STATUS OF DOUBLE BETA DECAY EXPERIMENTS

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ABSTRACT

The current status of two-neutrino and neutrinoless double beta decay processes is reviewed.

INTRODUCTION

The theoretical question of whether there exists a conservation law of leptons in a β-decay is identical with the experimental question of whether a neutrinoless double beta $(\beta\beta)_{0\nu}$ decay exists. Consider an isobaric triplet:

(N±1),Z∓1)

(N,Z)

(N±2,Z∓2)

with the intervening isobar of higher mass (or of very high spin) than either of the pair. This situation occurs only between a pair of stable even Z, even N isobar with an odd Z, odd N isobar as the intermediate state. The well-known examples are:

$${}^{48}_{20}\mathrm{Ca} \xrightarrow[\mathrm{MeV}]{4.267} {}^{48}_{22}\mathrm{Ti}; \quad {}^{130}_{52}\mathrm{Te} \xrightarrow[\mathrm{MeV}]{2.543} {}^{130}_{54}\mathrm{Xe}; \quad {}^{128}_{52}\mathrm{Te} \xrightarrow[\mathrm{MeV}]{0.872} {}^{128}_{54}\mathrm{Xe}$$

$${}^{76}_{32}\mathrm{CTe} \xrightarrow[\mathrm{MeV}]{2.045} {}^{76}_{34}\mathrm{Se} \quad {}^{82}_{34}\mathrm{Se} \xrightarrow[\mathrm{MeV}]{3.003} {}^{82}_{36}\mathrm{Kr} \quad {}^{150}_{60}\mathrm{Nd} \xrightarrow[\mathrm{MeV}]{3.390} {}^{150}_{62}\mathrm{Sm}$$

The direct decay of one of these to the other via the intermediate isobar is energetically forbidden. However, the nucleus (N,Z) can decay to (N±2,Z∓2) by double β-decay in a second order process. Since the beta decay interaction constant "g" is very weak to start with; the transition probability arising from the second order transition is extremely small. Furthermore, the probability of transition depends also sensitively on the validity of the law of lepton conservation.

In the absence of any conservation law of lepton, two possible reactions may occur: one is the two-neutrino double beta decay process, that is

$$(\beta\beta)_{2\nu} \; : \; (Z,A) \rightarrow (Z+2,A) + e_1^- + e_2^- + \nu_1 + \nu_2 \,, \qquad (1)$$

where ν_1 and ν_2 stand for any linear combination of

$$\nu_L, \nu_R, \bar{\nu}_L, \bar{\nu}_R \,.$$

The other is the neutrinoless double β-decay process

$$(\beta\beta)_{0\nu} \; : \; \underset{\ell_e = 0}{(Z,A)} \rightarrow \underset{\ell_e = 0}{(Z+2,A)} + \underset{\ell_e = +1}{e_1^-} + \underset{\ell_e = +1}{e_2^-} \,. \qquad (2)$$

In $(\beta\beta)_{0\nu}$ decay, the initial state has $\ell_e = 0$, but the final state has $\ell_e = 2$. Thus, the observation of a neutrinoless double β-decay implies the violation of the conservation law of leptons $\Sigma\ell_e \neq 0$. Prior to 1957, when the conservation law of leptons had not attained the respectability it enjoys now, the validity of lepton conservation was not in question yet. The occurrence of neutrinoless double β-decay was considered possible if the neutrino and antineutrino are the same particle, as suggested by Majorana. For the Majorana neutrino, $\nu \equiv \bar{\nu}$, a neutrino might be emitted into a virtual state with the emission of the first electron and then reabsorbed in the subsequent emission of the second electron. Write down Eq. (3) and (4) and transport Eq. (4) to Eq. (4') where the emission of a ν is equivalent to the absorption of a $\bar{\nu}$:

$$(Z,A) \rightarrow (Z+1,A) + e_1^- + \nu \;\; (3); \quad (Z+1,A) \rightarrow (Z+2,A) + e_2^- + \nu \qquad (4)$$

$$\bar{\nu} + (Z+1,A) \rightarrow (Z+2,A) + e_2^- \,. \qquad (4')$$

If $\nu \equiv \bar{\nu}$, as for the Majorana neutrino, Eq. (2) applies.

Figure 1 sketches the second-order neutrinoless double beta decay by emission and reabsorption of a neutrino. Figure 2, curve (a) the narrow energy peak at $E_T = E_{e1,0} + E_{e2,0}$ illustrates the

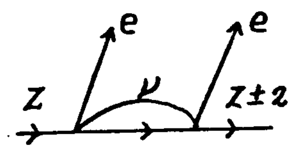

Fig. 1. Second-order neutrinoless double beta decay by emission and reabsorption of a neutrino.

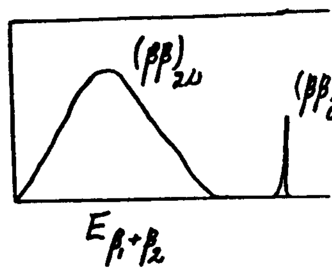

Fig. 2. The two-neutrino double beta $(\beta\beta)^2$ is shown by the continuous energy distribution. The non-neutrino double beta decay $(\beta\beta)^{0\nu}$ is indicated by the vertical line at the maximum energy of the two-neutrino spectrum.

energy sum of two electrons from the $(\beta\beta)_{0\nu}$ mode. (2b) The continuous distribution with a broad maximum at half the energy release represents the electron energy-sum distribution with two-neutrino emission $(\beta\beta)_{2\nu}$.

Furthermore, since the energy is conserved only between the initial and final states, but not in the intermediate state, the virtual neutrino may assume any energy up to approximate 30 MeV, where its de Broglie wavelength becomes short compared to the nuclear radius $\lambda_\nu < R_A$. The volume of phase space accessible to the intermediate state is therefore very much larger than that for the Dirac neutrinos, hence the greatly increased transition probability for Majorana neutrinos $(\beta\beta)_{0\nu}$.

A crude estimate for the transition rate of two-neutrino double β-decay can be made as follows:

If we have simple β-decay, the transition rate can be given by

$$\omega_\beta \simeq \frac{mc^2}{\hbar}\frac{G^2|M|^2}{2\pi^3}\frac{\varepsilon_0^5}{30} \qquad \begin{array}{l}\varepsilon \ll 1\\ \text{No coulomb effects}\end{array} \quad . \tag{5}$$

Thus it is plausible that the decay rate for double β-decay in units of the characteristic rate $mc^2/\hbar$ is a simple square of the rate for single β-decay. Consequently, for double β-decay, we may write approximately

$$\omega_{\beta\beta} \simeq \frac{mc^2}{\hbar}\frac{(G^2|M|^2)^2}{2\pi^3}\left(\frac{\varepsilon_0^5}{30}\right)^2 . \tag{6}$$

Using $\frac{mc^2}{\hbar} \simeq 10^{21}$ sec^{-1}, $\frac{G^2|M|^2}{2\pi^3} \simeq 3 \times 10^{-27}$ for β-decay of light nuclei. Assume $\varepsilon_o \simeq 5mc^2$, $\tau \simeq 3 \times 10^{20}$ yrs. In the absence of lepton-conserving selection rules, we should expect the rate of $(\beta\beta)_{0\nu}$ decay to be enhanced by a phase space factor of about 10^5 over the rate of two-neutrino double beta $(\beta\beta)_{2\nu}$ decay.

Or the lifetime for $(\beta\beta)_{0\nu}$ decay is expected to be about 10^5 - 10^6 shorter than for $(\beta\beta)_{2\nu}$ decay as the ratio is essentially equal to the fourth power of the energy ratio

$$(30\ \text{MeV}/1\ \text{MeV})^4 \simeq 10^6 .$$

Therefore $(\tau_{\beta\beta})_{2\nu} \simeq 10^{20}$ to 10^{22} yrs. and $(\tau_{\beta\beta})_{0\nu} \simeq 10^{14}$ to 10^{16} yrs.

The sensitivity as a test of lepton conservation. This implies that with maximum violation of lepton conservation, we should expect that rate of $(\beta\beta)_{0\nu}$ decay to be enhanced by a phase space factor of about 10^6 over the rate of two-neutrino double beta $(\beta\beta)_{2\nu}$ decay. The sensitivity which this enhancement gives to a search for $(\beta\beta)_{0\nu}$ decay as a test of lepton conservation will probably never be equalled by the sensitivity of measurements of electron polarization in ordinary β-decay.

With the establishment of the V-A theory for weak interactions, an alternative interpretation is that the absence of $(\beta\beta)_0$ decay may be entirely due to the complete polarization of the neutrino in the intermediate state, so that the neutrino emitted in the first step of the double beta decay cannot be reabsorbed by the second neutron. (ν, left-handed; $\bar{\nu}$, right-handed.) Thus, it is argued that the absence of this decay mode cannot be used to infer lepton conservation. Actually, the contrary is true.[1]

Theoretically, it has been shown that if $(\beta\beta)_{0\nu}$ is absolutely forbidden, then there must exist a way of assigning a leptonic number ℓ_e to the neutrinos such that the algebraic sum of $\Sigma\ell_e$ is always conserved in all beta interactions.

This conclusion can also be reached by the following reasoning: If lepton conservation is not valid, then the mass of a two-component neutrino is, in general, not necessarily zero. When the mass of the neutrino is not zero, it is very artificial to impose complete polarization of the neutrino in the intermediate state. In fact, the three intrinsic properties of the neutrino

1) its number of wave function components; two or four
2) a definite ℓ_e can be assigned
3) its rest mass (m_ν)

are all intimately correlated. Only if both the two-component theory and lepton conservation are valid must the mass of the neutrino then be zero.

EXPERIMENTAL METHODS

The identification of these two modes of double beta decay can be made by the direct detection of the sum spectrum of the two electron energies. In neutrinoless decay, $(\beta\beta)_{0\nu}$, they must add up to the available decay energy; if neutrinos are emitted, $(\beta\beta)_{2\nu}$, the energy will be statistically distributed among all four particles and the electron sum energy spectrum will be a broad distribution peaking at about half the available energy (see Fig. 2). So far, no direct observation of $(\beta\beta)_{0\nu}$ decay has been reported implicating the smallness of the lepton-violation parameter. The direct observation of the evidence of the $(\beta\beta)_{2\nu}$ decay has been strengthened by most recent cloud chamber work but its statistical reliability is nevertheless fragile because the large uncertainties involved in the interpretation and estimation of its background.

However, convincing evidence of double beta decay and its half lives have been also obtained by geological methods. These experiments use mass spectrometry to determine the relative abundance of $(\beta\beta)$ decay daughter nuclei in geologically old ores. Although leptons are not detected in these experiments, much insight concerning lepton conservation can be gained by comparing the measured ratio of the double beta decay half lives of $T_{1/2}(^{128}Te)/T_{1/2}(^{130}Te)$ to the theoretically predicted ratios based on $(\beta\beta)_{0\nu}$ or $(\beta\beta)_{2\nu}$ decays, or comparing the double beta decay life of ^{82}Se from the geological method to that of $(\beta\beta)_{0\nu}$ from the direct method.

GEOLOGICAL METHODS

By utilizing the high sensitivity of noble gas mass spectrometry as early as in 1950, Inghram and Reynolds[2] determined the half life of double beta decay of $^{130}Te \to {}^{130}Xe$ as 3.3×10^{21} yrs. The tellurium ores generally contain a sizeable amount of uranium concentration which greatly complicates the analysis. In the middle of the sixties, the activities of the geological method in the study of double beta decay were lively revived. Kirsten, Genthur, and Schaeffer[3] (1967) and Kirsten, Schaeffer, Norton and Stoner[4] (1968) obtained convincing evidence of double beta decay in Te and Se ores of known ages and yielded $T_{1/2}(\beta\beta)(^{130}Te) = 10^{21.34 \pm 0.12}$yrs. The half-life for double beta decay of ^{130}Te can be calculated by the geological analysis from the following equation:

$$T_{1/2}(^{130}Te) = T\{N(^{130}Te)/N^{excess}(^{130}Xe)\}\ln 2 \qquad (7)$$

where T is the ore age, $N(^{130}Te)$ = number of atoms of ^{130}Te/g of the sample, $N^{excess}(^{130}Xe)$ = number of atoms of excess ^{130}Xe/g of the sample. A similar result was obtained by Srinivasan et al.[5] (1972) with $T_{1/2}(\beta\beta)(^{130}Te) = 10^{21.38 \pm 0.10}$ yrs. The results of Kirsten et al. on native tellurium ore from the Good Hope Mine in Colorado are particularly significant as the uranium concentration in this ore was four orders of magnitude less than in samples used earlier. On the other hand, a large excess of ^{130}Xe was found unaccompanied by any other anomalies (as might be caused by nuclear fission and brought about by neutrons from uranium fission). This could only be from the double beta decay of ^{130} Te in the ore. The double beta decay rate calculated from the age of the ore and the concentrations of ^{130}Te and ^{130}Xe in it was consistent with lepton conservation. An upper limit could be set on the lepton conservation-violating fraction of the beta interaction amplitude of 3×10^{-3}.

In an earlier experiment by Takaoka and Ogata[6] (1966) using different tellurium ores, an excess of ^{128}Xe was found, but the authors cautioned that it was difficult to assign the excess of ^{128}Xe entirely to ^{128}Te double beta decay, because a small, persistent background in the mass spectrometer disturbed exact measurements at ^{128}Xe. If one takes the total amount of excess ^{128}Xe observed as due to ^{128}Te double beta decay, then the ^{128}Te half-life is $10^{22.5 \pm 0.5}$ yrs. $S \equiv T_{1/2}(^{128}Te)/T_{1/2}(^{130}Te)$.

Furthermore, it is not unreasonable to assume that nuclear matrix elements for $^{128}Te \to {}^{128}Xe$ and $^{130}Te \to {}^{130}Xe$ are approximately equal. Under this assumption, the ratio of double beta decay rates should be proportional to the ratio of the available phase spaces, which is the 8th through the 11th power of energy release for $(\beta\beta)_{2\nu}$ decay and the 4th through 5th power of energy release for $(\beta\beta)_{0\nu}$ decay. Since the energy release for ^{130}Te is three times that for ^{128}Te, one would expect $S \equiv T_{1/2}(^{128}Te)/T_{1/2}(^{130}Te) \approx 3^{8.4} = 10^{4.0}$ for $(\beta\beta)_{2\nu}$; $(^{128}Te)/T_{1/2}(^{130}Te) \approx 3^{4.6} = 10^{22}$ for $(\beta\beta)_{0\nu}$. Using the doubtful short lifetime of ^{128}Te as $10^{22.5\pm.5}$ yr. Then the measured lifetime ratio is

$$T_{1/2}(^{128}Te)/T_{1/2}(^{130}Te) = 10^{22.5\pm0.5}/10^{21.34\pm0.12} = 10^{1.2\pm0.6} .$$

This ratio seems to be in better agreement with that predicted for non-neutrino double β-decay.

On the basis of this rather questionable experimental indication, Pontecorvo proposed that the decays of ^{130}Te and ^{128}Te are, predominantly, the first order effect of a new super-weak ($\Delta Q = \pm 2$, $\Delta S = 0$) interaction which mediates non-neutrino double beta decay, rather than the second-order effect of the usual weak ($\Delta Q = \pm 1$, $\Delta S = 0$) interaction. This super-weak interaction also causes the observed slight CP violation in K° decay.

In 1975, Hennecke, Manual and Sabu carried out another investigation on the ratio "S" of $T_{1/2}(^{128}Te)/T_{1/2}(^{130}Te)$ by extracting Xenon by stepwise heating of the sample, and its isotopic abundances were measured in the mass region A = 122 to A = 136 in a mass spectrometer. For ^{130}Xe the excess over atmospheric abundance was $(^{130}Xe\ excess)/(^{130}Xe\ atmosphere) = 712 \pm 2$, which was more than an order of magnitude greater than in the previous experiments. Many sources of systematic errors in measuring the individual ββ-decay half-lives, such as errors in ore age T, in the tellurium determination $N(^{130}Te)$ and in the Xenon content $N^{excess}(^{130}Xe)$, (see Eq. (7)), cancel out in the determination of the ratio "S" of the half-lives. The experimental result found by Hennecke, Manuel and Sabu[7] is $S = 10^{3.20\pm0.01}$. It is quite different from $S = 10^{1.2\pm0.6}$ obtained by Takaoka and Ogata[6] but gives a value in between the predicted $(\beta\beta)_{0\nu}$ and $(\beta\beta)_{2\nu}$ rates and closer to the later. Using

$$T_{1/2}(^{130}Te) = 10^{21.34 \pm 0.10} \text{ yr.}$$

$$T_{1/2}(^{128}Te) = 10^{24.54 \pm 0.12} \text{ yr.}$$

In 1973, Srinivasan et al.[8] performed the geological analysis on Se ores and obtained

$$T_{1/2}(^{82}Se) = 10^{20.42 \pm 0.14} \text{ yr.}$$

In order to support the conclusion of the geological method, the measured excess of noble gases must all be due to the results of daughter nuclei generated in the double beta decay process. There are other possible origins of these noble gases (such as (α,2n), (α,n) and (α,r) reactions generated by Uranium and Thorium α-decays in the Te or Se ores or in surrounding rocks). Other reactions such as those that might be induced by solar neutrino cosmic ray particles and neutron capture processes must also be excluded.

DIRECT DETECTION

At first glance, the coincidence technique of simultaneous detection of the two e^- (or $2e^+$) in double beta decay may be sensitive to observing this rare process. Many experiments had been carried out with coincidence techniques prior to 1967 in the search for ($\beta\beta$) decay, but the sensitivity of those experimental searches was limited by background counting rates much larger than the expected $(\beta\beta)_{2\nu}$ rate. In the usual coincidence counting experiments, the background results principally from local gamma rays, either Compton scattering from counter to counter or producing recoil electrons in one counter which strike another counter. To achieve any substantial improvement in experimental sensitivity, one must identify and remove this overwhelming background. This is accomplished most directly by recording tracks of charged particles leaving the source in a magnetic field, which permits detailed reconstruction of each event, including charge, momentum, energy, direction and point of origin of each particle involved. The first experimental apparatus with such unique sensitivity and discrimination was reported by R. K. Bardin et al.[9] in 1967 in the study of double beta decay of ^{48}Ca. Figure 3 shows the cutaway drawing of the apparatus. Tracks in a magnetic field were produced in a two-gap discharge chamber containing a thin source as its centerplate. Scintillation counter arrays covering each face of the chamber provide triggering and energy signals. The source consists of 10.6 g of 97%-enriched ^{48}Ca deposited as CaF_2 in a uniform disc 46 cm in diameter. The deposit is sealed between two 3 mg/cm^2 Al foils to form the centerplate of the discharge chamber. The scintillation counters are 2 cm. thick NE-102 plastic and have a resolution of 30% (FWHM) at 1 MeV. Thirty-two wedge-shaped segments (Fig. 4) are used to reduce the chance that coincidence electrons will strike the same counter. Pictures are taken through the plastic scintillators and the outer mesh plates. The scintillators are left unwrapped and the photomultipliers are protected by defocussing them during the chamber flash.

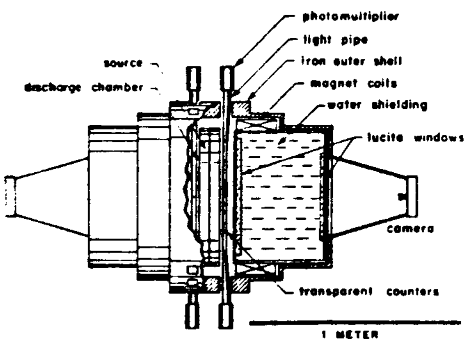

Fig. 3. The apparatus by Bardin et al. (1970) in the ^{48}Ca and Cleveland et al. (1975) in ^{75}Se neutrinoless doublet beta decay.

The magnet provides 400 gauss (±3%) over the chamber volume, and also provides 8 cm of iron or the equivalent in γ-ray shielding.

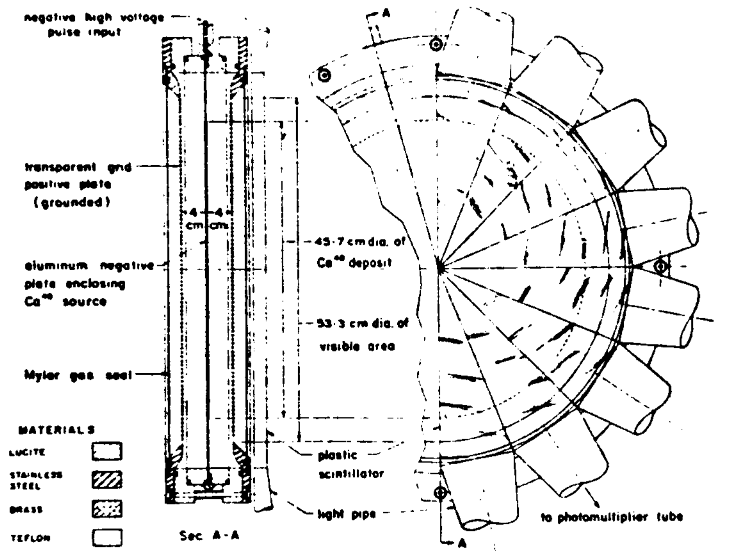

Fig. 4. Streamer chamber and scintillation counter. Thirty-two optically flat wedge-shaped scintillators of NE-102 plastic formed two segmented circled cover the faces of the chamber as shown. A strip of thin aluminum foil along the edge of each scintillator wedge prevented optical cross-talk between adjacent counters.

50 cm thick water tanks serve as the shield in the field of view of the cameras. Background was further reduced by running the experiment in the low radiation environment of a salt mine 2000 ft. below ground level. Figure 5 is a comparison of spectra taken with a 12.7 cm × 12.7 cm NaI crystal under various conditions on the surface and in the mine. The "intrinsic" background in the mine was found by placing the NaI crystal in a freshly dug pit in the salt, well-shielded from all other man-made objects, the 1.46 MeV gamma ray from the decay of ^{40}K in the salt was the only significant radiation naturally present in the salt. The 2.62 MeV line of Th C" (^{208}Th) was visible throughout the experimental area and appeared to be associated with objects brought from the surface of the earth.

A large component of the background came from airborne radon gas (^{222}Em, with a 3.8d half-life) coming from the decay of ^{226}Ra. The level of this activity increased noticeably in rainy weather even in the deep mine.

The data film was scanned for possible $(\beta\beta)_{0\nu}$ events by first selecting all events with a total energy above 3 MeV containing a single pair of tracks meeting at the source. In 1103 hrs. of lifetime with the ^{48}Ca source, 191 such events were found. All tracks

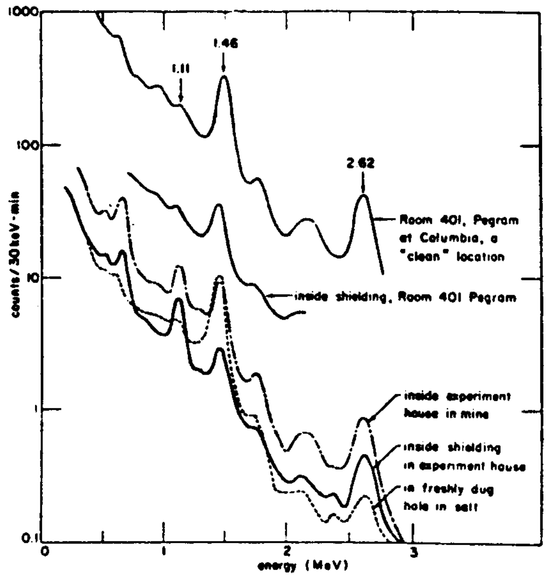

Fig. 5. Gamma-ray background at experiment site, measured with 12.7 cm × 12.7 cm NaI crystal; lowest background for the 2.62 MeV line was in the freshly dug hole in salt.

closer than 27° to the magnetic field were eliminated; these usually showed too little curvature for reliable measurement. Of the remaining 119 events, all but 23 were rejected for track curvature clearly of the wrong sign or particle momentum clearly inconsistent with recorded scintillation information. Most of the remaining 23 events showed tracks with no measurable curvature, passing through the source with little angular deviation. These were mostly high-energy Compton recoils or cosmic-ray muons crossing the chamber. Only one of the surviving ^{48}Ca events was within two standard deviations of 4.24 MeV, the expected $(\beta\beta)_{0\nu}$ sum energy. A half-life limit for the $(\beta\beta)_{0\nu}$ decay in ^{48}Ca was arrived at 1.6×10^{21} yr. at the 80% confidence level.

The scanning of the two-neutrino decay $(\beta\beta)_{0\nu}$ events obtained requires changing the criteria above. A lower limit of the two-neutrino decay obtained at an 80% confidence level is $> 10^{19.56}$ yrs.

The apparatus and measurement technique similar to that used for the study of ^{48}Ca by Bardin et al. were also applied to the study of the $(\beta\beta)$ decay of ^{82}Se by Cleveland et al.[10] in 1975. The selenium source contained approximately 46 g of metallic powder enriched to 56.5% of ^{82}Se formed the centerplate (diam. = 50 cm; t = 58 mg/cm^2) of a helium-filled double gap streamer chamber. The selenium was purified by precipitation of radium with separated ^{138}Ba and by multiple passes through ion-exchange columns. It was measured to have an activity of less than 3.5 dis/min for ^{40}K and less than 0.25 dis/min for various other suspected contaminants. In order to reduce background, the experiment was also conducted in the Morton salt mine (600 m below ground level) at Cleveland. The energy losses of $(\beta\beta)$ decay electrons due to the thickness of the source were found by a Monte Carlo calculation, shifting the searched-for peak in the electron energy-sum spectrum for neutrinoless $(\beta\beta)$ decay from 3.0 MeV to 2.75 MeV with a width of ≈ 0.3 MeV. The total number of events recorded was 65,500. The vast majority of these were background-induced, primarily Compton scattering of γ-rays in a scintillator, the recoil electron then passing through the chamber and hitting a second counter. Only 201 events are two-track events with the signature of $\beta\beta$-decay. Many of these were caused by double scattering within the source and it was difficult to distinguish them from true $\beta\beta$ events. By restricting the energy range to between 2.4 and 3.2 MeV and imposing appropriate acceptance criteria on the track curvature, the overall selection efficiency became 19% and no events were found in this energy region. At a confidence level of 68%, this null result implies the following lower limit on the half-life for no-neutrino $(\beta\beta)$ decay of ^{82}Se:

$$T_{1/2}^{0\nu} \geq 3.1 \times 10^{21} \text{ yr.}$$

Combining this with the measurement of the overall half-life by Srinivasan et al.[8] of $(2.76 \pm 0.88) \times 10^{20}$ yr., we find the branching ratio, R, to be

$$R = \frac{\text{non-neutrino rate}}{\text{total } (\beta\beta) \text{ rate}} \leq 9\% \ .$$

This is the first experimentally determined branching-ratio limit in $(\beta\beta)$ decay.

Another quite different direct detection of double beta decay was applied to ^{76}Ge by Fiorini, Pullia, Bertollini, Capellani and Restelli[11] to the high resolution Ge(Li) detector in 1973. A similar principle was also applied to the detection of $(\beta\beta)_{0\nu}$ in ^{48}Ca by Goldhaber and der Marrosian.[12] For ^{76}Ge, the single β-decay to the Z+1 nucleus ^{76}As is energetically forbidden and the $(\beta\beta)$ decay energy available for transitions to the ground state of ^{76}Se is 2.045 MeV. Ge(Li) detectors are fabricated out of high purity Ge metal with a natural abundance of ^{76}Ge of 7.67%. The Ge(Li) detector used by Fiorini et al. (1973) had an active volume of 68.5 C.C. and an energy resolution of 6 KeV at 2.615 MeV. A diagram of the experimental apparatus is shown in Fig. 6. The experiment was located in the Mont Blanc tunnel connecting Italy to France and the crystal was shielded from local radioactivity by layers of paraffin, cadmium, low-activity lead, bi-distilled mercury, nylon and high purity electrolytic copper. After 4400 hr. of running, no peak was found in the

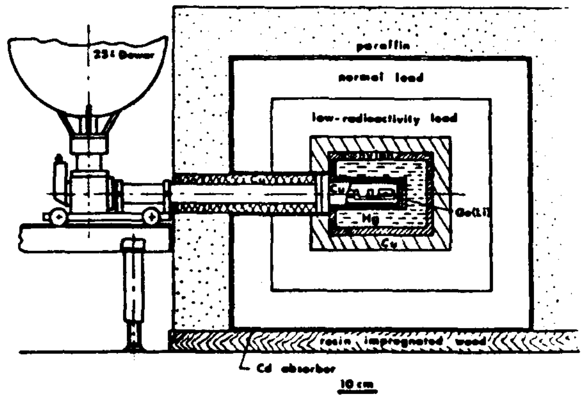

Fig. 6. The apparatus and local shielding used in the ^{76}Ge double beta-decay experiment of Fiorini et al. (1973).

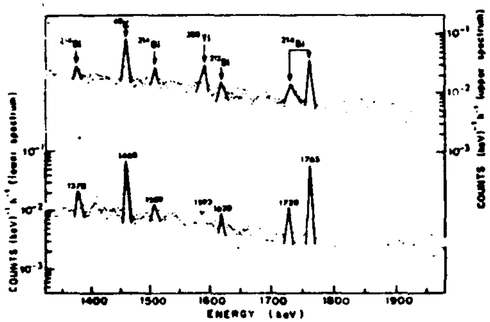

Fig. 7. The observed spectrum in the energy region of expected ^{76}Ge neutrinoless double beta decay, 2.045 MeV, from the experiment of Fiorini et al. (1973).

a) Upper spectrum: An initial run lasting 2100 hr.

b) Lower spectrum: The final run of 2300 hr. by using higher purity materials for the crystal support structure and cryostat cup.

2.045 MeV region of expected neutrinoless (ββ) decay (Fig. 7). Tests indicated that the residual backgrounds observed in this energy region were likely due to ^{40}K, ^{235}U, ^{238}U and ^{232}U contaminants of less than 10^{-5} ppm which originated inside the local shield, probably in the crystals crystat structure. Possible ^{222}Rn contaminants in the liquid nitrogen coolant were also suspected. Figure 7 shows the spectrum obtained in the final run of the experiment lasting 2300 hr. The background counting rate in the 2.045 MeV region was $(2 \pm 0.2) \times 10^{-4}$ counts KeV^{-1} $hr.^{-1}$, allowing a limit to be set on the half-life for the neutrinoless (ββ) decay of ^{76}Ge, $T_{1/2}^{0\nu} \geq 5\times10^{21}$ yr. at a 68% confidence level.

In the direct detection used by Bardin et al. in 1967 and Cleveland et al. in 1975 for the study of the (ββ) decay of ^{48}Ca, and ^{82}Se respectively, among the "$2e^-$" backgrounds, they noticed an unusually large number of double-beta-like events indistinguishable from the true double beta decays. After thorough investigations, it was concluded that the principal radioactive contaminant responsible for these mechanisms was ^{214}Bi, a member of the naturally occurring uranium series; its multiple (β-γ) cascades cause "two-electron" events to emerge from the source resembling the (ββ) decay. The second electron was produced by Møller or Compton scattering or by internal conversion. Although the ^{214}Bi nucleus is short-lived, its presence after a few days is maintained by its long-lived progenitor ^{226}Ra. It had been hoped that by chemical purification techniques, substantially lower levels of radiation in isotopically enriched double beta sources could be achieved, however, success had not been adequately demonstrated. The level of ^{226}Ra contamination that would prove troublesome is on the order of one part in 10^{15}.

Moe and Lowenthal[13] have made special efforts to modify the direct detection method in order to identify and eliminate a large fraction of double-beta-like events from ^{214}Bi. The general principle is as follows: ^{214}Bi beta decay is followed in 164 μs by emission of a 7.7 MeV alpha particle. The ^{214}Bi induced "two-electron" events thus can be identified if the α-particle can be detected. For the 164 μs delayed α-particle from ^{214}Bi to be detected, a track visualization chamber of longer sensitive duration of the post-trigger period as compared to 164 μs must be used. A large cloud chamber was chosen by Moe and Lowenthal for this purpose and its duration of post-trigger sensitivity was found to easily cover the delay of alpha particles attending ^{214}Bi decay.

A further requirement for detection of the alpha particle is that the double beta decay source be thin enough to assure that the alpha particles are not trapped within. The ^{82}Se sources, which they fabricated, consisted of an arrangement of parallel strips; each strip had selenium sandwiched between two sheets of aluminized mylar with thicknesses of (5.60 mg/cm^2 of ^{82}Se, 1.08 mg/cm^2 mylar and ≤ 0.8 mg/cm^2 formvar). The 46 cm diameter by 20 cm high cylindrical cloud chamber is illustrated in Fig. 8.

Although the sensitive time of the cloud chamber is long, typically 300 ms following expansion, the sensitivity is far too short to permit a reasonable accumulation of live time by random expansions. A trigger sensitive to pairs of electrons had to be developed.

The heart of the triggering scheme is a transparent multi-wire proportional counter across the top of the chamber volume. The 36 wires operate as independent counters and provide spatial and

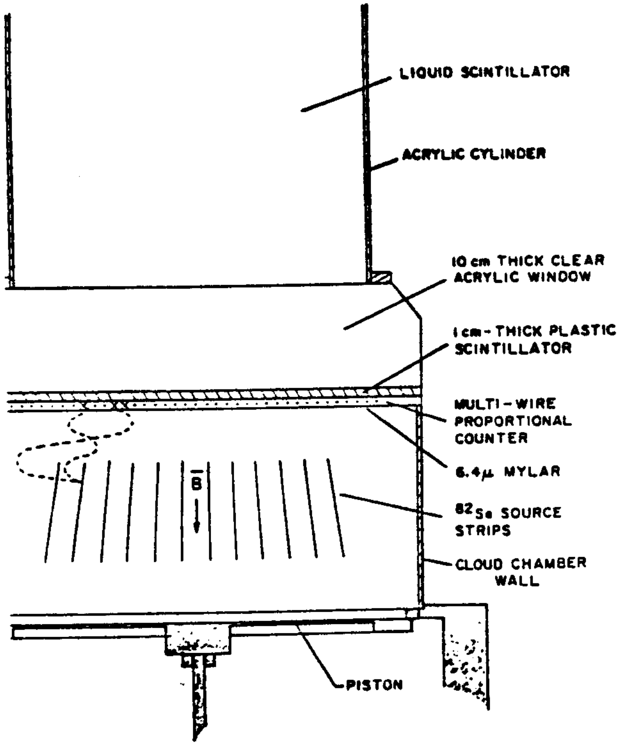

Fig. 8. Cross section view of the cloud chamber, with a double beta decay event producing a 2e$^-$ signature in the multi-wire proportional counter.

temporal information necessary to discriminate against single electron events. An imaginary double beta decay event is illustrated with the electron tracks emerging from a common point on one of the source strips (see Fig. 8). The electrons follow helical paths in the vertical magnetic field until they enter the 36-wire proportional counter. The electrons next enter and stop in a plastic scintillator which is used to impose a 1 MeV threshold on their sum energy.

Scintillation light is transmitted upward through a 10 cm-thick acrylic window and an 84 in. column of liquid scintillator. Just above the photomultipliers, are the cameras that provide stereo photographs of the cloud chamber through the liquid scintillator, acrylic window, plastic scintillator and proportional counter, all of which are transparent (Fig. 9).

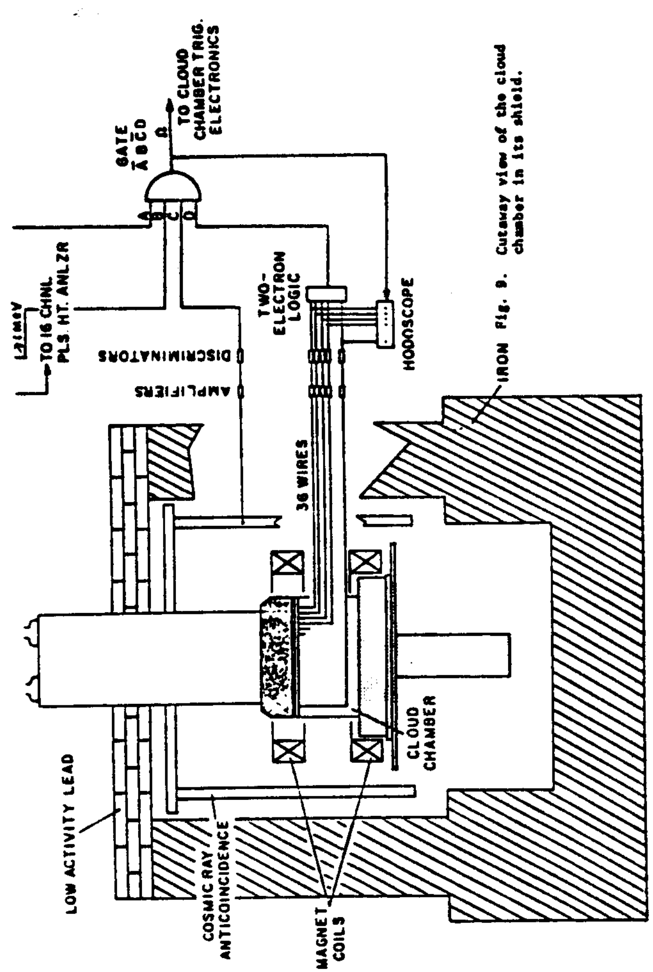

Fig. 9. Cutaway view of the cloud chamber in its shield.

OBSERVED EVENTS

At the end of 37 live days, 36 negatron pairs from the ^{82}Se source (13.34 g) strips had been observed. Of these, 20 were clean events ($2e^-$) and 16 were accompanied by alpha particles ($2e^- + \alpha$) (track pictures Figs. 10 and 11). The Se source had been constructed to permit the escape of 77% of the α particles from ^{214}Bi, using the relation

$$\frac{N(2e^- + \alpha)}{N(2e^- + \alpha) + N(2e^-)} = \frac{16}{16 + N(2e^-)} = 0.77 \qquad (8)$$

$$N(2e^-) = 4.8 \pm 1.2 \qquad \text{from } ^{217}Bi\ .$$

Since the observed total number of $2e^-$ events was 20, it appeared that ($2e^-$) from ^{214}Bi with the α-particles trapped in the source is responsible for only about 1/4 of them.

The half-life for ^{82}Se. $T_{1/2}$ for ^{82}Se can be calculated from the assumption that the 20($2e^-$) events observed were caused only by ^{82}Se (15.2 ± 4.6) and ^{214}Bi (4.8 ± 1.2) and the overall detection efficiency is calculated to be 0.022 ± 0.007. The half-life can be expressed as

$$T_{1/2} = \frac{N \ln 2}{dN/dt}\ . \qquad (9)$$

$$\text{Where } N = \frac{13.34\ g}{81.9\ g/mole} \times 6.03 \times 10^{23}\ \frac{atoms}{mole} = 9.82 \times 10^{22}\ atoms$$

$$\frac{dN}{dt} = \frac{15.2 \pm 4.6\ atoms}{37.0 \times 1365} \times \frac{1}{0.022 \pm \sim .007} = 6.8 \pm 3.0 \times 10^{3}\ atoms/yr.$$

Therefore $T_{1/2} = 1.0 \pm 0.4 \times 10^{19}$ yr.

All these events were observed with a sum energy below the 33 MeV value corresponding to two-neutrino double beta decay. This type of experiment, because of its low source mass, trigger efficiency and lifetime is not efficient for neutrinoless $(\beta\beta)_{0\nu}$ detection. Using the zero event observed above 3 MeV and the estimated detection efficiency 4% for neutrinoless decay, a limit on the neutrinoless half-life was estimated $T^{0\nu}_{1/2} > 2.4 \times 10^{20}$ yr.[12] with a 68% confidence. This is to be compared with another determination of $T^{0\nu}_{1/2}(^{82}Se)$ by Cleveland et al.[10] in a limit of 3.1×10^{21} yr. at the same confidence level.

SUMMARY AND CONCLUSIONS

The geological method, in conjunction with a high sensitive noble gas mass spectrometer, offers a very potent was to determine the relative noble isotopes accumulated. Particularly, in some selected high purity Te ores, where an extremely large excess of ^{130}Xe above atmospheric abundance was not accompanied by other Xe isotopic

Table 1. Summary of (ββ) Half-Lives by Geological Methods

ββ-decay	Authors	$T_{1/2}$ yrs.
$^{130}Te \rightarrow {}^{130}Xe$	Inghram and Reynolds(2) 1950	3.3×10^{21} yrs.
$^{130}Te \rightarrow {}^{130}Xe$	Kirsten, Gentner, Schaeffer(3) 1967 Kirsten, Schaeffer, Norton and Stoner(4) 1968	$10^{21.34 \pm 0.12}$ yrs.
$^{130}Te \rightarrow {}^{130}Xe$	Srinivasan, Alexander Manuel(5) 1972	$10^{21.38 \pm 0.10}$ yrs.
$^{128}Te \rightarrow {}^{128}Xe$ $^{130}Te \rightarrow {}^{130}Xe$	Takaoka & Ogata(6) 1966	$S = T_{1/2}(^{128}Te)/T_{1/2}(^{130}Te)$ $= 10^{1.2 \pm 0.6*}$
$^{128}Te \rightarrow {}^{128}Xe$	Hennecke, Manuel and Sabu(7) 1975	$S = 10.^{3.20 \pm 0.01}$
$^{82}Se \rightarrow {}^{82}Kr$	Srinivasan, Alexander Beaty, Sinclair and Manual(8) 1973	$T_{1/2}(^{82}Se = 2.76 \times 10^{20}$ yrs.

anomalies, it was possible to conclude that the ^{130}Xe excess was due unambiguously to the (ββ) decay of $^{130}Te \rightarrow {}^{130}Xe$.

Table 1 summarizes the half-life of ^{130}Te, ^{128}Te and ^{82}Se by geological methods. From the direct detection methods, no $(\beta\beta)_{0\nu}$ have been detected yet, but the lower limits of the half-lives were set as shown in Table 2. It can be seen that the limit of the non-neutrino lifetime $T^{0\nu}_{1/2}$ determined in direct detections are much higher than the lifetime observed in geological methods where $T_{1/2}(0\nu + 2\nu)$ were determined. It implies the double beta decay is dominated by the lepton conserving part of $(\beta\beta)^{2\nu}$ and the lepton-violating part of $(\beta\beta)^{0\nu}$ plays a rather insignificant part. If we designate η as the "lepton-non-conservation" parameter and use the experimental half-lives of ^{128}Te and ^{130}Te; Bryman and Picciotto[14] gave in their review paper a value of $\eta = (4.3 \pm 0.1) \times 10^{-5}$. From the above η value, one can also calculate the ratio of neutrinoless to total rates for ^{82}Se

$$R(^{82}Se) = \frac{(\beta\beta)_{0\nu}\ rate}{(\beta\beta)_{total}\ rate} = \frac{\eta^2 f_4}{\eta^2 f_4 + f_2} < 0.09\ ,$$

which is comparable to the experimental result

Table 2. Summary of Direct Detection Results on ($\beta\beta$) Decay

($\beta\beta$) decay	Authors	$T_{1/2}$ Yrs.
$^{48}Ca \xrightarrow[MeV]{4.27} {}^{48}Ti$	Bardin, Gollon, Ullman & Wu[(9)] 1967	$T^{0\nu}_{1/2} > 1.6 \times 10^{21}$ yrs. at 80% C.L. $T^{2\nu}_{1/2} > (3.5\pm0.9) \times 10^{19}$ yrs. Tentatively
$^{76}Ge \xrightarrow[MeV]{2.04} {}^{76}Se$	Fiorini, Pullia, Bestolini Capellani and Restelli[(11)] 1973	$T^{0\nu}_{1/2} > 5 \times 10^{21}$ yrs at 68% C.L.
$^{82}Se \xrightarrow[MeV]{3.00} {}^{82}Kr$	Cleveland, Leo, Wu, Kasday Rushton, Gollon and Ullman[(10)] (1975)	$T^{0\nu}_{1/2} > 3.1 \times 10^{21}$ yrs. at 68% C.L. $T^{2\nu}_{1/2} > 3 \times 10^{19}$ yrs at 68% C.L.
$^{82}Se \rightarrow {}^{82}Kr$	Moe and Lowenthal[(13)] (1979)	$T^{0\nu}_{1/2}$ See no events $T^{2\nu}_{1/2} = (1\pm0.4) \times 10^{19}$ yrs.

$$R(^{82}Se) < \frac{2.76 \times 10^{20}}{3.1 \times 10^{21}} < 0.09$$

reported by Cleveland et al.[10] in 1975.

From the latest direct detection method developed at Irvine, Moe and Lowenthal have succeeded in detecting the associated α-particles following β-decays of ^{214}Bi in the cloud chamber sensitive volume. This was indeed a great improvement in many respects. This enabled them to identify and eliminate nearly half of the ($2e^-$) events due to ^{214}Bi. They also reported detectable differences in the ($2e^-$) energy-sum spectra and the distributions of the ($2e^-$) opening angles between the ($2e^-$) from ^{214}Bi and the double beta ($\beta\beta$) from ^{82}Se. However, the $T^{2\nu}_{1/2}$ for ^{82}Se thus determined was nearly 20 to 30 times shorter than that from the geological method. Nevertheless, the total ($\beta\beta$) events observed were only 15.2 ± 4.6. The statistics are too fragile to regard the result as conclusive. Maybe it is time to rekindle the crucial question concerning the retention of noble gases in ore. Although several experimental investigations have shown that the diffusion and escaping of noble gases from ores were negligible, the early determinations might not have the degree of precision required now.

Theoretical calculations of the double beta decay half-lives are generally very difficult. For instance, in ^{48}Ca, because of large cancellation, the matrix element becomes very small. However, on the contrary, the half-life of ^{82}Se calculated by Haxton and Stephenson[15] recently gives a value far shorter than that obtained

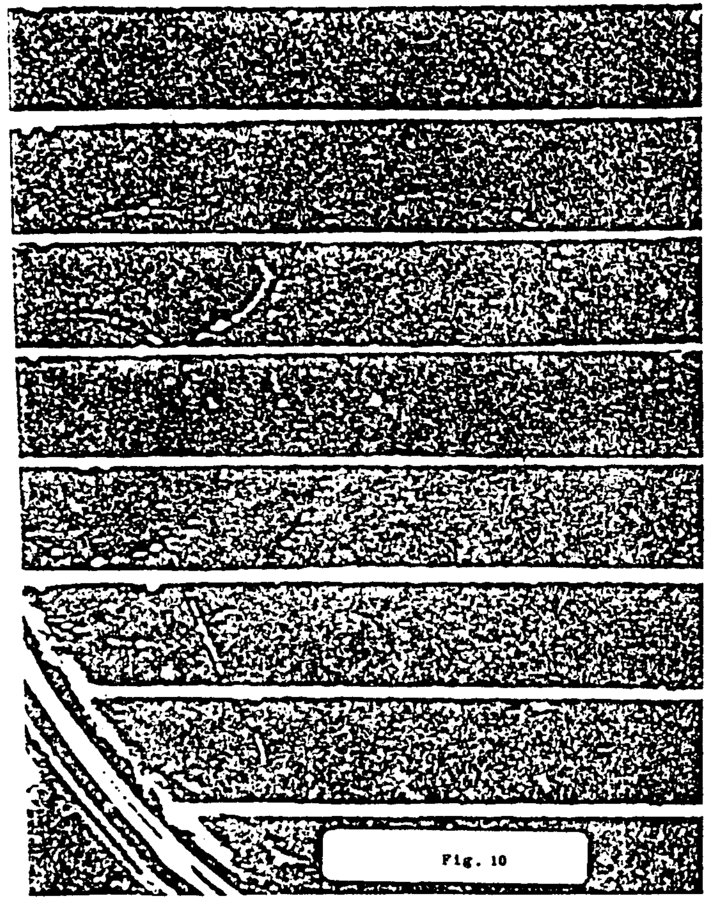

Fig. 10. A cloud chamber photograph of a negatron pair ($2e^-$) originating from one of the ^{82}Se source strips. The electrons pass through the strips quite freely.

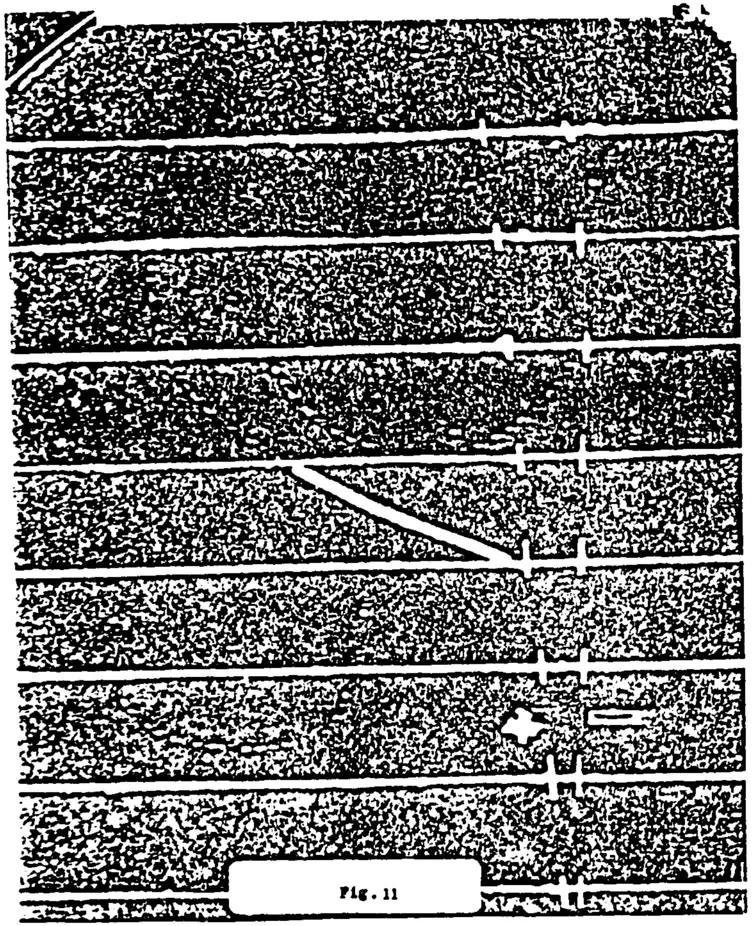

Fig. 11. A negative pair from ^{214}Bi contamination as revealed by an accompanying alpha particle $(2e^- + \alpha)$.

by the geological method. Therefore, it seems that the requirement of a definitive experiment is highly desirable. Moe and Lowenthal have started on, several years ago, a time projection chamber (TPC) to replace the cloud chamber at Irvine Laboratory. It is hoped that the new system will give much better detection efficiency, shorter dead time and much higher energy resolution so that the $(\beta\beta)_{2\nu}$ spectra of ^{82}Se will be observed and determined and the lower limit of $(\beta\beta)_{0\nu}$ decay will be estimated.

At the present moment, there is also great activity and enthusiasm among physicists in contemplating how to apply the newly developed "resonance-ionization-spectroscopy method"[16] or "counting the atoms"[17] to detect or count the rare daughter nuclei in the double beta decays or neutrino reactions. All kinds of possibilities, this novel and ultra-sensitive method will offer, which will far exceed our imagination and expectations.

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