented the scientific justification for this experiment and discussed the design of the detector system. At the present time two of the dual detector systems (i.e., four out of a final total of eight detectors) are operating in the complete active/passive shield in the low background laboratory at LBL. Early results (1620 hrs) of an experiment using two detectors yield a limit of 4 x 10^{22} years (68% confidence) for the half life of the neutrinoless double beta decay ($\beta\beta_{0\nu}$) of ^{76}Ge. Although this experiment was carried out above ground, the result approaches those achieved by other groups in deep underground laboratories. Based on studies of the origins of background in our system, we hope to reach a limit of 3 x 10^{23} years (or more) in a two month/four detector experiment to be carried out soon in an underground facility.

Introduction

An abbreviated list of energetically possible nuclear transitions involving simultaneous emission of two electrons is given in Table 1. This list (from 24 candidates) contains nuclei of particular interest because of their convenience for investigation by experimental methods. For example, geochemical measurements are applicable to the ^{82}Se ⟶ ^{82}Kr, ^{128}Te ⟶ ^{128}Xe and ^{130}Te ⟶ ^{130}Xe transitions while most of the other listed cases are candidates or investigation by direct counting techniques. We focus on the ^{76}Ge ⟶ ^{76}Se transition because ^{76}Ge constitutes almost 8% of the natural germanium used to fabricate germanium detectors that can be employed as excellent electron spectrometers.

TABLE 1

Potential Double Beta Decay Nuclei

		A	Z	Abundance Percent	E(MeV)
Ca	Ti	48	20	.185	4.267
Ge	Se	76	32	7.67	2.041
Se	Kr	82	34	9.19	3.003
Mo	Ru	100	42	9.62	3.034
Te	Xe	128	52	31.79	0.872
Te	Xe	130	52	34.49	2.543
Xe	Ba	136	54	8.87	2.718

Total 24 Cases

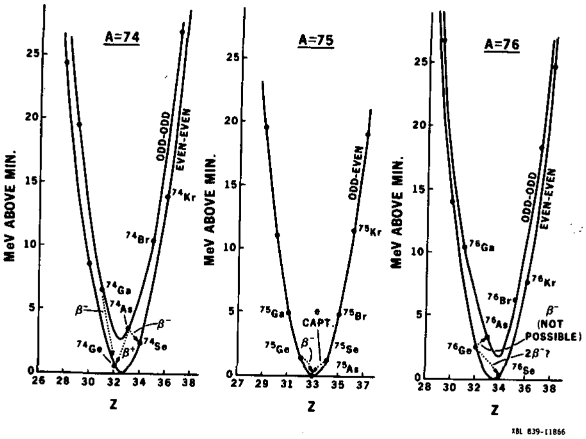

Fig 1: Binding energy plots for nuclides near ^{76}Ge.

Figure 1 shows the binding energy curves for the atomic mass range 74 to 76. We observe that even/even to even/even transitions such as ^{76}Ge ⟶ ^{76}Se involving the emission of two electrons can be energetically possible while single beta decay (^{76}Ge ⟶ ^{76}As) cannot occur. Table 1 shows the energy available for the $\beta\beta$ decay process as well as the natural abundances of the parent isotopes. ^{76}Ge is a favorable candidate because in addition to its reasonably high abundance, the relatively high-energy release (2.041 MeV) enhances the chance of observing it in the presence of background which is dominately in the low energy region. Nevertheless, other constraints on $\beta\beta$ decay make it very rare. In fact, although there is strong geochemical evidence for its existence, no direct observation of $\beta\beta$ decay has yet been made. Furthermore, the process may occur in two distinct ways:

i) $^{76}\text{Ge} \longrightarrow {}^{76}\text{Se} + 2e^- + 2\bar{\nu}_e$ (+2.041 MeV). Here two neutrinos are emitted together with the two electrons and the process is equivalent to two simultaneous normal beta decays.

ii) $^{76}\text{Ge} \longrightarrow {}^{76}\text{Se} + 2e^-$ (+2.041 MeV). Here no neutrinos are emitted and consequently no energy is lost to neutrinos.

In principle the transitions may be from the 0+ ground state of ^{76}Ge to excited levels of ^{76}Se. For the transition to the ground state (0+ to 0+) the full 2.041 MeV will be shared by the two electrons and possibly the two neutrinos; for the transition to the first excited state of ^{76}Se (0+ to 2+) the excitation energy (559 keV) in ^{76}Se will be lost to the electrons and possibly the two neutrinos, and emitted as a 559 keV γ ray when deexcitation occurs. (Half life = 12.3 ps.)

Experimentally the spectrum resulting from these alternative paths should have the Form I (decay with two neutrinos) or II (decay with no neutrinos) shown schematically in Fig. 2. The main theoretical interest is in the neutrinoless decay both because observation of this process would represent the first observation of lepton non-conservation in nuclear processes and because theory can relate the rate of decay to the mass of the neutrino--a subject of intense interest in particle physics and astronomy.

The basic physical process involved in neutrinoless $\beta\beta$ decay is illustrated by Fig. 3. Here, (upper line) a neutron is shown decaying into a proton emitting an electron and a (virtual) neutrino while a similar process occurs (lower line) with another neutron. If the (virtual) neutrino from the upper process can be absorbed by the neutron in the lower process and simulate the emission of a neutrino, then no neutrinos are emitted externally. According to theory, this can only happen if the neutrino is a Majorana particle (i.e., the particle and its anti-particle are identical) and either the neutrino has some mass (m_ν) and/or a small admixture of right-handed current exists in the process.) If, for the moment, we neglect the possibility of a right-handed admixture, the measured decay rate of ^{76}Ge can be theoretically interpreted in terms of a value for m_ν. Recent theoretical studies suggest that a ^{76}Ge half life of 10^{23} years corresponds to m_ν = 10eV and it varies as m_ν^{-2} (i.e., 10^{25} years ≅ 1eV). Today's theories predict a half life ten times larger for a given m_ν than was anticipated only a year ago--an indication of the theoretical uncertainties.

The possible presence of a right-handed current complicates the interpretation of any observed "$\beta\beta$ decay" peak in a spectrum, but an important consideration in our experiment is that the 0+ to 2+ transition (i.e., 1.482 MeV) can only result from a right-handed current whereas the 0+ to 0+ transition (2.041 MeV) can result from this mechanism or from a finite neutrino mass. Therefore, measuring the relative intensities of these two lines is important.

A critical value for the neutrino mass appears to be about 10 eV, because a Russian group[2] measuring the effect of neutrino mass on the shape of the end point region of the tritium beta spectrum reports a neutrino mass in the 10 eV range. Also, neutrino mass values in this range would be particularly interesting to astrophysicists concerned with the "missing mass" problem. Therefore, present interest focuses on the ^{76}Ge half life range of 10^{23} years. For 1 kg of natural germanium this corresponds to about 5 disintegrations/year. Obviously this very low rate represents a major challenge in the design of a low background counting system and the design we discuss here is an attempt to meet this target.

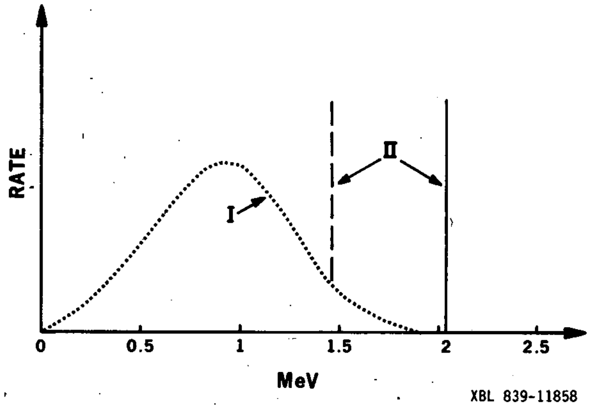

Fig 2: Spectral features expected for neutrinoless decay (II) and decay with emission of neutrinos (I).

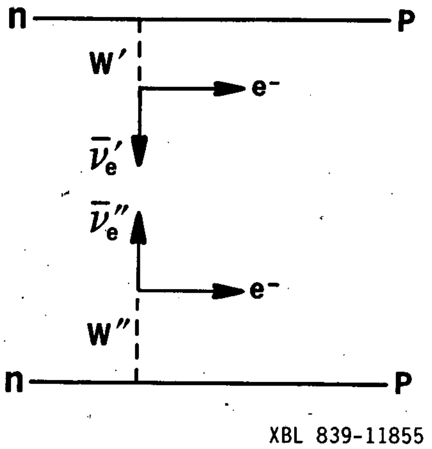

Fig 3: Model for the $\beta\beta$ decay process.

An illustration of the background problem is given in Fig. 4 taken from the pioneering work of the Fiorini group[3]. This shows the Ge detector background spectrum published in 1983 both above ground and under Mont Blanc. This example illustrates the effect of the two major background contributions--cosmic rays that are largely not present in the underground laboratory and natural radioactivity present in the detector system and its surroundings.

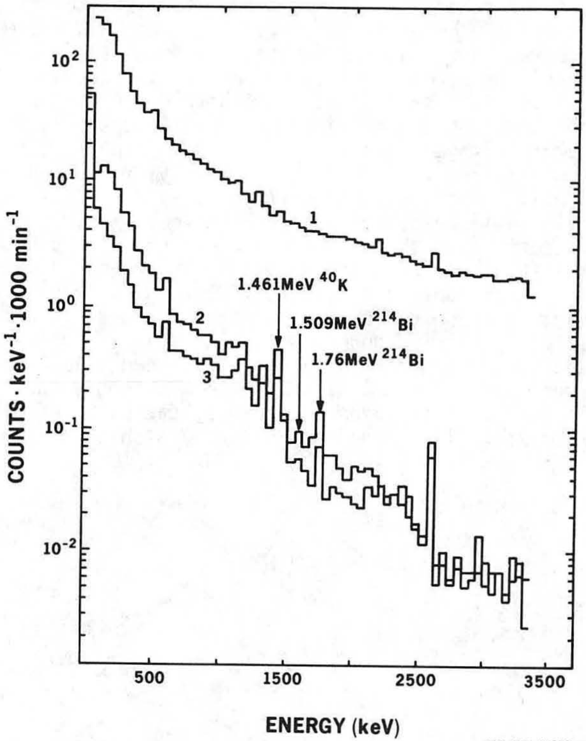

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Fig 4: Typical background spectra in a Ge detector system (Fiorini). Spectrum (1) is taken in an above gound laboratory while (2) and (3) are underground with slight differences in shielding.

System Design and Construction

A number of basic concepts have been applied in our design and fabrication of the detector system. These include:

a) Extremely careful testing was performed on every component in the system to detect the presence of natural radioactivities. This testing used the LBL low-background counting facility for almost two years as quantities of each material and components were counted for several days. Many common fabrication materials used in detector systems such as aluminum and magnesium were found to be unacceptable for this application and virtually all steel contained substantial ^{60}Co. Oxygen-free high conductivity (OFHC) copper was the only metal found that was almost always free of activity to our limits of measurements. Materials such as foam rubber, glass windows, etc., commonly used in mounting the NaI crystals to be used as a Compton shield were found to contain substantial levels of activity and these were replaced by substitutes or by selected materials (e.g., quartz windows). The crystals were canned in pretested OFHC copper.

b) Since the greater part of the background at 2 MeV in germanium detectors is due to partial absorption of higher energy γ rays, it was decided at the outset to surround the germanium detectors with as close to a 4π Compton shield as we could achieve. A 6-inch thickness of NaI was chosen as being adequate to absorb nearly all γ rays escaping from the germanium detectors. In order to ensure that Compton-scattered γ rays leaving the germanium can be detected by signals in the NaI detectors, it is essential to minimize all γ-ray absorbing material between the germanium and NaI. Consequently, very thin copper enclosures are used for the Ge and NaI detectors and we chose to use single crystal silicon cold fingers in the Ge detector cryostats.

The NaI scintillation shield is also used as a coincidence detector for the 559 keV γ ray that escapes when the first excited state of ^{76}Se deexcites leaving two electrons having a total energy of 1.482 MeV in the germanium detector.

c) The extremely low anticipated counting rate of neutrinoless ^{76}Ge $\beta\beta$ decays suggests immediately that a very large volume of germanium should be employed. We chose to design a system containing eight 150 cm^3 germanium detectors. This means that the whole system will contain 6.4 kg of germanium so the counting rate of the desired decays will be about 32 counts/year if the ^{76}Ge half life is 10^{23} years. Consideration of mounting difficulties and general system convenience led to the use of four cryostats each containing two detectors.

d) The design of the associated electronics is predicated on eventual automatic unattended operation in an underground facility chosen to reduce cosmic-ray background.

Figures 5 and 6 show the whole detector assembly. The assembly consists basically of a central volume six inches deep, six inches wide and 10 inches long containing the eight germanium detectors. This is surrounded by 10 large NaI(Tl) detectors with the only spaces through the shield being those for the flat vacuum boxes of the germanium cryostats. A 4-inch space surrounding the NaI has been filled with a boron-loaded plastic neutron absorber for our above ground tests: this will be partly filled with clean lead in underground work. Finally, a 6 inch thick clean lead shield surrounds the whole assembly. The total weight of the system is about eight tons. The liquid nitrogen dewars associated with the germanium detectors sit outside the lead shield.

A photograph of a dual germanium detector system is presented in Fig. 7. The stainless steel dewar is connected to a flat stainless steel vacuum chamber that penetrates the outer lead shield of the system. Within this portion of the vacuum chamber a OFHC copper cold finger is used. A transition box then converts to a thin-walled copper vacuum box and a single crystal flat silicon cold finger. Each detector is enclosed in a thin walled cylindrical copper can. The flat copper vacuum box and the cylindrical detector cans are fabricated by copper plating on an aluminum mandril, then etching away the aluminum. Finally, a thin nickel plating is applied to prevent corrosion.

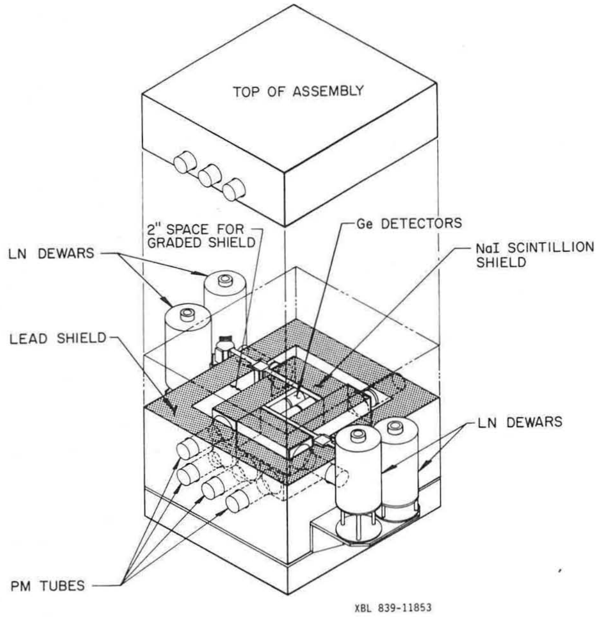

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Fig 5: Cut away view of the complete LBL/UCSB detector system.

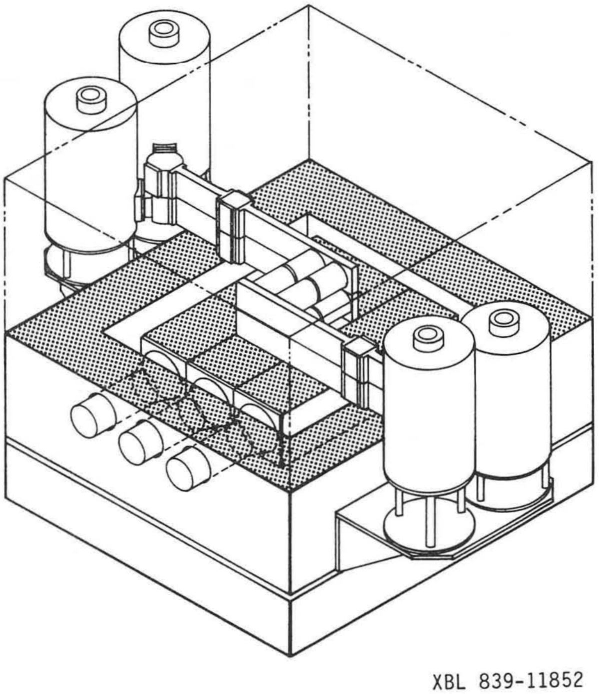

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Fig 6: View of the LBL/UCSB system with all but the bottom layer of the scintillator shield removed.

Figure 8 shows the method used to mount the germanium detectors (each weighing about 2 lbs). Dacron strings hold the detectors in place and a lexan plate with adjusting screws applies tension to the strings.

As shown in the cutaway diagram Fig. 9, each coaxial detector is mounted onto the cold finger via a silicon cylinder and a small boron nitride insulator ring. The bevel on the germanium detector mates with a similar bevel on the silicon cylinder to center the detector. The germanium detector outer surface is metallized to reduce IR absorption from the warm walls of the cryostat and thereby minimize IR-generated detector leakage current. All other cold parts are also metallized to reduce their emissivity and consequently diminish liquid nitrogen usage. A small metallized lexan spring contacts the metallized p+ inner contact of the detector and connects through a quartz feedthrough in the vacuum wall to a miniature FET resistor/capacitor feedback front end preamplifier stage mounted on the quartz feedthrough. The detector bias (positive) is connected via the silicon cylinder to the outer detector surface. A grounded cylinder surrounds the signal lead to reduce microphony that would be caused by movement of this lead with reference to the silicon cylinder which is at high voltage.

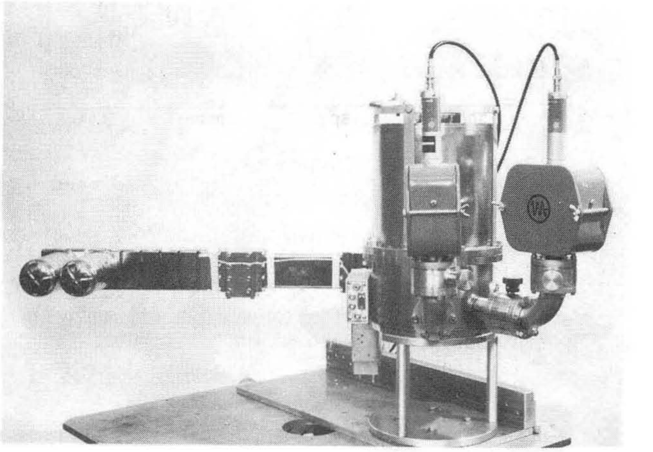

Fig 7: Photograph of the dual Ge-detector system.

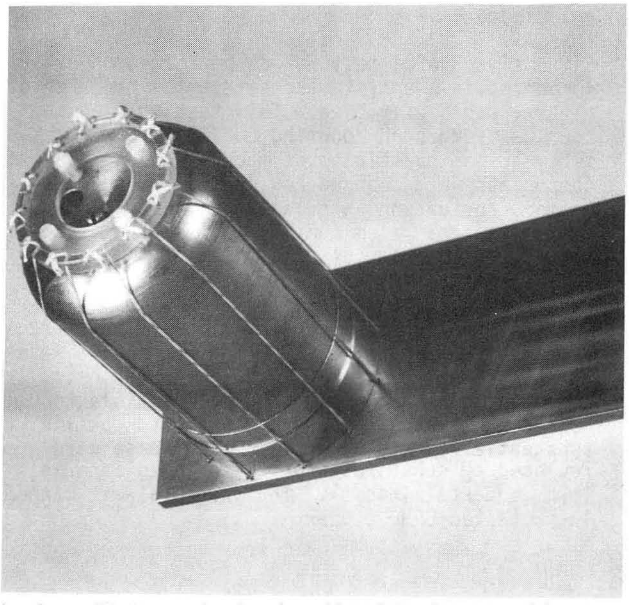

Fig 8: Photograph showing the detector mounting on the cold finger.

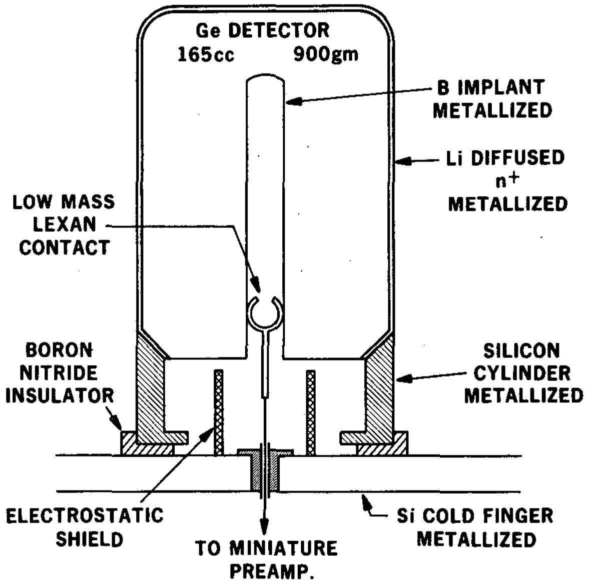

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Fig 9: Cut away view of the detector and its mounting hardware.

Experimental Results

Initial testing of the system has been carried out for several months in the LBL above ground low background counting facility. This testing, using one dual germanium detector system housed in the complete NaI and lead shield, has focused on checking the background and determining its origins preparatory to operation in an underground facility. The background reduction due to the highly efficient Compton shield yielded a background in these above-ground tests approaching that achieved by other groups in deep underground facilities. This result means that a relatively shallow underground experimental site is likely to reduce the cosmic-ray background below that due to natural radioactivity. The turbine generator room of a hydroelectric dam at Oroville in Northern California has been selected on the basis of its convenient location with reference to our laboratory. Measurements at this site, where approximately 700 feet of rock and soil overburden exists, indicate a reduction factor of 500 for cosmic rays and a relatively favorable natural radioactivity background.

At the present time two dual detector systems are being used (i.e., four detectors) in final testing before moving the experiment to Oroville. The remaining two dual detector cryostats (without detectors) are completed and we aim to have the complete eight detector system in operation at Oroville in the first half of 1985.

Figures 10, 11, and 12 show the background spectrum measured in a two-month period using one dual detector system. As expected, the background is predominantly at low energies (Fig. 10) continually decreasing to the highest energies (Fig. 12). Lines observed in these spectra permit identification of a broad range of natural activities (see Table 2) as well as cosmic-ray neutron induced activities in germanium. The ^{40}K peak is probably attributable to the glass in the phototubes; this peak has provided a convenient calibration line that is used to correct for gain shifts between various short runs

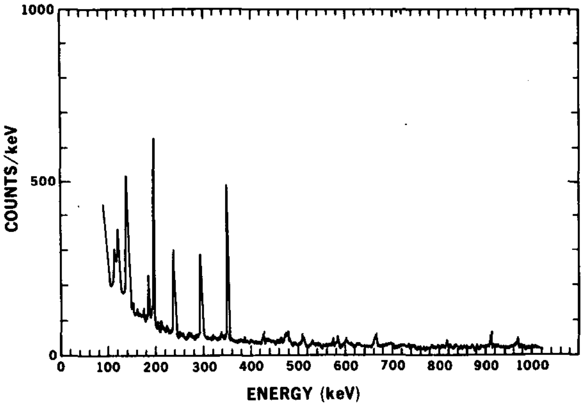

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Fig 10: Background spectrum in the 0 to 1 MeV range. The spectrum shown here and those in Figs. 11 and 12 were accumulated in 1620 hours of counting in a total of 300 cm^3 of germanium.

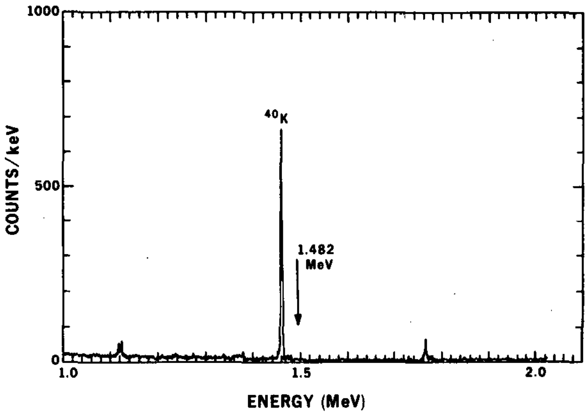

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Fig 11: Background spectrum in the 1 to 2 MeV range.

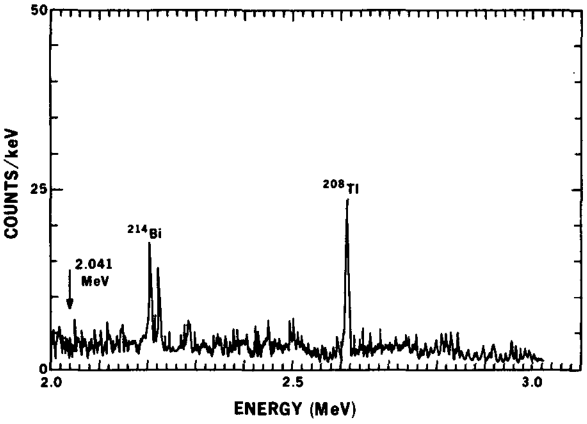

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Fig 12: Background spectrum in the 2 to 3 MeV range.

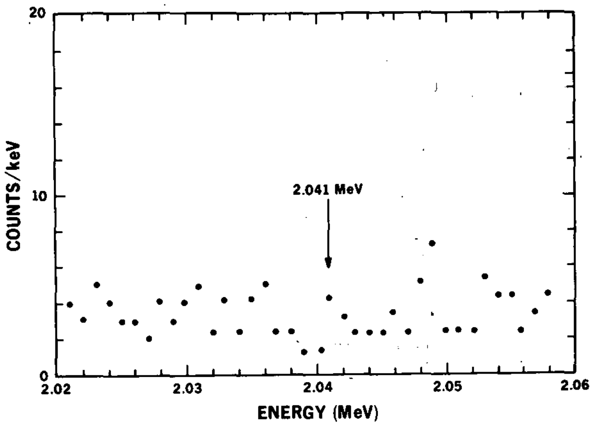

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Fig 13: Background in the neighborhood of the 2.041 MeV predicted peak position for neutrinoless ββ decay.

before summing the spectra. We intend to deliberately increase the ^{40}K line intensity in the future to make this gain correction more accurate. The 2.6-MeV line from ^{208}Tl is due mainly to the components and the P.C. board materials used in the phototube base circuits. New components and material have been selected and tested for radioactivity and the present tube bases are being replaced. These bases are outside the NaI shield but the quality of the system is so good that even the low activities associated with the present bases are still extremely important.

Figure 13 shows the observed spectrum in the energy range near the possible 2.041-MeV line arising from neutrinoless ββ decay. As expected, no such spectral line is detected above background. The background in this region amounts to about 9 counts in the ~ 4 keV FWHM resolution width of the system in the 1620 hours of counting using 300 cm^3 of germanium (i.e., approximately 5 x 10^{-6} c/hr/keV/cm^3). The best number achieved only very recently by other groups in deep underground facilities is approximately 2 x 10^{-6} c/hr/keV/cm^3.

It is important to establish the origin of our background in order to judge the quality of the system and the gain to be expected from reducing cosmic rays by moving underground. Obviously, no improvement would be achieved if the background was due to natural radioactivity in the system itself. Based on the line intensities of U and Th series members seen in the spectra of Figs. 10, 11 and 12, we are able to say that the background in the 2.041-MeV region is much larger than can be explained by ^{214}Bi electrons or by Compton scattering of the 2.6-MeV γ rays of ^{208}Tl or other naturally occurring γ rays.

These results suggest that the background in this energy region can very largely be attributed to prompt γ rays produced by cosmic-ray induced neutrons. This is confirmed by measurement of the background at higher energies shown in Fig. 14. In this spectrum a broad peak is observed at about 5.1 MeV. The width of the peak is almost 200 keV which is consistent with a Doppler broadened line produced by an (n,nγ) reaction producing a very short lived (~ 10^{-13}s) excited state. Such short-lived levels exist both in

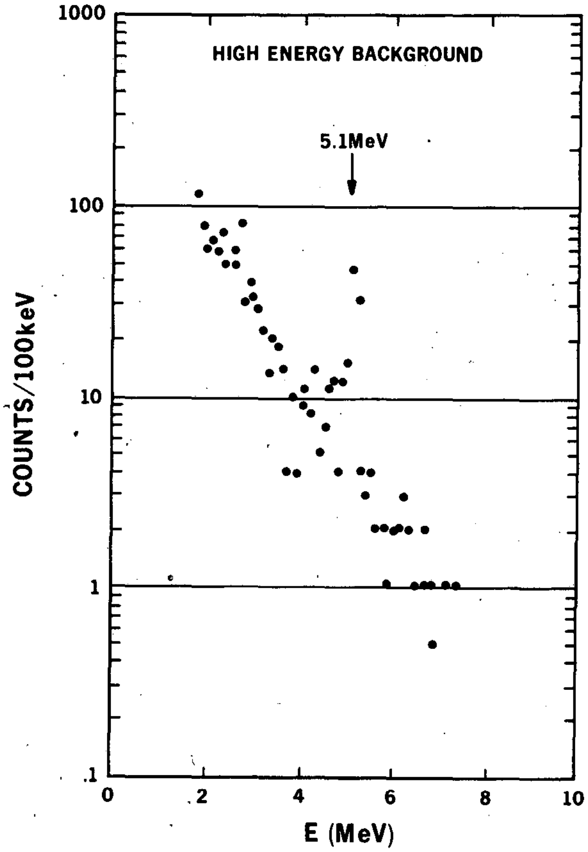

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Fig 14: High energy background spectrum.

TABLE 2

Nuclides in Background Spectrum

E keV	Parent	Note
143	U235	to 42 keV level
186	U235,Ra226	GS
238	Pb212	GS
242	Pb214	to 53 keV level
295	Pb214	GS
352	Pb214	GS
604	Bi214	GS
662	Cs137(?)	GS
911	Ac228	to 58 keV level
964	Ac228	" " "
968	Ac228	GS
1378	Bi214	GS
1461	K40	GS
1661	Bi214	GS
1729	"	GS
1764	"	GS
1848	"	GS
2204	"	GS
2448	"	GS
2614	Tl208	GS

nitrogen and silicon and the cross sections for their excitation by fast neutrons are substantial. Because we have relatively large amounts of silicon inside the main counting volume, we tend to attribute the 5.1 MeV feature to a $^{28}Si(n,n\gamma)^{28}Si$ reaction but it is quite possible that the liquid nitrogen (which is outside the lead shield) may also contribute. In either case, the high-energy γ rays may produce detector background at 2 MeV in two ways:

a) Normal Compton distribution seen in all γ-ray spectra--however, these will be largely suppressed by the Compton shield, the degree of suppression depending on the efficiency of the shield in detecting the photons escaping from the germanium detectors. We note that the shield also suppresses the double and single escape peaks normally seen in high-energy γ-ray spectra where pair production is a major γ-ray absorption mechanism. In fact, tests show no detectable single and double escape peaks for high-energy γ rays.

b) The range of the electrons (and positrons) produced by γ-ray interactions in the germanium detectors is a few millimeters. Consequently, a peripheral region exists in the detector from which degraded (i.e., not full energy) signals may arise. This effect is known to produce a rather flat background at energies smaller than the full energy peak. We intend to use a slow component electronic reject to detect electrons passing through the Li-diffused outer region of the detectors and thereby to reject a substantial fraction of this background as well as that due to any possible ^{214}Bi electrons entering the detector through its outer surface.

We are inclined to attribute the steady increase in background as the energy decreases in Fig. 14 to a whole range of $(n,n\gamma)$ interactions produced by neutrons caused by cosmic-rays. Many energy levels exist in the elements present in any detector system and, in general, the high energy excited states are very short lived, so Doppler broadening makes it difficult to distinguish individual lines. Assuming this speculation is correct, we expect a large background reduction when our system is operated in the Oroville underground site. As stated earlier, the muon background will be reduced by a factor of 500 and the high-energy neutron flux produced by these muons should be similarly reduced.

Interpretation of Results

A simple way to express the significance of results obtained in ^{76}Ge $\beta\beta$ decay experiments uses the concept of "sensitivity" defined by Fiorini[4]. This is based on the following argument:

Let V be the total detector volume (cm^3)
T be the counting time (hrs)
H be the ^{76}Ge neutrinoless $\beta\beta$ decay half life (yrs)
ΔE be the FWHM resolution (keV)
B be the background counting rate in the energy region of interest ($c/hr/keV/cm^3$)

For the background counts beneath the peak (FWHM) we have:

$$\text{Counts} \propto VT\Delta EB \qquad (1)$$

$$\text{RMS fluctuations} \propto (VT\Delta EB)^{1/2} \qquad (2)$$

also:

$$\text{Counts in } \beta\beta \text{ decay peak} \propto VT/H \qquad (3)$$

Equating Eqs 2 and 3 and inserting constants we have:

$$H = 2.74 \times 10^{17} \left(\frac{VT}{\Delta EB}\right)^{1/2} \text{ yrs} \qquad (4)$$

The value of H derived here represents the half-life for which a real peak could be detected with 68% confidence. While others have used different criteria to express their results, this method provides a fair method of comparing the results obtained by various experimental groups.

Advances made toward detection of neutrinoless $\beta\beta$ decay in ^{76}Ge depend on increases in detector volume V and reductions in background B expressed as background counts per cm^3 of germanium. The energy resolution ΔE does not vary greatly between experiments being, in general, in the 3 to 4 keV range at 2 MeV. Our system has been designed and fabricated with a strong focus on background reduction. While the experiment has not yet moved to an underground facility, the comparison given in Table 3 for background levels achieved by various research groups indicates that our efforts have been successful and that the move underground will make the sensitivity of our experiment substantially better than that of

TABLE 3

Experimental Results

	Expt Group	V(cc)	T hrs	B (x 10^{-6})
	Above Ground			
B1	Battelle/S. Carolina	125	4050	64
C1	Cal Tech	90	2600	18
O1	Osaka	160	1300	16
L1	LBL/UCSB	300	1620	5
	Underground			
G/A	Guelph/Aptec	194	2360	20
M1	Milano	120	12000	14
M2	Milano	143	3000	2.6
C2	Caltech	90		2.2
B2	Battelle/S. Carolina	125	1000	1.6
	Predicted LBL/UCSB			
L2	LBL/UCSB (3/85)	600	-	< 0.25
L3	LBL/UCSB (12/85)	1200	5000	< 0.25

(B is expressed in $c/keV/hr/cm^3$)

systems used by earlier experimental groups. The background values used in this comparison are derived in some cases from publications by the research groups but the most recent values have been obtained by word of mouth and from unpublished talks. The last two lines of this table represent target projections for our underground experiments during 1985. Despite the measured cosmic ray reduction factor of 500 at the Oroville facility we have assumed here only a factor of 20 reduction in background between our above ground and underground experiments. We note that the Battelle/S. Carolina group achieved a background reduction factor of 40 when they moved to an underground facility (the Homestake Mine).

Another way of representing these results is given in Fig. 15. This figure recognizes the fact that the time track of any experiment obeys the $(VT)^{1/2}$ relationship indicated by Eq 4. Figure 15 shows the "sensitivity" that has been achieved in the various experiments and which will be achieved in the future assuming no improvement in the basic quality (i.e., background) of each experiment. Again, our present experimental results in an above-ground location approach the best results achieved by other groups in underground facilities and our predicted results should significantly alter the limits that can be placed on the half life of ^{76}Ge.

Acknowledgment

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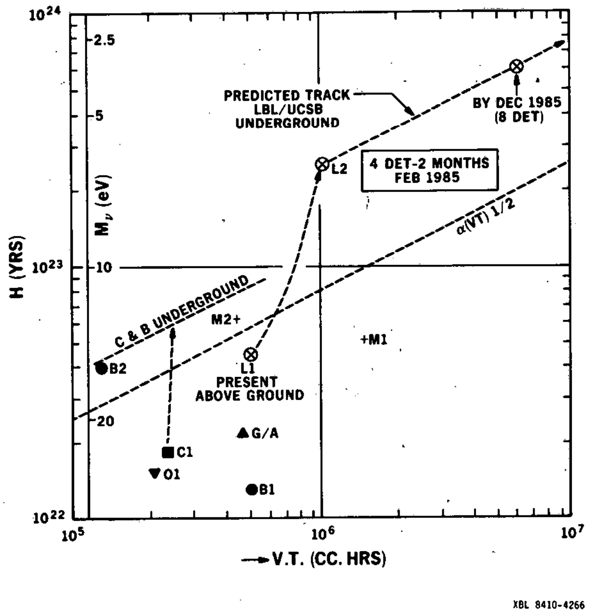

Fig 15: Plot showing the current results of several experimental groups and predicted results for LBL/UCSB experiment in an underground site. The neutrino mass scale is subject to considerable theoretical uncertainty and should be considered as a good estimate according to present theory. The predicted LBL/UCSB results represent targets and are subject to the uncertainties of all projections.

TECHNICAL INFORMATION DEPARTMENT
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