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March 1987

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LBL-21834 c.2

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

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New Limits on the Double Beta Decay Half-Lives of ^{94}Zr, ^{96}Zr, ^{116}Cd, and ^{124}Sn

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Abstract

Searches have been made for the double beta decays of $^{94,96}Zr$, ^{116}Cd, and ^{124}Sn to excited states in their daughter nuclei. No evidence of any of these decays was found, and lower limits on the half lives against such decays have been established to be $10^{18} - 10^{19}$ years. In addition, the single beta decay half-life of ^{96}Zr has been established to be $\geq 1.7 \times 10^{18}$ years.

Much of the current interest in the subject of double beta decay stems from its relevance to the questions of lepton number conservation and of the mass of the neutrino. Neutrinoless double beta decay can result from a finite neutrino mass and/or from the presence of right-handed weak currents. The principal transitions expected from the neutrino mass term are $J^{\pi} = 0^{+} \rightarrow J^{\pi} = 0^{+}$ decays. However, right-handed currents can lead to $J^{\pi} = 0^{+} \rightarrow J^{\pi} = 2^{+}$ and $J^{\pi} = 0^{+} \rightarrow J^{\pi} = 0^{+}$ decays with comparable strengths. Thus, searches for this type of decay are important for a complete understanding of the double beta decay process.

For a number of nuclei, double beta decays to excited states in their daughter nuclei are energetically possible. A signature of this type of double beta decay would be the emission of a gamma ray from the nucleus (Z+2,N-2) in a sample of the nucleus (Z,N). Previous searches for double beta decay to excited states have been limited to a few nuclei.[2,3,4] We have chosen ^{94}Zr, ^{96}Zr ^{116}Cd, and ^{124}Sn for the present study. The possible decay schemes of these nuclei are shown in fig. 1. All energies, spins, and parities used in the present work are taken from ref. 5. For each of these nuclei, double beta decay to one or more excited states in the respective daughter nucleus is possible. In addition, for ^{96}Zr single beta decay to ^{96}Nb is also energetically allowed.

To detect the gamma-ray signature of double beta decay to an excited state, a 110-cm^3 coaxial high-purity germanium detector was used. In order to maximize the amount of material that could be counted with high efficiency, each sample was distributed around the detector. Several 5-cm x 5-cm plates stacked to yield approximately 1-cm total thickness were mounted directly against the front face of the detector. The rest of each sample, in the form of thin sheets, was wrapped around the cylindrical outer can of the detector to produce a total thickness of up to 0.5 cm. This assembly was shielded on all sides with 10 - 15

cm of low-activity lead. The experimental apparatus was located in the Low Background Counting Facility at Lawrence Berkeley Laboratory. In order to minimize background radiation, this facility was constructed with 1.3 - 1.6 meter thick walls of low activity concrete and has an air flow of 10 room volumes/hour. All of the samples studied were natural isotopic composition metals of at least 99% purity obtained from Alpha Products. The masses and counting periods for all of the samples are listed in table 1. Energy and efficiency calibrations were performed in the experimental geometry using standard calibrated sources. Data were accumulated in 1024 channels using a multichannel analyzer and were recorded for off-line analysis.

For ^{94}Zr, the only excited state that can be reached via double beta decay is the $J^{\pi} = 2^{+}$ level at 871 keV in ^{94}Mo. For ^{96}Zr, several levels could be populated in double beta decay. However, they all decay with large branching ratios to the $J^{\pi} = 2^{+}$ level at 778 keV in ^{96}Mo. Consequently, a search for this gamma ray alone can be used to establish limits on the double beta decay rates to all of these states. Similarly, for ^{116}Cd and ^{124}Sn, searches for the 1294-keV and 603-keV gamma rays, respectively, can be used to set limits on all of the possible double beta decay modes.

The relevant portions of the spectra observed from the zirconium, cadmium, and tin samples are shown in fig. 2. In all of these spectra, the only gamma-ray lines observed are due to the decays of long-lived isotopes such as ^{232}Th, ^{235}U, and ^{238}U contained in the shielding material and/or in the detector itself. The expected positions and widths of the various lines from double beta decays were determined from those of known lines that appear in the spectra. The number of counts observed in each such window was determined. In each spectrum, background windows containing the same number of channels as the peak window

were chosen above and below each peak. Using a linear fit to the background, the net number of counts in each peak window was determined. No excess of counts above background was observed at any of the expected peak positions. Taking the measured 1-sigma uncertainties as upper limits on the numbers of counts in each peak, we established 68% confidence level lower limits on the applicable double beta decay half-lives of ^{94}Zr, ^{96}Zr, ^{116}Cd, and ^{124}Sn. These results are summarized in table 2.

The results obtained in the present study can be compared to theoretical estimates of neutrinoless double beta decay half lives. The quantity $t_{1/2}\eta^2$ calculated using the formula of Rosen and Primakoff[6] is listed in table 2 for several transitions. From our experimental results, one can set a limit on the lepton number non-conserving probability η^2 of ≤ 0.027. While we are not aware of any previous searches for the double beta decays of ^{94}Zr, ^{96}Zr, ^{116}Cd, or ^{124}Sn to excited states, searches have been made for neutrinoless ground-state $\rightarrow$ ground-state double beta decays of these nuclei. Zdesenko et al.[7] have established that for this mode the half life of ^{96}Zr is $\geq 3 \times 10^{19}$ years. Winter[8] showed that the half life of ^{116}Cd against this type of decay is $\geq 1 \times 10^{17}$ years, and McCarthy[9] set a limit on the corresponding half life of ^{124}Sn of $\geq 1.5 \times 10^{17}$ years.

The results obtained from the zirconium sample can also be used to establish a limit on the single beta decay half-life of ^{96}Zr. The product of this type of decay is ^{96}Nb which decays with a 23.4-hour half-life to excited states in ^{96}Mo that cascade through the $J^{\pi} = 2^{+}$ level at 778 keV. Thus the absence of this peak in our spectrum allows us to establish that the single beta decay half life of ^{96}Zr is $\geq 1.7 \times 10^{18}$ years. This is approximately a factor of five greater than the limit established by Eichler et al.[10] Assuming that the principal single beta decay

mode of ^{96}Zr is the fourth-forbidden transition to the $J^{\pi} = 4^{+}$ level at 142-keV excitation energy in ^{96}Nb, we find that the log ft for this decay is ≥ 22.3 .

We wish to thank A. R. Smith for his assistance in the use of the Low Background Counting Facility. We also thank K. T. Lesko for assistance with some of the data analysis and for his comments regarding the manuscript. One of us (DMM) wishes to thank the Monticello Foundation for support during her visit to LBL. This work is supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U. S. Department of Energy under Contract No. DE-AC03-76SF00098.

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Figure Captions

Fig. 1. Possible decay schemes of (a) ^{94}Zr, (b) ^{96}Zr, (c) ^{116}Cd, and (d) ^{124}Sn.

Fig. 2. Relevant portions of the gamma spectra observed in counting (a) 912 hours with the zirconium sample, (b) 668 hours with the cadmium sample, and (c) 666 hours with the tin sample. Peaks labeled only by energy are due to long-lived background activities (such as thorium and uranium) contained in the shielding material and/or in the detector itself.

Table 1. Samples examined in the present study.

Element	Mass (grams)	Isotopic Abundance	Counting Period (hours)
Zirconium	646	(^{94}Zr) = 17.4% (^{96}Zr) = 2.80%	1565
Cadmium	690	(^{116}Cd) = 7.5%	668
Tin	647	(^{124}Sn) = 5.64%	666

Table 2. Lower limits on the half lives of ^{94}Zr, ^{96}Zr, ^{116}Cd, and ^{124}Sn established in the present study compared with theoretical estimates.

Decay	Final State J^{π}, E_x (keV)	$t_{\frac{1}{2}}$ (years) (Expt.)	$t_{\frac{1}{2}}\eta$ (years) (Theor.)
$^{94}Zr \rightarrow {}^{94}Mo$	2^+, 871	1.3×10^{19}	1.2×10^{22}
$^{96}Zr \rightarrow {}^{96}Mo$	2^+, 778	2.0×10^{18}	5.3×10^{16}
	0^+, 1148	1.8×10^{18}	
	2^+, 1498	1.3×10^{18}	
	2^+, 1626	1.7×10^{18}	
	4^+, 1628	1.8×10^{18}	
$^{116}Cd \rightarrow {}^{116}Sn$	2^+, 1294	2.7×10^{18}	4.0×10^{17}
	0^+, 1757	2.4×10^{18}	
	0^+, 2027	2.5×10^{18}	
	2^+, 2112	1.0×10^{18}	
	2^+, 2225	1.6×10^{18}	
$^{124}Sn \rightarrow {}^{124}Te$	2^+, 603	2.4×10^{18}	2.2×10^{17}
	2^+, 1325	2.0×10^{18}	
	(0^+), 1656	2.2×10^{18}	

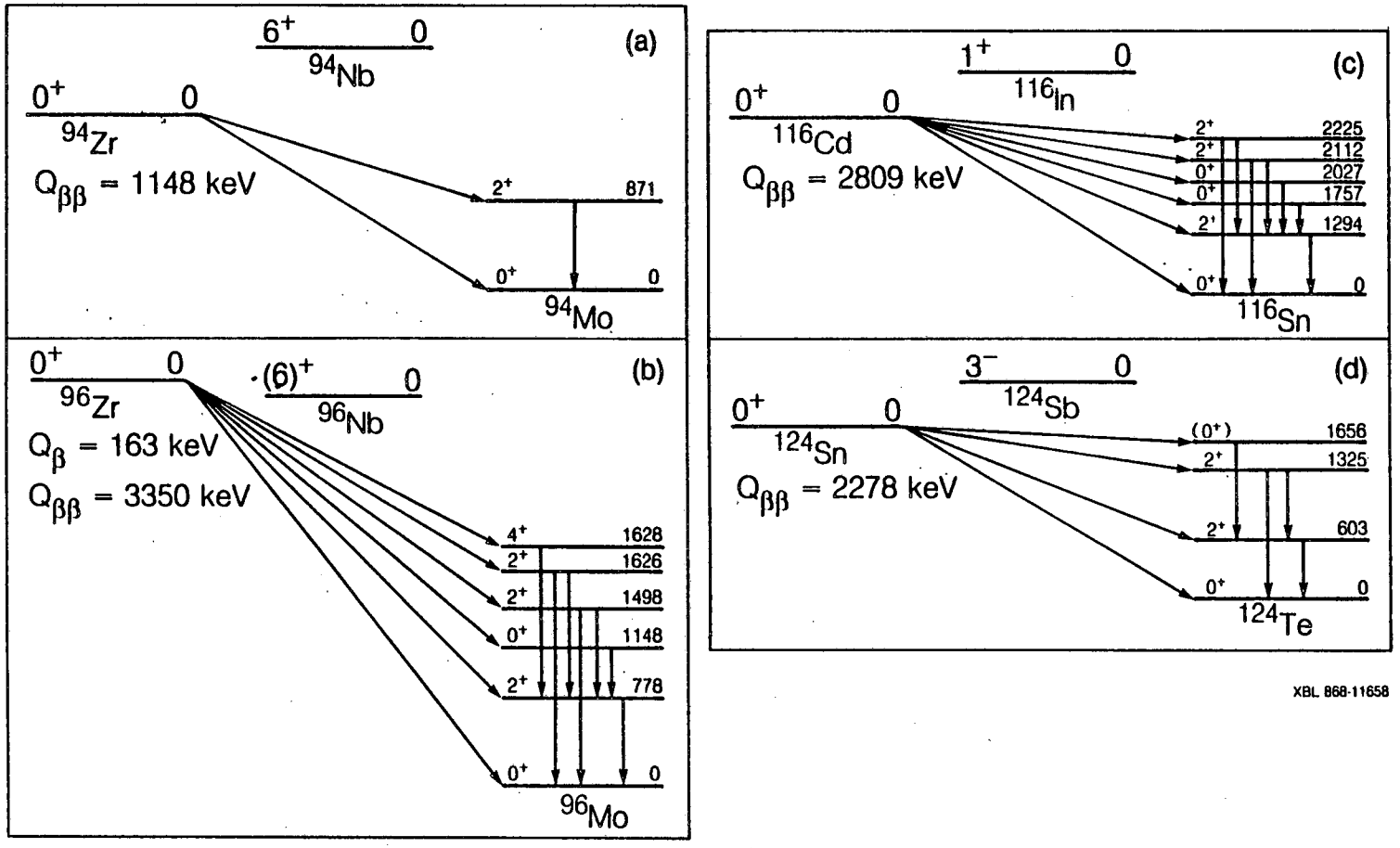
(a)
6+ 0
94Nb
0+ 0
94Zr
Qββ = 1148 keV
2+ 871
0+ 0
94Mo
(b)
0+ 0
96Zr
(6)+ 0
96Nb
Qβ = 163 keV
Qββ = 3350 keV
4+ 1628
2+ 1626
2+ 1498
0+ 1148
2+ 778
0+ 0
96Mo
(c)
1+ 0
116In
0+ 0
116Cd
Qββ = 2809 keV
2+ 2225
2+ 2112
0+ 2027
0+ 1757
2+ 1294
0+ 0
116Sn
(d)
3− 0
124Sb
0+ 0
124Sn
Qββ = 2278 keV
(0+) 1656
2+ 1325
2+ 603
0+ 0
124Te
XBL 868-11658

Fig. 1

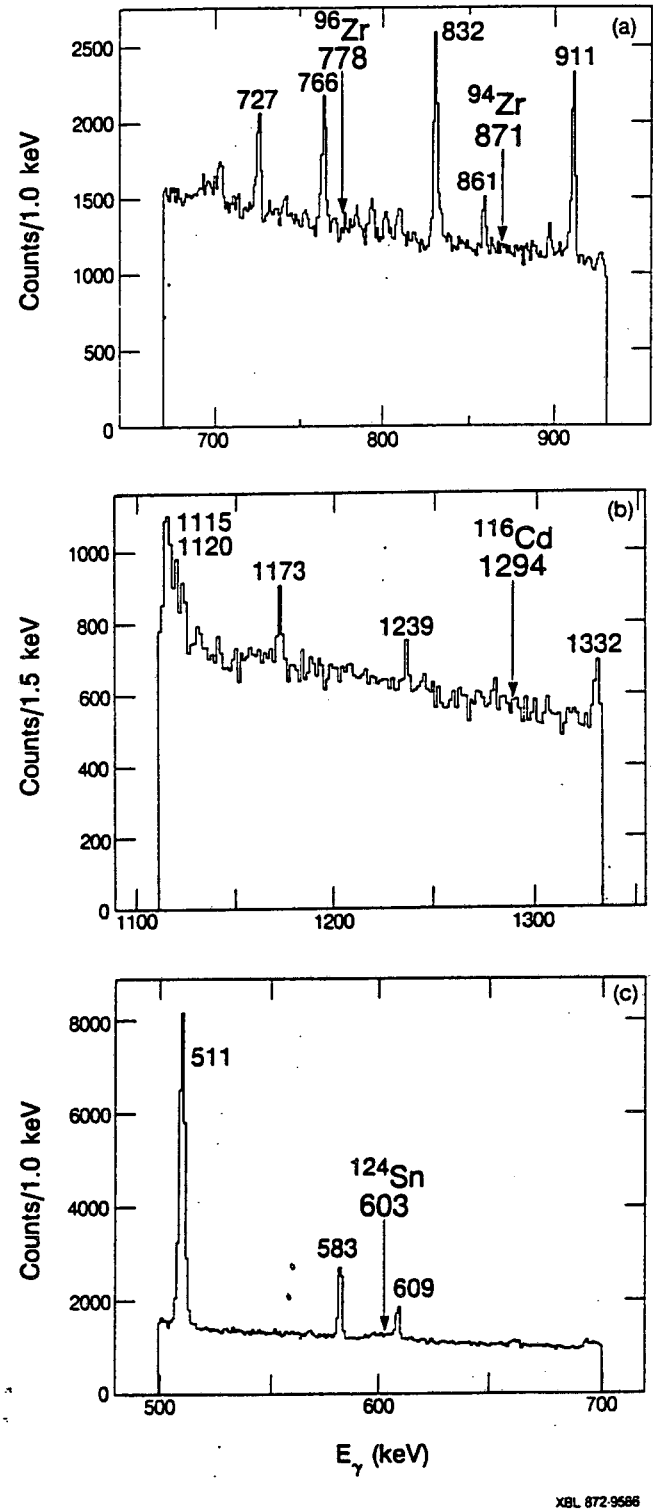
(a)
Counts/1.0 keV
96Zr
778
766
727
832
911
94Zr
871
861
(b)
Counts/1.5 keV
1115
1120
1173
116Cd
1294
1239
1332
(c)
Counts/1.0 keV
511
124Sn
603
583
609
Eγ (keV)
XBL 872-9586

Fig. 2

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

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