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Weak Decay of Tellurium and Barium Isotopes in Geological Samples: Current Status

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The accurate experimental determination of half-lives for $2\nu\beta\beta$-decay could be used to adjust parameters of the QRPA model, the strength of the particle-particle interaction g_{pp} and to improve the calculation of Nuclear Matrix Element for $0\nu\beta\beta$ (neutrinoless) decay and neutrino mass $\langle m_\nu \rangle$ estimations. Presently high precision direct counting experiments are difficult due to low decay rates of tellurium and barium isotopes, but their daughter nuclei accumulating in geological samples for millions of years, are clearly observable in xenon isotopes, which have extremely low background in terrestrial rocks. This work reviews current status of the previously determined half-lives of ^{130}Te and ^{128}Te and presents new estimates of half-life of ^{130}Ba weak decay. Our new estimates take into account the spallogenic production of ^{130}Xe, significantly reducing the disagreement between the only two published values of ^{130}Ba half-lives. Based on this result and on our early experiments we propose a new class of geological samples, which can provide an even more accurate determination of the ^{130}Ba half-life.

KEYWORDS: double beta decay, double electron capture, ^{130}Ba, ^{130}Te, ^{128}Te.

1. ^{130}Te and ^{128}Te half-lives.

Since the first positive experimental observation of ^{130}Xe generated by the double β^- decay of ^{130}Te [1] and until 2008 all ^{130}Te half-lives determined from analyses of geological Te minerals were falling into two distinct groups, the “long” and the “short” ones (Fig. 1). In 2008 it was shown that among these two groups of the reported values the ”short” ^{130}Te half-life were correct ones. The samples yielded “long” half-lives experienced several documented heating episodes in their geological histories and, as a result, suffered significant losses of ^{130}Xe from ^{130}Te double β^- decay [2]. This conclusion was initially confirmed by independent analyses of different geological samples [3] and later by the first successful direct counting experiment NEMO-3 [4]. Based on three most recently reported ^{130}Te half-lives (7.9 ± 1.0)×10^{20} yr [5], (9.0 ± 1.4)×10^{20} yr [2] and (8.0 ± 1.3)×10^{20} yr [3], all of which came from geologically qualified samples, we propose the current best estimate of ^{130}Te half-life to be (8.2 ± 0.7)×10^{20} yr. The average recommended value obtained from reported direct counting experiments [4, 6] is (6.9 ± 1.3) ×10^{20} yr [7]. A small, barely statistically significant, difference between the contemporary ^{130}Te half-life determined by counting experiments and that found from million years old geological samples could be due to temporal variability of Fermi constant G^4_F [8]. Additional studies are needed to verify this hypothesis, as only the upper limit of the G^4_F variability can be set at this time.

The half-life of ^{128}Te can be calculated from our best current estimate of ^{130}Te half-life and the observed ratio of ^{128}Te-derived ^{128}Xe to ^{130}Te-derived ^{130}Xe (3.74 ± 0.10) × 10^{-4} [9].

Therefore we propose ^{128}Te half-life to be (2.2 ± 0.2)×10^{24} yr. The proposed ^{128}Te half-life constrains the upper limit for the effective Majorana mass ⟨m⟩ of an electron neutrino, which (depending on different estimates of C_{mm}) varies from ⟨m⟩ < 1.9 eV to ⟨m⟩ <2.4 eV.

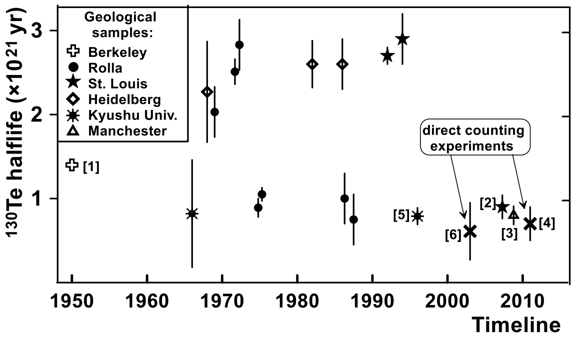

Fig. 1. Published double β^- decay half-lives of ^{130}Te measured in geological Te-samples. References for the measurements performed before 1996 are given in [2]. Only statistical uncertainties are plotted for direct counting experiments MIBETA [6] and NEMO-3 [4] experiments.

2. ^{130}Ba weak decay

The ^{130}Ba decay (2νECEC is likely the main channel [10]) is currently beyond the reach of direct counting experiments. The first search for ^{130}Xe from ^{130}Ba decay was negative [11] for both analyzed barites. Later the original 1976 measurements were re-analyzed. This re-evaluation suggested the ^{130}Ba half-life < 4×10^{21} yr for one barite and possible indication of ~ 2.1×10^{21} yr for the second one [12]. The first positive observation of ^{130}Ba in natural barite yielded a half-life of (2.2 ± 0.5)×10^{21} yr (68% C.L.) [13]. Later based on analyses of an Archean barite a 3.4 times shorter value was reported (6.0 ± 1.1×10^{20} yr [14]). These are the only two ^{130}Ba half-lives published to date.

Xe isotopes released from Archean barite [14] are plotted in Figure 2 which demonstrates linear correlation between ^{128}Xe and ^{130}Xe. This correlation points to the common origin of these isotopes. Most likely they both come from spallation by high-energy cosmic-ray interactions. These nuclei are also accompanied by other spallogenic isotopes, namely ^{124}Xe and ^{126}Xe, typical for Archean barites [11, 12].

To subtract the contribution of the spallogenic ^{130}Xe we extrapolated the linear fitting line to the Y-axis intercept where there should be no spallogenic ^{128}Xe (Figure 2). The confidence interval (95%) at this intercept provides the upper limit for

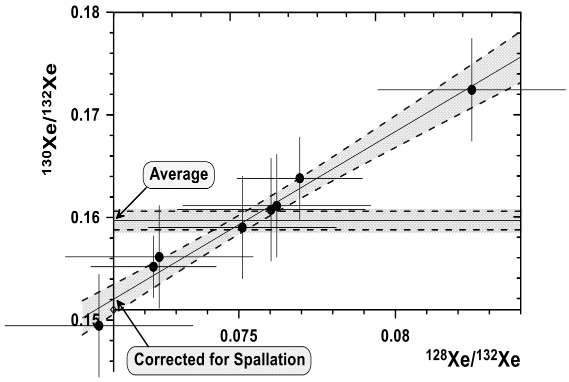

Fig. 2. Isotopic composition fractionated by 2.1 %/u of Xe released from Archean barite [14]. The origin of the axes corresponds to the composition of atmospheric Xe. Linear correlation between ^{130}Xe and ^{128}Xe indicates spallation contribution. Averaging the ^{130}Xe/^{132}Xe ratios evidently increases apparent amount of ^{130}Xe underestimating ^{130}Ba half-life [14].

the amount of ^{130}Xe from weak decay of ^{130}Ba and corresponds to the lower limit of the ^{130}Ba half-life estimate: > 2.4×10^{21} yr. This limit turns out to be in agreement with the ^{130}Ba half-life of $(2.2 \pm 0.5)\times10^{21}$ yr [13] and ~ 2.1×10^{21} yr [12].

Xe isotopic analyses of geologically-old barite ($BaSO_4$) are often confounded because spallation reactions take place at shallow hydrothermal conditions when barites form. There are volcanogenic barites, which might be better shielded from cosmic rays and we are currently looking for these samples to verify the only available ^{130}Ba half-life measurement [13] that is not compromised by the high energy cosmic-ray interactions.

Conclusion

All published Xe isotopic analyses in geologically qualified samples indicating spallation-free weak decay products were re-evaluated and compared with the results of direct counting experiments. We suggest the following best current estimates of the weak decay half-lives:

^{130}Te: $(8.2 \pm 0.7)\times10^{20}$ yr (6.9 ± 1.3 $\times10^{20}$ yr. - direct counting experiments [7]),

^{128}Te: $(2.2 \pm 0.2)\times10^{24}$ yr (no direct counting experiment is presently reported),

^{130}Ba: $(2.2 \pm 0.5)\times10^{21}$ yr (no direct counting experiment is presently reported).

Acknowledgment

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