# Rare decays of cadmium and tellurium

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We report on the pulse height spectrum observed with a CdTe detector in a low-background shield. The spectrum is dominated by the $T_{1/2} \sim 10^{16}$ yr $\beta^-$ decay of $^{113}$Cd. Limits are set on the double beta decay of the isotopes $^{106,114,116}$Cd and $^{128,130}$Te, and the prospects for a more sensitive search for this mode of decay are discussed.

## I. INTRODUCTION

Of the total of 17 naturally occurring isotopes of Cd and Te, seven are unstable against decays which have half-lives longer than $10^{13}$ yr. Table I summarizes the known properties of these decays, the most interesting of which is double beta ($\beta\beta$) decay. If observed in its "neutrinoless" mode, $\beta\beta$ decay would signal the violation of lepton number conservation and the existence of massive Majorana neutrinos; clear evidence of new physics beyond the standard model. The signature of the neutrinoless decay is a mono-energetic peak in the pulse-height spectrum, corresponding to two electrons emitted with a total energy equal to the Q value of the decay.

Among the most sensitive searches for this process[9] are those in which the detector is also the source, since in experiments of this type the efficiency for detecting the electrons is close to unity and energy measurement is not hindered by losses in the source. The $\beta\beta$ decay of $^{76}$Ge, using high resolution Ge spectrometers, has so far produced the most stringent limits on the half-life of neutrinoless $\beta\beta$ decay,[10] $T_{1/2} > 5 \times 10^{23}$ yr (90% confidence level).

CdTe, a room-temperature semiconductor from which high resolution devices can be constructed, provides an ideal laboratory to study rare decays of Cd and Te isotopes, especially the $\beta\beta$ decay of $^{116}$Cd and $^{130}$Te whose Q values of 2802 and 2533 keV, respectively, are sufficiently high to be in a region of low background. The relatively large Q values also increase the phase space available for the decay, thereby enhancing the decay rate.

In order to extract limits on the neutrino mass from the experimentally measured half-life limits, knowledge of the nuclear matrix elements relating to the decay are required. Recent calculations[11–13] indicate that the $\beta\beta$ decay of $^{116}$Cd and $^{130}$Te may proceed as much as factors of 5–60 times faster than the $^{76}$Ge decay, and so an experiment to probe half-lives longer than $10^{22}$ yr for these decays can be used to conduct a sensitive search for neutrino mass in the range less than 10 eV. Tellurium, in particular, is an interesting candidate as it is one of only two elements for which compelling evidence for double beta decay has been found[8] in geochemical experiments. Since experiments of this type are sensitive to the sum of the second order weak decay allowed in the standard model (the "two-neutrino mode") and the neutrinoless mode, laboratory experiments can provide information regarding the relative contributions of the two processes.

In this paper we report on the pulse height spectrum obtained from a 0.27 cm$^3$ CdTe detector well shielded from external gamma-ray sources and charged cosmic-ray particles. The results are analyzed to set limits on the $\beta\beta$ decay of $^{106}$Cd, $^{114}$Cd, $^{116}$Cd, $^{128}$Te and $^{130}$Te, and to obtain parameters for the $^{113}$Cd $\beta^-$ decay.

## II. EXPERIMENTAL DETAILS

The detector used in the study was supplied by R.M.D. Inc.[14] It was a standard spectrometer grade device, manufactured from a 16 mm diameter CdTe wafer 2 mm thick, with an active area of 1.33 cm$^2$. The typical response of the detector to photons is shown in Fig. 1. Although CdTe has a high average $Z$ (50) and therefore a large cross section for gamma-ray absorption, the 662 keV full-energy peak is small relative to the Compton continuum, owing to the small size of the device. The energy resolution is limited by two contributions, the dominant one being due the small hole mobility and short hole lifetime[15] in CdTe. A smaller contribution ($\sim 11$ keV FWHM in our case) is from electronic noise which arises from the leakage current of the device. The sum of both contributions produces a peak broadening of $\sim 50$ keV FWHM which is essentially independent of energy.

The CdTe wafer was mounted in a holder manufactured from oxygen-free high-conductivity copper (OFHC) and Delrin, materials known to have low levels of radioactivity. Electrical contact to the detector was made by OFHC copper pressure contacts. The detector was installed in a sub-basement room at Caltech, where about 1 m of concrete (3 meters of water equivalent) overburden provided some shielding from cosmic-ray primaries. The detector shield consisted of a 19 x 19 x 19 cm$^3$ cube of OFHC copper, surrounded by 15 cm of lead in all directions. Charged cosmic-ray particles were vetoed by 12 0.64 cm plastic scintillator paddles which surrounded the shielding. Each time a pulse was received from the plastic scintillators, the ADC was turned off for 20 $\mu$s. The effect of the veto paddles was to reduce the cosmic-ray contribution by a factor of 150.

Pulses from the CdTe detector were amplified and fed to a LeCroy 3500-based data acquisition system, where they were digitized into 4096 channels. Every 1800 s, the

 

TABLE I. Properties of naturally occurring but unstable isotopes of Cd and Te.

| Isotope | Decay mode | $T_0$ (keV) | Abundance (%) | Half-life[h] (yr) Previous work | Half-life[h] (yr) This work |
|---|---|---|---|---|---|
| $^{106}$Cd | $\beta^+\beta^+$ | 734±8 | 1.25 | $>6\times10^{16}$ [a] | $>5\times10^{17}$ |
| $^{113}$Cd | $\beta^-$ | 316±4 | 12.2 | $(9.3\pm1.9)\times10^{15}$ [b] | $(4-12)\times10^{15}$ |
| $^{114}$Cd | $\beta^-\beta^-$ | 534±4 | 28.7 | $>5\times10^{15}$ [c] | $>7\times10^{18}$ |
| $^{116}$Cd | $\beta^-\beta^-$ | 2802±4 | 7.5 | $>1\times10^{17}$ [a,d] | $>5.3\times10^{17}$ |
| $^{123}$Te | EC(K) | 51.3±2.1 | 0.89 | $>10^{15}$ [e] <br> $(1.2\pm0.1)\times10^{13}$ [f] | |
| $^{128}$Te | $\beta^-\beta^-$ | 868±4 | 31.7 | $>2\times10^{15}$ [c,i] | $>1.3\times10^{19}$ |
| $^{130}$Te | $\beta^-\beta^-$ | 2533±4 | 34.5 | $>1.2\times10^{21}$ [g,i] <br> $>1.0\times10^{19}$ [j] | $>2.8\times10^{18}$ |

[a] Ref. 1.
[b] Ref. 2.
[c] Ref. 3.
[d] Ref. 4.
[e] Ref. 5.
[f] Ref. 6.
[g] Ref. 7.
[h] Values quoted for $\beta\beta$ decay are limits for the neutrinoless mode from counter experiments.
[i] Limits of $8\times10^{24}$ yr and $2.6\times10^{21}$ yr for $^{128}$Te and $^{130}$Te, respectively, can be inferred from the geochemical measurements of Ref. 8.
[j] Our reanalysis of the data from Ref. 7 (see text).

data were written onto disc as a safeguard against time dependent problems with the system. Dead time was measured by feeding a pulser into the preamplifier as well as into a scaler which accurately accounted for both computer and veto induced dead time. The pulser was also used to measure variations in the gain, which were insignificant over the course of the experiment. $^{241}$Am, $^{133}$Ba, $^{109}$Cd, $^{137}$Cs and $^{22}$Na gamma-ray sources were used for energy calibration before and after the runs.

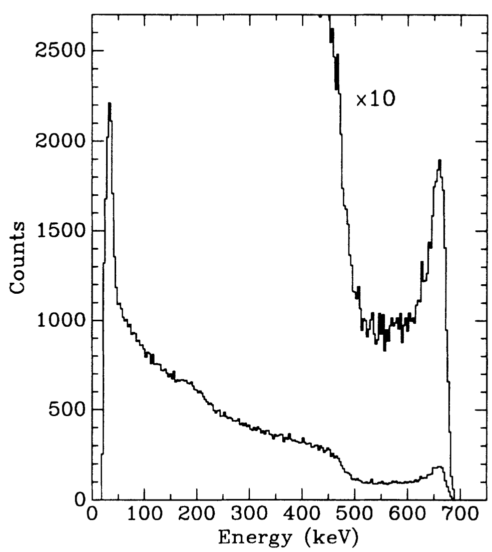


FIG. 1. Response of the CdTe detector to photons from a $^{137}$Cs source incident on the grounded side of the detector. Most of the width of the 662 keV full-energy peak is from the depth dependent pulse height: the 33 keV Ba x ray is absorbed in a thin layer of the detector, and so is narrower. For photons incident from the positive electrode side, the x-ray peak is smeared into the noise because of hole trapping, but the spectrum is otherwise unchanged.

## III. RESULTS

The spectrum from the CdTe detector, with and without cosmic-ray veto, is shown in Fig. 2. Since the detector was oriented with its face horizontal, a typical minimum-ionizing particle traversing the 2 mm thick detector deposits about 1 MeV, and this is the origin of

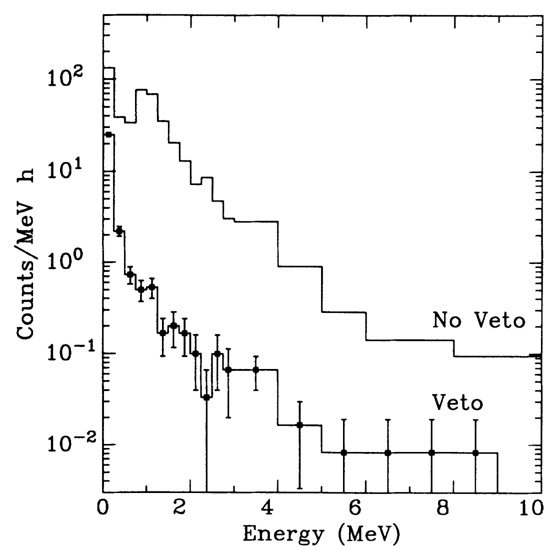


FIG. 2. Typical pulse height spectra from the CdTe detector with and without cosmic-ray veto. Below 3 MeV, the data are binned in 250 keV bins, above 3 MeV bin size is 1 MeV. Error bars on the veto spectrum reflect statistical uncertainties.

the broad peak at 1 MeV in the no-veto spectrum. The rise in counts at low energies is in part due to particles traversing the dead area of the detector, and the subsequent poor charge collection from these events.

Twenty-four events were recorded in the interval between 2.0 and 3.0 MeV in a total of 433 hours of live time. The regions in which the $^{116}$Cd and $^{130}$Te $\beta\beta$ decay events would appear each contain 1 count, entirely consistent with the average background level of $0.06\pm0.01$ counts/MeV h in the 2–3 MeV interval. Before a limit on the $\beta\beta$ half-life can be established, the detection efficiency for an event must be ascertained.

The efficiency for containing the two electrons from a neutrinoless $\beta\beta$ decay event in the CdTe crystal was calculated using a standard Monte Carlo package [GEANT 3.10 (Ref. 16)]. In the Monte Carlo, two electrons were generated at random locations in the crystal, with their opening angles and energy distributions chosen by sampling the appropriate distributions. Each electron was then tracked in small steps until all its energy was deposited or it left the crystal. The total energy deposited by the two electrons was then summed and binned into a histogram. The efficiency for detecting all the energy for $^{116}$Cd and $^{130}$Te decays was found to be 18% and 22%, respectively. With these efficiencies, we are able to set limits on the $^{116}$Cd and $^{130}$Te half-lives of $T_{1/2}(0\nu) > 5.3\times10^{17}$ yr and $2.8\times10^{18}$ yr, respectively, at the 90% confidence level.

Similar analyses of the $^{114}$Cd and $^{128}$Te decays yield half-life limits of $T_{1/2}(0\nu) > 7\times10^{18}$ yr and $1.3\times10^{19}$ yr, respectively. For the double positron decay of $^{106}$Cd, the efficiency for not collecting any energy from the annihilation gamma rays was included in the total efficiency estimate, and a half-life limit of $T_{1/2}(0\nu) > 5\times10^{17}$ yr (90% confidence level) was obtained.

The spectrum of events below 500 keV is shown in Fig. 3. The increase in counts below 320 keV can be attributed to the fourth-forbidden $\beta^-$ decay of $^{113}$Cd, whose half-life has been measured[2] to be $(9.3\pm1.9)\times10^{15}$ yr by comparison of the counting rates from a natural and enriched $^{113}$Cd sample. No spectral information on this decay has been reported previously. The shape of the measured spectrum differs slightly from the real shape because some events will not be fully contained in the active region of the detector, thereby lowering their pulse height. This effect is small (even at the endpoint of the decay, our Monte Carlo simulation indicates that only 5% of events lose more than 20% of their energy) and so we have not attempted to correct for this in Fig. 3. The endpoint of the decay, $320\pm10$ keV, is in good agreement with the value[17] of $316\pm4$ keV from atomic mass differences.

The count rate between 30 and 325 keV in our spectrum is $7.5\pm0.3$ counts/h. If all of these events are attributed to $^{113}$Cd decay, we deduce a half-life of $(5.3\pm0.2)\times10^{15}$ yr, somewhat shorter than the previously published value. However, since we are unable to remove the source of the radiation to get a measure of background in this region, this value must be seen as a lower limit to the half-life. With a very conservative estimate of the background we obtain $T_{1/2}=(4-12)\times10^{15}$ yr, in good agreement with Ref. 2.

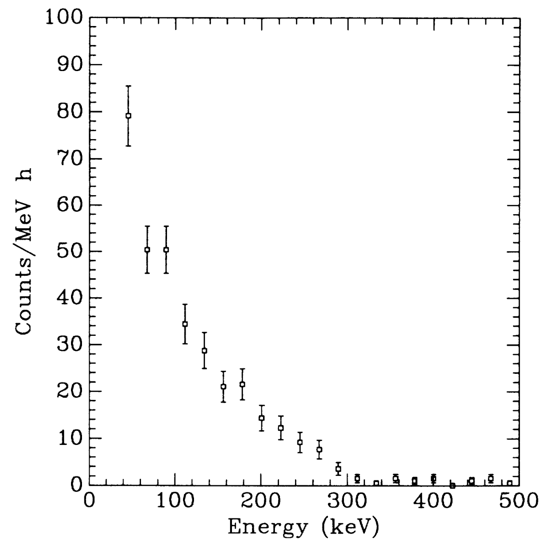


FIG. 3. Low-energy spectrum from the CdTe detector, representing 87.4 h live time. The increase in counts below 320 keV is attributable to the $T_{1/2}\sim10^{16}$ yr $\beta^-$ decay of $^{113}$Cd. Bin size is 22.2 keV.

There is considerable disagreement in the literature regarding the half-life of $^{123}$Te against $K$ electron capture.[5,6] The signature of the electron capture (EC) decay is the Sb atomic x ray which accompanies the capture. Unfortunately, this could not be observed unambiguously in the present experiment as its energy is very near our noise threshold. Although the lower level discriminator corresponded to $\lesssim 30$ keV for events depositing energy near the negative contact, hole trapping was sufficient to reduce the pulse height of similar events elsewhere in the detector below the noise level. Another experiment tailored to search for this decay would be feasible, as we note that the reported half-life[6] of $(1.25\pm0.1)\times10^{13}$ yr would produce $\sim250$ decays per hour in our detector, and the potential sensitivity is sufficient to go beyond the limit of $10^{15}$ yr from Ref. 5.

## IV. DISCUSSION

The $\beta\beta$ decay half-life limits from the present work represent substantial improvement over previous laboratory measurements, except possibly in the case of $^{130}$Te. We would like to point out here that we have difficulty reconciling the experimental parameters quoted by Zdesenko[7] with the half-life limit of $1.2\times10^{21}$ yr which he derives for $^{130}$Te. In particular, the energy resolution of the scintillator does not seem to be properly taken into account. Our analysis of his data, assuming energy resolution of 20% FWHM, yields a half-life limit of $1.0\times10^{19}$ yr, more than two orders of magnitude shorter than the published value. (When comparing the present results to previous limits, it should also be noted that we quote 90% confidence level, whereas no confidence level is assigned to most earlier measurements.)

Our present limits are, however, still several orders of magnitude from those required to probe neutrino masses of order of a few eV. Although limits from geochemical experiments are much more stringent for the Te isotopes, longer half-lives for neutrinoless $\beta\beta$ decay cannot be investigated by this technique, because of its inability to distinguish between the allowed two-neutrino mode and the neutrinoless mode. If we are to construct a competitive $\beta\beta$ decay experiment using CdTe, we need to consider the three parameters which determine the sensitivity of the search, namely radioactive backgrounds, energy resolution and detector size.

The absence of evidence of U or Th $\alpha$ or $\beta$ decay in the present experiment indicates that the intrinsic radioactivity in the CdTe wafer is low, and is dominated by the decay of $^{113}$Cd. The fact that the spectrum with the cosmic-ray veto retains similar features to the no-veto spectrum may indicate that the veto is not 100% efficient, and that substantial improvement might be expected if the detector were taken underground. Whether intrinsic radioactive backgrounds would limit the sensitivity of a $\beta\beta$ decay search using a large detector cannot be determined from the small device studied here.

In the presence of background, the sensitivity of a $\beta\beta$ decay experiment is inversely proportional to the energy resolution. Although the device studied here is considered spectroscopy grade, its resolution of $\sim 2\%$ at 2.5 MeV is still significantly poorer than that of a Ge detector ($\sim 0.1\%$). There are however several prospects for improving the resolution of CdTe devices. The dominant contribution to the energy resolution stems from the very different velocities of the holes and the electrons and the short hole lifetime in CdTe. Thus an event which deposits its energy near the positive electrode has a different pulse shape, and pulse height, than one depositing near the negative electrode. Significant improvements to the resolution can be made by rejecting pulses which have a long rise time (corresponding to the arrival of the hole signal), however the large dead time introduced by such a procedure is unwelcome in a $\beta\beta$ experiment. An alternate approach is to process the pulses so as to separate the hole and electron signals, and then recombine them—by either analogue or digital means—to get the energy signal. A correction for hole trapping can be made by using the ratio of the electron signal to the hole signal to determine an average interaction depth for each event. Such an approach[18] has been shown to improve the energy resolution of $HgI_2$ detectors, which have very similar properties to CdTe devices, by as much as a factor of 2.5, with no appreciable increase in dead time. An even more exciting development is the advent of high-voltage positive-intrinsic-negative ($p$-$i$-$n$) CdTe detectors.[19] These devices have shown energy resolution of 1.5% at 662 keV,[19,20] an improvement of a factor of $\sim 5$ over spectrometer grade low-voltage devices due to the increased mobility of the electrons and the holes at high fields.

Given adequately small backgrounds and good energy resolution, the major limiting factor in a $\beta\beta$ decay experiment is the number of candidate atoms available for study. To probe neutrino masses of the order of a few eV, half-lives of about $5\times10^{22}$ yr or longer need to be studied and so at least $10^{23}$ atoms of the candidate isotope are required if several events per year are to be detected. For CdTe, a detector of at least 100 cm$^3$ would be desirable. Although the fabrication of CdTe devices of greater than $\sim 5$ cm$^3$ seems beyond the present state of the art, our Monte Carlo simulation suggests that a 100 cm$^3$ detector segmented into 20 or more separate detectors would offer a substantial reduction of gamma-ray-induced backgrounds. This improvement arises from the high probability of multiple Compton scattering of high energy photons in the array, whereas a $\beta\beta$ decay event would fire one or two (adjacent) detectors only. Such an array would also, unlike the small detector studied here, have a $\beta\beta$ efficiency close to unity.

As our next step towards a competitive $\beta\beta$ decay experiment, we are planning the construction of a CdTe array of several cm$^3$ which would allow us to investigate longer half-lives for $\beta\beta$ decay, and to assess better the prospects for an array of $\sim 100$ cm$^3$.

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