Searching for ^{123}Te Electron Capture in CUORE

M. Moore on behalf of the CUORE collaboration
Wright Laboratory, Department of Physics, Yale University, New Haven, CT 06520, USA

Summary. — The electron capture of ^{123}Te is a unique second-order forbidden process with a Q-value of 51.9 keV. It provides an excellent means to explore the limits of current theoretical models of electron capture at high daughter nucleus angular momentum and low Q-value. The Cryogenic Underground Observatory for Rare Events (CUORE) is a $0\nu\beta\beta$ experiment located at the Laboratori Nazionali del Gran Sasso, which consists of 988 natural TeO_2 crystals operated using a source-detector method. New analysis techniques have allowed the use of approximately 2 years of data with thresholds down to 3 keV for a total TeO_2 exposure of 11.0 kg-yr. Preliminary results from the first study with CUORE data of K- and L-shell electron captures of ^{123}Te are presented in this work. These peaks are observed with constant signal rates at the L1- and K-shell binding energies of ^{123}Sb.

1. – Introduction

^{123}Te is foreseen to undergo electron capture to ^{123}Sb. This process is rare because it is suppressed by the small Q-value of the interaction and the large angular momentum of the daughter nucleus. It is described by the following equation:

$$(1)\qquad ^{123}Te\ [J_i^{\pi_i} = \frac{1}{2}^+] + e^- \rightarrow\ ^{123}Sb\ [J_f^{\pi_f} = \frac{7}{2}^+] + \nu_e, \qquad \text{with Q} = 51.9 \text{ keV}$$

The first observation claim of this process was made in 1962 by Watt & Glover but it has since been excluded [1, 2]. Positive evidence was again claimed in 1996, but was later ascribed to ^{121}Te, which is the only other Tellurium isotope that can undergo electron capture [2]. TeO_2 bolometric experiments that have preceded CUORE, namely CCVR2 (CUORE Crystal Validation Run 2) and CUORICINO released data which showed their TeO_2 crystal spectrum down to $\sim$2 keV [3]. In this spectrum, a peak was observed consistent with the Tellurium electron capture L1 line, although they did not claim it as such due to disagreements with branching ratios predicted by current theoretical models.

A measurement of ^{123}Te electron capture would be the first measurement of a second-order unique forbidden electron capture with such a small Q-value. Therefore, it provides

TABLE I. – *Electron shell binding energies for the K-and L-shells of Antimony (Sb).*

Shell	Energy [keV]
K	30.5
L1	4.7
L2	4.4
L3	4.1

an excellent means to analyze the performance of current electron capture models in these limits. This submission presents preliminary observations of the peaks corresponding to the L1- and K-shell electron captures of ^{123}Te using a high-quality subset of CUORE data down to 3 keV.

2. – The CUORE Experiment

The CUORE (Cryogenic Observatory for Rare Events) Experiment is a neutrinoless double beta ($0\nu\beta\beta$) decay experiment at the Laboratori Nazionali del Gran Sasso in Assergi, Italy. The detector consists of an array of 988 natural TeO_2 crystals arranged into 19 towers and 13 floors with 4 crystals on each floor. The experiment was designed to search for $0\nu\beta\beta$ decay of ^{130}Te but has had a successful physics program beyond this search. The experiment started taking data in 2017 and has since accumulated over 2 ton-years of exposure. Recent efforts to allow data to be used down to keV scales have resulted in a successful new low-energy-dedicated analysis chain [4]. This new analysis chain has enabled a subset of 11.0 kg-year of CUORE data to be usable down to 3 keV.

The crystals used in CUORE are natural TeO_2 which has a large isotopic abundance of ^{130}Te ($\sim$34%), the isotope of interest for the $0\nu\beta\beta$ search. This also means that other Tellurium isotopes can be present in the crystals, including ^{123}Te, which has a much smaller abundance of $\sim$0.9%. The experiment has large exposures, good energy resolution and low backgrounds, and, since the isotopic abundance of ^{123}Te is nonzero, it provides a vessel for measuring this electron capture. In a bolometer experiment such as CUORE, because the Tellurium atoms are bound in the crystal, when an electron capture occurs in an atom, the total energy of the deexcitation cascade is absorbed as a single energy deposit. Therefore, the signature of ^{123}Te electron capture in CUORE is a peak at the electron binding energy of the respective shell of the daughter nucleus. Depending on the shell from which the electron is captured, the energy released in the deexcitation cascade will differ. The expected energy for each shell is listed in Table I. Only the K-shell and L-shell energies are listed since the M-shell binding energies are all below the thresholds of the CUORE crystals.

3. – Theoretical Predictions

Internally, initial calculations were performed using the formula for partial decay constants[5]:

TABLE II. – *Intensity of L-shell lines with respect to the K-shell line for the electron capture of ^{123}Te.*

Shell Ratio	Fraction
L1/K	15
L2/K	0.4
L3/K	390

$$\lambda_x = \frac{8}{15\pi} G_\beta^2 \frac{p_x^{2(k_x-1)} q_x^{8-2k_x}}{(2k_x-1)!(7-2k_x)!} \beta_x^2 B_x \times B(\hat{T}^+_{3,2,1}; i \to f) \tag{2}$$

The variables were extracted from the review by Bambynek [6]. Atomic overlap and electron exchange effects were not taken into account ($B_x = 1$). From this we calculated the expected ratios of electron captures from the different shells, listed in Table II. These results suggest that the K-shell electron capture is mostly suppressed with respect to the L-shells due to the small Q-value of the process and that the L3-shell is preferred to the L1-shell likely due to the large angular momentum of the daughter nucleus.

4. – Experimental Results

As mentioned previously, in CUORE a new low energy analysis chain was designed and implemented, which has allowed the selection of high-quality data down to 3 keV [4]. All M1 or multiplicity-1 events that pass our selection cuts are plotted in Fig. 1. Multiplicity-1 refers to the number of crystals that detected energy deposits from a single process, so in this case only processes that were contained in a single crystal. This is relevant to electron capture because the signature of electron capture is the sum of a deexcitation cascade within a single crystal.

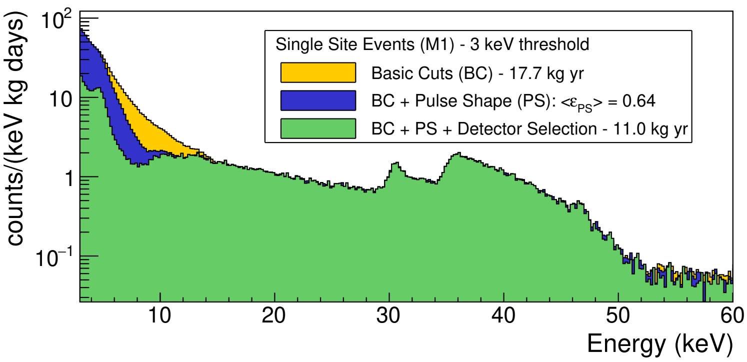

Fig. 1. – The CUORE energy spectrum for the range [3, 60] keV. The data has been passed through the low energy analysis chain using a threshold energy of 3 keV. This spectrum displays events that were contained in a single crystal (M1 or multiplicity-1 events). Plot from [4].

In this spectrum, the peaks of interest for this electron capture analysis are at 4.7 keV and at 30.5 keV, the binding energies of the L1- and K-shell of Antimony, respectively. A fitting framework was developed using RooFit and modeling the signal peaks as Gaussians. Then, fits were performed for each dataset ($\sim$1.5-month data collection period) on events that passed the 3 keV selection cuts. The peaks are reconstructed at energies consistent with the L1 line (4.1 keV) and K line (30.5 keV) at constant signal rates over the two-year data collection period.

5. – Conclusion

Peaks at energies corresponding to L1 and K-shell electron capture of ^{123}Te are observed in CUORE data. Preliminary results show the rates of these two peaks to be constant across the data collection period available with the 3 keV channel selection. However, there is no observation of a line at the L3-shell energy of 4.1 keV, which is predicted to be the most intense peak in this electron capture (see Table II). Currently, efforts are ongoing to finalize the systematics on the rates of the two peaks. There are also ongoing theoretical efforts to test various effects on the electron capture model to determine if there is an atomic effect suppressing the L3 line.

* * *

The CUORE Collaboration thanks the directors and staff of the Laboratori Nazionali del Gran Sasso and the technical staff of our laboratories. This work was supported by the Istituto Nazionale di Fisica Nucleare (INFN); the National Science Foundation under Grant Nos. NSF-PHY-0605119, NSF-PHY-0500337, NSF-PHY-0855314, NSF-PHY-0902171, NSF-PHY-0969852, NSF-PHY-1307204, NSF-PHY-1314881, NSF-PHY-1401832, NSF-PHY-1913374, and NSF-PHY-2412377; Yale University, Johns Hopkins University, and University of Pittsburgh. This material is also based upon work supported by the US Department of Energy (DOE) Office of Science under Contract Nos. DE-AC02-05CH11231, and DE-AC52-07NA27344; by the DOE Office of Science, Office of Nuclear Physics under Contract Nos. DE-FG02-08ER41551, DE-FG03-00ER41138, DE-SC0012654, DE-SC0020423, DE-SC0019316, and DE-SC0011091. This research used resources of the National Energy Research Scientific Computing Center (NERSC). This work makes use of both the DIANA data analysis and APOLLO data acquisition software packages, which were developed by the CUORICINO, CUORE, LUCIFER, and CUPID-0 Collaborations. The author acknowledges the Advanced Research Computing at Virginia Tech and the Yale Center for Research Computing for providing computational resources and technical support that have contributed to the results reported within this paper.

REFERENCES

[1] Watt D. E. and Glover R. N., *The Philosophical Magazine: A Journal of Theoretical Experimental and Applied Physics*, **7** (1962) 105-114.
[2] Alessandrello A., Arnaboldi C., et al., *Phys. Rev. C.*, **67** (2003) 014323.
[3] Alessandria F. et al., *Journal of Cosmology and Astroparticle Physics*, **01** (2013) 038.
[4] CUORE Collaboration, *Exploring the keV-scale physics potential of CUORE*, arXiv:2505.23955 [hep-ex].
[5] Bianchetti, M. and Quaglia, M. R. et al.,*Phys. Rev. C*, **56** (1997) 1675.
[6] Bambynek W. et al., *Rev. Mod. Phys.*, **49** (1977) 77.