Cross sections for neutron interactions in the CUORE neutrinoless double beta decay experiment

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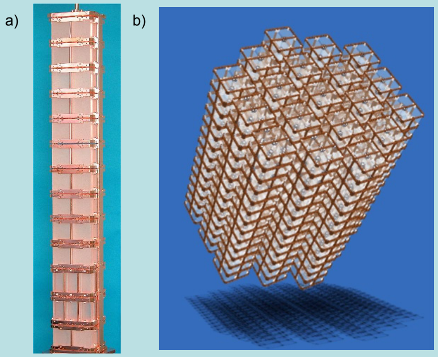

Figure 1. a) The Cuoricino detector is a tower of 62 TeO_2 crystals. It contains 11.64 kg ^{130}Te, and it has been taking data since 2003. b) The CUORE detector will consist of 19 Cuoricino-like towers, with a total ^{130}Te mass of 200 kg.

The search for neutrinoless double beta decay is currently the only practical experimental method to probe the quantum nature of the neutrino. The observation of neutrinoless double beta decay would prove that neutrinos are Majorana particles (i.e. their own antiparticles) and give information on the absolute neutrino mass scale. CUORE (Cryogenic Underground Observatory for Rare Events) is a next generation double beta decay experiment that will search the inverse neutrino mass hierarchy for the decay of ^{130}Te using unenriched TeO_2 bolometers [C. Arnaboldi, et. al., arXiv:hep-ex/0302021 (2003)]. Cuoricino (Italian for "little CUORE") is both an independent double beta decay experiment and a proof of principle for CUORE. See Figure 1.

The physics goal of CUORE is to explore the inverse neutrino mass hierarchy (See Figure 2). The sensitivity of CUORE to neutrino mass is given in Table I for different background levels, where the spread in detectable Majorana mass is caused by differences in calculations of nuclear matrix elements.

Table I. Background and sensitivity for the CUORE detector.

Rate (cts/keV/kg/yr)	$t_{1/2}$ (10^{26} y)	$<m_{\beta\beta}>$ (eV)
0.01	2.1	0.019 - 0.100
0.001 (Optimistic)	6.5	0.011 - 0.057

CUORE Collaboration, http://crio.mib.infn.it/wig/

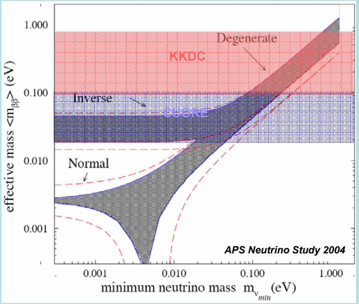

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Figure 2. A plot of the effective Majorana neutrino mass as a function of the minimum neutrino mass. Indicated are the KKDC claim region and the projected sensitivity of CUORE.

The most important backgrounds for $0\nu\beta\beta$ are lines in the region of the $0\nu\beta\beta$ peak, which lies at the Q-value of the reaction. Such lines can mimic the $0\nu\beta\beta$ signal. For ^{130}Te, $Q_{\beta\beta}$ equals 2530.30 ± 1.99 keV [G. Audi, A.H. Wapstra and C. Thibault,*Nuclear Physics A* 729 (2003)].

Recent measurements at the University of Kentucky have shown γ-ray peaks from inelastic scattering of neutrons in the $0\nu\beta\beta$ region in two stable isotopes of Te. A γ-ray signal at 2530 keV was observed in ^{122}Te, which occurs with 2.60% natural isotopic abundance [Hicks et. al., *Phys Rev C* 71, 034307 (2005)]. In another experiment, a peak was observed at 2528 keV in ^{126}Te, with 18.95% isotopic abundance (See Table III). These reactions could create a false $0\nu\beta\beta$ signal in CUORE. In order to accurately account for this possibility, we must know the relevant cross sections.

Table III: Levels in ^{126}Te

J^{π}	E_x (keV)	E_{γ} (keV)	E_f (keV)	BR %
1^+	3132.31(9)	1711.60(6)	1420	45(10)
		3132.90(6)	0	55(10)
2^+	3143.65(7)	2477.57(5)	666	76(4)
		3143.40(13)	0	24(2)
3^+	3166.80(9)	1747.53(5)	1420	48.4(53)
		1804.62(5)	1361	37.1(67)
		2500.45(13)	666	15(17)
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	3201.91(9)	1781.83(6)	1420	57(18)
		2535.56(7)	666	43(14)

Vanhoy et. al., Phys Rev C 69, 064323 (2004)

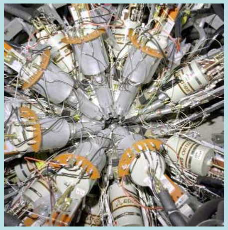


Figure 5. The GEANIE detector at LANSCE.

In order to improve simulations of the neutron-induced background in the CUORE detector, we will be measuring γ-ray production cross sections from neutron interactions on tellurium as a function of energy. These measurements will be carried out using the GEANIE detector at the Los Alamos Neutron Science Center (LANSCE).

The GEANIE detector is a spherical array of 26 Compton-suppressed high purity Ge detectors at the Weapons Neutron Research facility at LANSCE. The spallation neutron beam is generated by an 800 MeV pulsed proton beam incident on a tungsten target. Neutron energies are determined by time of flight down a 20 m beam path. The beam is monitored by two fission chambers upstream of the target. This detector configuration is capable of measuring neutron interaction cross sections as a function of energy for neutron energies up to ~100 MeV.

An 1.3 g, 99.4% isotopically enriched ^{130}Te target was run at GEANIE from January 9 - 20, 2004 [R. Nelson, et. al., ^{130}Te Proposal #2003580], and the analysis is currently in progress. A preliminary spectrum is discussed below (See Figures 6 and 7).

Figure 3. The CUORE experiment will be housed underground at the Gran Sasso National Laboratories in Italy. The underground facility consists of 3 experimental halls. CUORE will operate in Hall A, next to Cuoricino. There is also an R&D cryostat located in Hall C.

In order to reduce the cosmic ray background and backgrounds from cosmogenic radioactivity in detector components, CUORE will be located in Hall A of the Gran Sasso National Laboratories (LNGS), an underground laboratory in Assergi, Italy, with a 1500 m rock overburden (~3300 m.w.e.). See Figure 3. Cuoricino is currently operating and taking data in this location.

A recent paper by Mei and Hime questions whether the underground facility at LNGS is deep enough to provide the necessary shielding from cosmic ray muons and μ-induced neutrons for the next generation of Ge-type double beta decay experiments [D.-M. Mei and A. Hime, arXiv:astro-ph/0512125 (2005)]. Simulations were also carried out by the CUORE Collaboration for the CUORE detector geometry. Four sources of neutrons underground were considered:

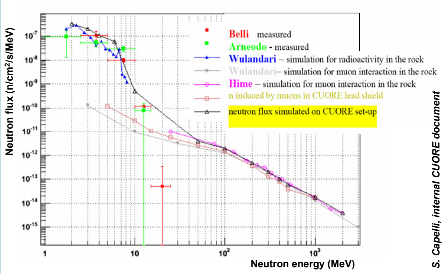
1) $E_n < 10$ MeV: (α,n) reactions from U and Th contamination and spontaneous fission of ^{238}U in rock, concrete

2) $E_n < 10$ MeV: (α,n) reactions from U and Th contamination and spontaneous fission of ^{238}U in detector materials

3) $E_n > 10$ MeV: μ–induced neutrons in rock

4) $E_n > 10$ MeV: μ–induced neutrons in Pb shields

Figure 4 summarizes both the measured and simulated data on the neutron flux at Gran Sasso, including the neutron energy spectrum used in the CUORE simulations (black curve). The results of these simulations, shown in Table II, indicate that the neutron background at Gran Sasso will not be a limiting background for CUORE. However, the parameters that go into these simulations must be tested.



S. Capelli, internal CUORE document

Figure 4. A compilation of data and simulations of the neutron energy spectrum underground at LNGS. The black curve represents the neutron flux as a function of energy used in Monte Carlo simulations of the neutron-induced background in CUORE.

Table II. Simulation of neutron backgrounds in the double beta decay region.

Source	E_n	Background (cts/keV/kg/yr)
Rock radioactivity	< 10 MeV	~ 10^{-4}
Detector radioactivity	< 10 MeV	negligible
μ–induced neutrons in rock	> 10 MeV	6×10^{-7}
μ–induced neutrons in Pb	> 10 MeV	2×10^{-4}

*These backgrounds will be further reduced by a neutron shield and an efficient muon veto, which have not yet been implemented in the simulation.

S. Capelli, internal CUORE doc.

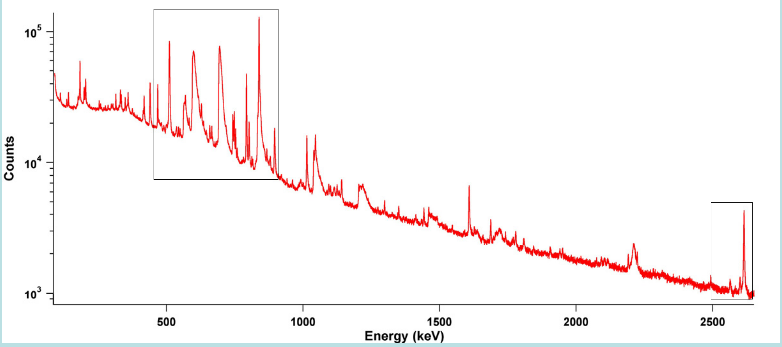


Figure 6. ^{130}Te spectrum at GEANIE. This spectrum is a sum over the 14 coaxial Ge detectors in GEANIE. This spectrum represents about half of the total data from the 2004 run. Visible lines include neutron interactions on ^{130}Te as well as traces of other Te isotopes in the target, neutron interactions with the Ge in the detectors, and room backgrounds. For more information on the boxed regions, see Figure 7.

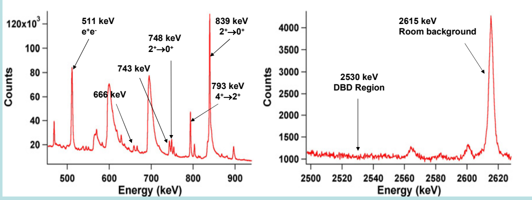


Figure 7. Zoomed regions in ^{130}Te spectrum at GEANIE. The spectrum on the left shows many of the excited state transitions in ^{130}Te, excited by inelastic scattering, $^{130}Te(n,n')^{130}Te$. These include the following transitions: first $2^+ \rightarrow 0^+$ (839 keV), second $2^+ \rightarrow 0^+$ (748 keV), and $4^+ \rightarrow 2^+$ (793 keV). This spectrum also includes first excited state transitions of ^{126}Te (666 keV) and ^{128}Te (743 keV), which are present in trace amounts in the enriched target, as well as the background at 511 keV from electron-positron annihilation. The spectrum on the right shows the region of interest for neutrinoless double beta decay. There is no visible peak. Also shown is the 2615 keV background from 208Tl decay.

Future Plans

Because the TeO_2 crystals used in CUORE will be grown using unenriched Te, the target for the next experiment will be a disc of unenriched tellurium metal. This experiment is planned for October. If necessary, we will also conduct experiments with enriched samples of ^{122}Te (2.60%), ^{126}Te (18.95%), and ^{128}Te (31.69%). The results of these experiments will be combined with Monte Carlo simulations and Cuoricino data to place an experimental limit on the flux of μ-induced neutrons at LNGS. In addition, the cross-sections obtained from these measurements will be used in simulations to study further the feasibility of the background requirements for CUORE in its planned location.♥

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