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The Development of Nuclear Frequency Standard with the Use of Ion Crystals Manipulation System

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Abstract

The perspectives for the increase in the accuracy of optical frequency standards by means of the development of "nuclear clocks" – a novel frequency standard based on the nuclear transition to the long-living isomer nuclear state of thorium-229 with energy ~7.6 eV are discussed. Theoretical estimations give a possible accuracy Δν/ν ~1×10-20, that allows wide scope of applications for a frequency standard, from satellite navigation systems to experimental verification of the principles of the general theory of relativity. The results are presented and the future prospects for research are discussed on the measurement of the isomeric transition in the nucleus of thorium-229 and creation on its basis the frequency standard of the new generation.

Keywords: nuclear isomeric transition, thorium-229, Paul trap

1. Introduction

Currently, major advances have been achieved in the construction of frequency standards based on atomic clocks with use of atomic transitions [1-5]. Experiments on atomic clocks have already provided the most accurate tests of

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general relativity and many fundamental constants. At the same time, this success caused the boost for development of a more accurate time reference, because, despite all the advances, traditional experiments with atomic clocks are rather bulky: atomic transitions, which are high-quality oscillators, are highly sensitive to the environment. To reduce the influence of the environment, modern experiments include complex schemes, such as atomic fountains and three-dimensional optical lattices. An interesting change would be the creation of an optical clock based on the nuclear transition. As in the case of the atomic clock, a high-quality oscillator, i.e. the nuclear transition, could be made available for modern laser technology, with additional benefits arising from the decrease of sensitivity to the environment due to the shielding of the nucleus by atomic electrons. Coherent excitation of electronic states of atoms and molecules with laser is the main procedure of modern spectroscopy and metrology. If it were possible to extend this technique to nuclear states, it would be a spectacular breakthrough in science.

2. Nuclear isomeric transition

The existence of the long-lived isomeric state of the ^{229}Th nucleus was confirmed in gamma spectroscopy experiments [6-8]. In [9] a method based on the hyperfine transition between the electron shells was provided for detection of laser excitation of the nucleus by double resonance technique. ^{229}Th is, apparently, a unique system in nuclear physics, which has the only known isomeric state with a lifetime of about 1 hour and an excitation energy of 7.6±0.5 eV (Fig. 1) [10] (about 160 nm), located in the energy range of optical photons and in the range of electronic transitions of outer shells [11–13]. The transition energy lies in the vacuum ultraviolet region and is available for the study by laser spectroscopy.

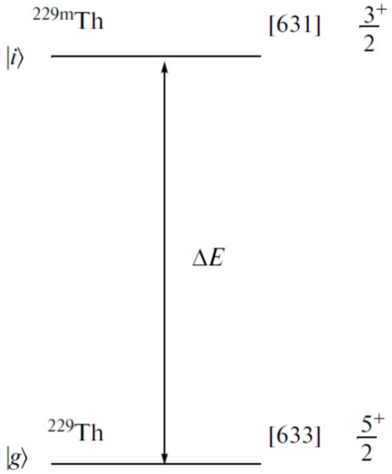

Fig. 1. The ground and first excited (isomeric) state of $^{229\mathrm{Th}}$. The classification of levels is according to Nilsson model. ΔE=7.6±0.5 eV.

The isomeric state of ^{229}Th can be obtained by alpha decay of ^{233}U; the probability of this process is about 2%. In turn, ^{233}U is a product of the uranium cycle in nuclear power plants, and can also be obtained by irradiating the ^{232}Th isotope in thermal reactors.

The accuracy of measurement of the frequency of the nuclear transition in ^{229}Th is determined by significant suppression of systematic frequency shifts due to the screening of the nucleus by layered electron shell. This is summarized in the fact that the main contribution to the error will be given by statistical error of measurement, which, in turn, can be reduced with long integration time. The expected accuracy and stability of the new standard can make 10^{-20}–10^{-22} and 10^{-18}, respectively. Currently existing standards has the accuracy of 10^{-18}, and stability of 10^{-16}. The new frequency standard can be used in various fields, such as the development of a gamma laser of optical range; improvement of global communication networks and accurate satellite navigation systems; checking the exponential mechanism of decay of excited states; study of nuclear interactions by high-precision methods and technologies of nuclear physics; as well as in various military and counterterrorism developments.

3. Generation of ions

To study the isomeric state of ^{229}Th one usually uses ^{229}Th^{+} and ^{229}Th^{3+} ions. The singly charged ion has a complex system of electronic levels, but can be relatively easily obtained and used in the mechanism of electron bridge for excitation of the isomeric state [14]. The triply charged ion is more suitable for determining the energy of the isomeric state due to the high ionization potential (27 eV) and a relatively simple electronic structure [9].

In addition to great technical difficulties associated with the measurement of extremely weak magnetic dipole isomeric transition, the problem of producing ^{229}Th^{+} and ^{229}Th^{3+} ions is also non-trivial. The ^{229}Th^{+} isotope can be produced artificially only and in very small amounts. Furthermore, ^{229}Th^{+} isotope is radioactive. The most common method of producing ^{229}Th^{+} ions is laser ablation with use of thorium-containing solid targets [15]. The main disadvantages of this technique are small number of resulting ions (this factor is important because of the high cost and radioactivity of ^{229}Th^{+} isotope), and numerous impurities due to the presence of the target.

A more promising method of producing ions of ^{229}Th isotope is reported in [16]. In this method ions are generated by inductively coupled plasma technique from liquid solutions of thorium.

4. Paul trap

The most common way of confinement of ions is capturing of ions in the Paul trap [19]. The potential of the trap is created by the system of electrodes located symmetrically around the center of the trap, and oscillates with a certain frequency providing the confinement of ions along the trap axis. The endcap electrodes provide confinement of ions inside the trap. In this configuration, ions can be stored for a long time up to several days.

Fig. 2. Five-section quadrupole Paul trap of linear configuration with energy filter and ion source.

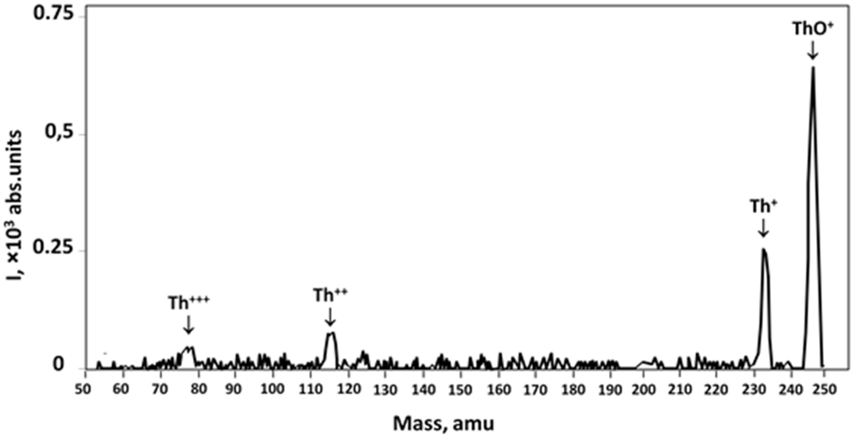

Fig. 3. Mass spectra of singly, doubly and triply charged ions of thorium-232, obtained with the use of the five-section quadrupole Paul trap.

Figure 2 shows the five-section quadrupole Paul trap of linear configuration with energy filter and ion source, designed and constructed at the Department of Physical and Technical Problems of Metrology in NRNU MEPhI, Russia. The trap consists of five consecutive quadrupole independent segments, which makes it possible to vary the potential inside each quadrupole, and to form a complex potential profile for capturing and retaining ions of various elements of a wide energy range of 1–500 eV. Simultaneous turning on (time of synchronization is 1 ms) of 100 V potential is provided on endcap electrodes for successful capture of thorium ions. This value of the potential is specified by the need to slow the ions with initial energy up to 100 eV, which are formed by electron beam evaporation of thorium-containing targets. The recording of mass spectra is realized sequentially in different energy ranges from 100 to 110 eV. The width of the energy range of 10 eV is due to the fact that in the quadrupole the filtering of ions with resolution of 1 amu is secured for ions with energy less than 10 eV. Ions with energy lower than 100 eV are unable to overcome the bias potential of the quadrupole and lost in the region between the ion lens and the quadrupole. Ions with energies above 110 eV enter the quadrupole and may have the probability of passing through it. To exclude their influence on the results of the analysis, the output of the quadrupole is equipped with the energy filter.

Figure 3 shows the spectra of singly, doubly, and triply charged ions of thorium-232, obtained with the use of the system described above. The calibration of the scale of mass to charge ratio was carried out with use of chemically inert and monoisotopic element of Au. This setup allows one to start ultra-precision research of optical and nuclear isomeric emission and absorption spectra of ^{229}Th isotope.

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