Physics Letters B 684 (2010) 17–21

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Accurate Q value for the ^{74}Se double-electron-capture decay

V.S. Kolhinen [a,*], V.-V. Elomaa [a], T. Eronen [a], J. Hakala [a], A. Jokinen [a], M. Kortelainen [b,c], J. Suhonen [a], J. Äystö [a]

[a] Department of Physics, Post Office Box 35 (YFL), FIN-40014, University of Jyväskylä, Finland
[b] Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, USA
[c] Physics Division, Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, TN 37831, USA

ARTICLE INFO

Article history:
Received 12 November 2009
Received in revised form 7 December 2009
Accepted 23 December 2009
Available online 7 January 2010
Editor: V. Metag

Keywords:
Double-electron-capture decay
Q value
Penning trap

ABSTRACT

The Q value of the neutrinoless double-electron-capture (0νECEC) decay of ^{74}Se was measured by using the JYFLTRAP Penning trap. The determined value is 1209.169(49) keV, which practically excludes the possibility of a complete energy degeneracy with the second 2^+ state (1204.205(7) keV) of ^{74}Ge in a resonant 0νECEC decay. We have also computed the associated nuclear matrix element by using a microscopic nuclear model with realistic two-nucleon interactions. The computed matrix element is found to be quite small. The failure of the resonant condition, combined with the small nuclear matrix element and needed p-wave capture, suppresses the decay rate strongly and thus excludes ^{74}Se as a possible candidate to search for resonant 0νECEC processes.

© 2010 Elsevier B.V. All rights reserved.

1. Introduction

Progress in obtaining detailed information on neutrino properties has been very fast, thanks to present-day high-precision neutrino-oscillation experiments. The differences of the squared neutrino masses and the elements of the neutrino mixing matrix are well established [1–3]. To access the fundamental nature and the absolute mass scale of the neutrino, one needs, in particular, to explore rare decays of the atomic nuclei of their neutrinoless double beta ($0\nu\beta\beta$) decay. The existence of the $0\nu\beta\beta$ decay would mean that the neutrino is a so-called Majorana particle, i.e. it is its own antiparticle. A massive Majorana neutrino is an indication of physics beyond the standard model. The ongoing and future large-scale $0\nu\beta\beta$ experiments have the potential to discover this decay mode at least in the case of degenerate and inverted neutrino-mass hierarchies [4]. However, to extract information on the neutrino mass from the data, one needs to know the involved $0\nu\beta\beta$ nuclear matrix elements [5,6].

The search for the $0\nu\beta\beta$ decay is mostly concentrated on the $0\nu\beta^-\beta^-$ decays due to their favorable Q values. On one hand, the positron-emitting modes of $0\nu\beta\beta$ decay, $0\nu\beta^+\beta^+$, and $0\nu\beta^+$EC are hard to detect, owing to their small decay Q values [5]. On the other hand, the neutrinoless double electron capture, 0νECEC, can only be realized as a resonant decay [7] or a radiative process with or without a resonance condition [8]. The 0νECEC decay with a resonance condition has attracted a lot of experimental interest recently [9–13]. The resonance condition — close degeneracy of the initial and final (excited) atomic states — can enhance the decay rate by a factor as large as 10^6. This resonant condition can be reached if the decay Q value between the initial and the final atomic masses minus the energies of the two captured electrons matches with the energy of the excited state of the daughter atom. In this work we study the following type of 0νECEC process:

$$e^- + e^- + (A,Z) \rightarrow (A,Z-2)^* \rightarrow (A,Z-2) + \gamma + 2X, \tag{1}$$

where the capture of two atomic electrons leaves the final nucleus in an excited state that decays by one or more gamma-rays and the atomic vacancies are filled by outer electrons with emission of X-rays.

The daughter state $(A,Z-2)^*$ is a virtual state with energy

$$E = E^* + E_H + E_{H'}, \tag{2}$$

including the nuclear excitation energy E^* and the binding energies E_H and $E_{H'}$ of the two captured electrons. For the half-life of the parent atom, the resonant condition can be written as [7,14]

$$\frac{\ln 2}{T_{1/2}} = \frac{\mathcal{M}^2}{(Q-E)^2 + \Gamma^2/4}\Gamma, \tag{3}$$

where $\mathcal{M}$ contains the leptonic phase space and the nuclear matrix element, Q is the decay energy difference between the initial and the final atomic states, Γ denotes the combined nuclear and

---

* Corresponding author.
E-mail address: veli.kolhinen@jyu.fi (V.S. Kolhinen).

0370-2693/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.physletb.2009.12.052

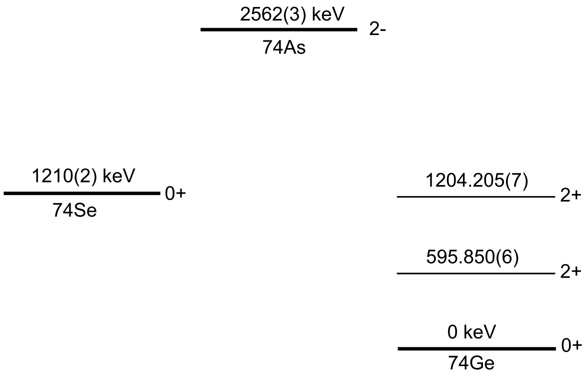

Fig. 1. Level scheme of ^{74}Se decay to ^{74}Ge showing ground states of both isotopes and two lowest energy levels of ^{74}Ge.

atomic radiative widths and $|Q-E|$ is the so-called degeneracy parameter containing the energy (2) of the virtual final state and the Q value. The width Γ is dominated by the radiative width of the two holes created by the electron captures. For the K and L orbital captures this width ranges from few to tens of electron volts [15].

Possible candidates for the resonant decays are many [7,8], one of them being the case of the decay of ^{74}Se to the second 2^+ state in ^{74}Ge. Therefore, it has been proposed [13] that one should measure the atomic mass difference of ^{74}Se and ^{74}Ge accurately enough to confirm or exclude the resonance enhancement. Such a measurement we already did for the decay $^{112}\mathrm{Sn} \rightarrow {}^{112}\mathrm{Cd}(0_4^+)$ in [16], where the possibility of a favorable value of the degeneracy parameter for this decay was excluded. A recent paper by Green et al. [17] studied the energy and character of this 0_4^+ state and confirmed the conclusions of Ref. [16]. In this article we proceed to study the resonant 0νECEC decay of ^{74}Se by measuring the decay Q value. Fig. 1 shows the illustration of the Q value and energy levels of ^{74}Ge [18].

2. Experimental setup

The Q value measurement was performed at the Ion Guide Isotope Separator On-line (IGISOL) facility [19,20] at the University of Jyväskylä, Finland. The ion guide method was used with an electric discharge ion source [21], which had electrodes containing germanium and selenium. The ion source was operated by applying voltage between the electrodes in the helium gas, creating a discharge, evaporating part of the electrode material as ions. The created germanium and selenium ions were extracted from the ion source by using electric fields and helium gas jet and guided into a sextupole ion guide (SPIG) [22]. The extracted beam was accelerated to 30 keV energy and guided through a 55° dipole magnet allowing for a mass separation of the order of $M/\Delta M \approx 500$. The mass-separated continuous beam was guided into an RF-quadrupole cooler/buncher [23] where the emittance and the energy spread of the beam were decreased, and the beam was bunched before injecting the ions into the double Penning trap spectrometer JYFLTRAP [24]. An overview sketch of the setup is shown in Fig. 2, displaying the ion guide and the beam line components, together with the Penning traps.

The JYFLTRAP spectrometer consists of two identical cylindrical Penning traps placed in one 7.0-T superconducting magnet with 160 mm warm bore. The magnet has been fine tuned so that it has two homogeneous field regions at the trap centers. The first trap is used to purify the ion bunch isobarically by applying a buffer gas-cooling technique [25] while the second trap is used for the measurement of the cyclotron frequency of the ions of interest $\nu_c = \frac{1}{2\pi} qB/m$ by using a time-of-flight ion-cyclotron resonance (TOF-ICR) technique [26].

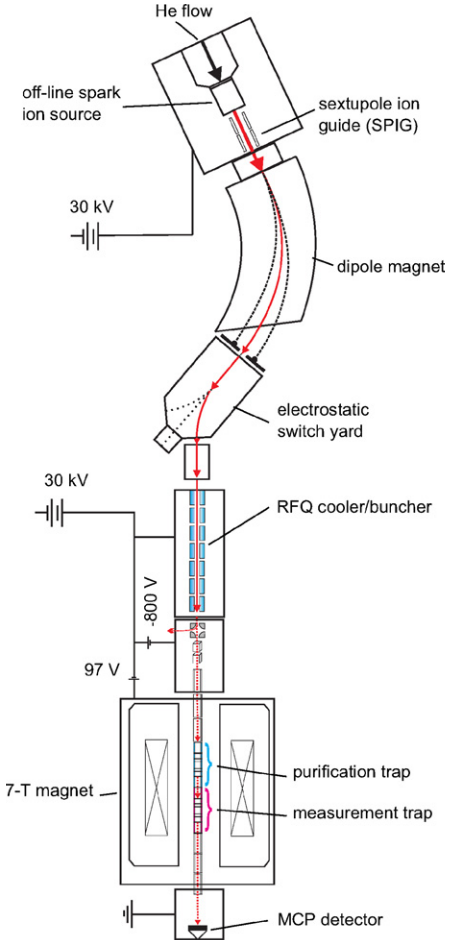

Fig. 2. Schematic illustration of the JYFLTRAP beam line showing the ion guide, dipole magnet, switch yard, RFQ cooler/buncher, and Penning traps.

3. Results

In this Q-value measurement, a Ramsey-type ion motion excitation [27,28] with two 25 ms fringes, separated by a 350 or 750 ms long waiting time, were used in the measurement trap. Fig. 3 is showing typical resonance curves made by this technique by using a 25–750–25 ms excitation scheme.

Both masses were scanned almost simultaneously by measuring 2 cycles of ^{74}Se and then 2 cycles of ^{74}Ge and then repeating this pattern. This was done to minimize the effects arising from the magnetic field drifts [29]. Since both the mother and the daughter nuclei have the same mass number and charge state, the mass-dependent frequency shift becomes negligible. The collected data were divided into 15-cycles-long samples, and a count-rate class analysis was applied [30] to the frequency determination in order to correct the count-rate-dependent shift. In this count-rate analysis the final result was extrapolated by using a linear fit to 0.6, which is estimated to correspond to the frequency of a single ion in the trap (60% detection efficiency). This extrapolated frequency and its corresponding uncertainty were used in the Q-value calculations by using the relation

$$Q = m_m - m_d = \left(\frac{\nu_{\mathrm{c,Ge}}}{\nu_{\mathrm{c,Se}}} - 1\right)(m_{\mathrm{Ge}} - m_{\mathrm{e}}) + \frac{\nu_{\mathrm{c,Ge}}}{\nu_{\mathrm{c,Se}}} B_{\mathrm{e,Ge}} - B_{\mathrm{e,Se}} \tag{4}$$

Download English Version:

https://daneshyari.com/en/article/1852212

Download Persian Version:

https://daneshyari.com/article/1852212

Daneshyari.com