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Measurement of the double-β decay half-life and search for the neutrinoless double-β decay of ^{48}Ca with the NEMO-3 detector

David Waters[1] and Cristóvão Vilela[2] (for the NEMO-3 collaboration)
[1]Department of Physics & Astronomy, University College London, London WC1E 6BT, UK
[2]Department of Physics & Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA

E-mail: `cristovao.vilela@stonybrook.edu`

Abstract. Neutrinoless double-β decay is a powerful probe of lepton number violating processes that may arise from Majorana terms in neutrino masses, or from supersymmetric, left-right symmetric, and other extensions of the Standard Model. Of the candidate isotopes for the observation of this process, ^{48}Ca has the highest $Q_{\beta\beta}$-value, resulting in decays with energies significantly above most naturally occurring backgrounds. The nucleus also lends itself to precise matrix element calculations within the nuclear shell model. We present the world's best measurement of the two-neutrino double-β decay of ^{48}Ca, obtained by the NEMO-3 collaboration using 5.25 yr of data recorded with a 6.99 g sample of isotope, yielding ≈ 150 events with a signal to background ratio larger than 3. Neutrinoless modes of double-β decay are also investigated, with no evidence of new physics. Furthermore, these results indicate that two-neutrino double-β decay would be the main source of background for similar future searches using ^{48}Ca with significantly larger exposures.

1. Double-β decay of ^{48}Ca

Neutrinoless double-beta decay ($0\nu\beta\beta$) is the only known process that can be used to elucidate the nature of neutrino masses. This lepton number violating decay can proceed via the exchange of light Majorana neutrinos, or processes arising from extensions to the Standard Model such as R-parity violating ($\not{R}_p$) supersymmetry or left-right symmetric models. A similar process in which two neutrinos are emitted ($2\nu\beta\beta$) is allowed by the Standard Model and has been directly observed in nine different isotopes with half-lives ranging from 10^{19} to 10^{24} years[1].

An isotope of particular interest for $0\nu\beta\beta$ searches is ^{48}Ca. It has a $Q_{\beta\beta}$-value of 4.27 MeV, which is the highest of all candidate isotopes and above all naturally occurring β emissions. The relatively low Z of ^{48}Ca allows for detailed calculations of nuclear matrix elements (NME) for double-β processes in the nuclear shell model (NSM)[2]. The main disadvantage of ^{48}Ca as a double-β decay source is its very low natural abundance of 0.187% and the lack of enrichment techniques that can be used at large scales.

2. The NEMO-3 experiment

The NEMO-3 experiment[4] operated in the Laboratoire Souterrain de Modane between 2003 and 2011. It used a unique tracking and calorimetry technique that allowed for the measurement of individual electron kinematics as well as a substantial reduction of background levels through the selection of events containing two electrons. A further advantage of this technique was the detector's ability to host a number of different source isotopes.

The ^{48}Ca source consisted of nine disks of compressed CaF$_2$ powder, where the calcium had been enriched in ^{48}Ca to a fraction of 73.2% through electromagnetic separation. The source yielded 6.99 g of ^{48}Ca, giving an exposure over the duration of the experiment of 37 g yr.

3. Measurement of the double-β decay half-life of ^{48}Ca

Events with electron vertices originating in the ^{48}Ca source are categorised according to their topology, with dedicated channels being used to measure both background activities and the $2\nu\beta\beta$ signal. A selection requiring only a single electron (Figure 1) provides a high-statistics sample in which to measure β-decaying isotopes, such as the ^{90}Sr/^{90}Y system, while events with one or two additional γ's constrain $(\beta + \gamma)$ decays with one or more photons in the final state, like ^{214}Bi or ^{208}Tl. An additional channel is used to measure primarily surface deposits of ^{214}Bi, by requiring the coincidence of an electron (from ^{214}Bi β-decay) and a delayed α from the subsequent ^{214}Po decay. Backgrounds originating in materials other than the source are measured in channels where a time-of-flight criterion is consistent with an external hypothesis.

The double-β decay signal is measured in a channel where two-electrons are required, with time-of-flight consistent with the internal hypothesis and no other activity observed in the detector (Figure 2).

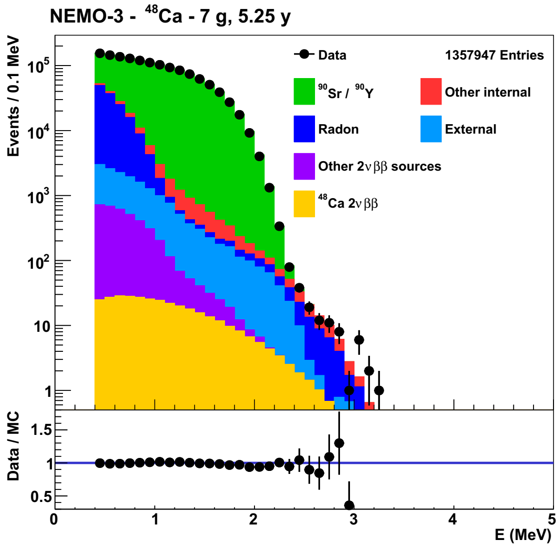

Figure 1: Electron energy spectrum of selected single-electron events.

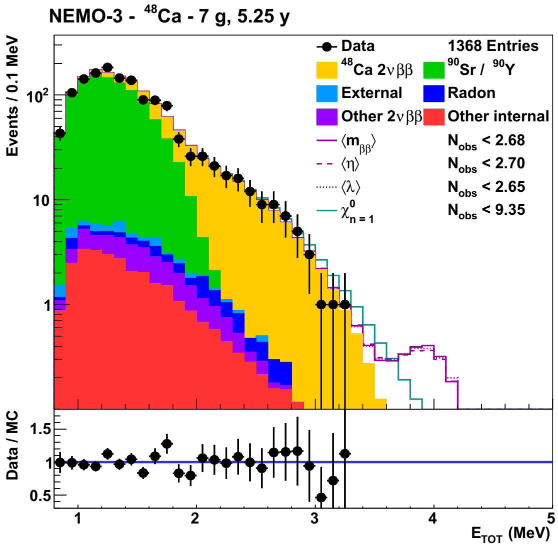

Figure 2: Summed energy of electrons in selected two-electron events.

A likelihood function is built over all the analysis samples, and Gaussian terms are included to reflect externally measured constraints on the background activities.

The likelihood function is maximised to yield 153 $2\nu\beta\beta$ events with $S/\sqrt{B} \approx 23$. A signal selection efficiency of 3.1% is estimated from Monte Carlo simulation to give:

$$T^{2\nu}_{1/2} = [6.4\,^{+0.7}_{-0.6}(\text{stat.})\,^{+1.2}_{-0.9}(\text{syst.})] \times 10^{19}\,\text{yr}\;,$$

with the systematic uncertainties detailed in Table 1.

This result is a significant improvement over the two previously existing measurements: $T^{2\nu}_{1/2} = 4.2^{+3.3}_{-1.3} \times 10^{19}\,\text{yr}$[5] and $T^{2\nu}_{1/2} = [4.3^{+2.4}_{-1.1}(\text{stat}) \pm 1.4(\text{syst})] \times 10^{19}\,\text{yr}$[6].

Origin	Uncertainty on $T^{2\nu}_{1/2}$
^{90}Sr/^{90}Y background	$[+2.0, -2.4]\%$
Other backgrounds	$\pm 0.3\%$
^{48}Ca enrichment fraction	$\pm 2.1\%$
^{48}Ca source construction	$[+3.7, -5.5]\%$
Electron reconstruction efficiency	$[+7.5, -6.5]\%$
Calorimeter energy scale	$[+4.4, -4.0]\%$
Two-electron angular distribution	$[+16, -10]\%$
Total	$[+19, -14]\%$

Table 1: Systematic uncertainties on the $2\nu\beta\beta$ measurement.

4. Search for the neutrinoless double-β decay of ^{48}Ca

As no evidence of $0\nu\beta\beta$ is found in the analysed data (background-only p-value = 0.83) limits on neutrinoless modes are calculated at 90% C.L. using the CL$_s$ method, including systematic variations of the uncertainties given in Table 1.

The resulting lower half-life lower limits are given in Table 2 for $0\nu\beta\beta$ occurring via light neutrino exchange, right-handed currents η and λ, and with the emission of a single Majoron.

Mechanism		Efficiency (%)	$T^{0\nu}_{1/2}$ 90% C.L. (10^{22} yr) Expected	Observed
Light neutrino exchange		16.9	$> 1.71 - 2.02$	> 2.02
Right-handed currents	η	15.8	$> 1.57 - 1.88$	> 1.87
	λ	9.91	$> 1.03 - 1.20$	> 1.19
Single Majoron emission ($n = 1$)		13.4	$> 0.25 - 0.50$	> 0.46

Table 2: Limits on $0\nu\beta\beta$ modes obtained with the full set of NEMO-3 ^{48}Ca data.

5. Conclusions

The $2\nu\beta\beta$ half-life of ^{48}Ca was measured with a significant precision improvement over previous measurements. While this result is in good agreement with past experiments, it is in slight tension with NSM prediction of $\approx 4\times10^{19}$ yr. A limit of 2.0×10^{22} yr was placed on $0\nu\beta\beta$ that did not improve on the result obtained by the ELEGANT IV collaboration of 5.8×10^{22} yr.

6. Acknowledgments

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