Method of the production and trapping of thorium ions for nuclear transition investigation

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Abstract. This paper describes the techniques of production and trapping of thorium ions required to perform spectroscopic studies of thorium nuclear transition.

1. Introduction

Laser spectroscopy plays a key role in the solving fundamental physics problem such as the testing of the general theory of relativity [1], the determination of fundamental constants [2], the development of new quantum technologies [3], and the creation of precise frequency standards [4].

The currently achieved fractional frequency uncertainty does not allow to perform some fundamental physics investigation, such as testing the theory of fundamental constants variation. The usage of nuclear transitions instead of atomic ones would allow us to increase the precision of measurements by several orders of magnitude [5]. Nucleus is characterized by extremely low polarizability and is shielded from external perturbation by an electron cloud. The narrowness of the spectral line and the low transition intensity make nuclear transitions a good candidate for creation new generation of frequency standards. Unfortunately, the typical energies of nuclear transitions are within the keV to MeV range, no common sources of coherent radiation are available at this spectral range. The unique exception is the isomeric transition in the thorium-229 isotope nucleus, its energy, according to the latest data, is 7.8 ± 0.5 eV [6].

To study the isomeric state of thorium-229,²²⁹Th⁺ and ²²⁹Th³⁺ ions are used, the former is relatively easy to obtain, it has a complex system of electronic levels, so it can be used in the realization of the electronic bridge mechanism for excitation of the isomeric state [7], and the latter is most convenient...
for investigate isomeric transition energy, due to the high ionization potential (27 eV) and the simple electronic levels structure [8].

In addition to the enormous technical difficulties associated with the measurement of an isomeric nuclear transition energy, production of the thorium ions and trapping it for subsequent laser cooling and spectroscopic studies, are also a serious problem. The isotope of thorium-229 can only be produced artificially and only in very small quantities. In addition, thorium-229 isotope is very radioactive. In the experiments to determine the energy of the isomeric transition in the thorium-229 nucleus researchers use, either individual ions are placed in an ion trap [9], or thorium-229 ions are embedded into a crystal transparent in the vacuum ultraviolet range [10]. In this paper, the methods of production and trapping thorium ions in a quadrupole linear ion trap are reported.

2. Production of ions
Thorium ions are generated by laser ablation. During short laser pulse plasma plume containing large number of particles (~10^{14}) is generated. Large number of ions, inside trap at the same time, allows you to trap sufficient number of ions. In addition, the laser ablation provides local evaporation of the target [11], which is good for working with a limited target material. This is important because of $^{229}$Th radioactivity. Allowed sample amount of $^{229}$Th in laboratory is nanograms of matter.

Due to the high radioactivity of the isotope $^{229}$Th initial stages of work were carried out using a model sample of monoisotopic and chemically inert gold $^{197}$Au and stable thorium isotope $^{232}$Th.

Laser ablation system is based on Q-switched Nd:YAG laser. Laser pulse parameters are following: duration of the laser pulse $\tau = 25$ ns, pulse energy $E = 50$ mJ, the laser spot radius on the sample $r = 100 \, \mu m$. Thus the obtained power density is about $I \sim 1 \, \text{GW/cm}^2$. Mass spectra of gold ions, generated via laser ablation, obtained by quadrupole mass filter is shown in Fig. 1.

![Figure 1. Mass spectra of gold ions generated by laser ablation.](image)

3. The trapping of ions
Multisectional quadrupole linear ion trap [12] was used for trapping ions. The trap (Fig. 2) consists of five separated quadrupole segments, which makes it possible to vary the potential of each quadrupole individually and thus forming a potential profile for capturing and keeping ions in a wide energy range of $1 - 500$ eV. Each quadrupole section consists of four stainless steel cylindrical rods with a diameter of 8 mm mounted at a diagonal distance of 7.1 mm between the surfaces of the rods.
Trap’s rods are supplied with voltage oscillating at a frequency 1.22 MHz. In addition, a DC bias voltage can be applied to one of the sections to perform mass filtering. Power supplies allow mass filtering a range of $2 - 250$ Da, with a resolution $\sim 1$ Da.

Figure 2. Scheme of experimental setup. 1 – ablation Nd:YAG laser, 2 – sample, 3 – quadrupole linear Paul ion trap, 4 – end cap electrodes, 5 – energy analyser, 6 – secondary electron multiplier.

Trapping process was implemented by supplying DC voltage to end cap electrodes, synchronized (synchronization time 1 µs) with the laser pulse. End cap electrodes have 2 mm diameter apertures coaxial with the ion trap axis. Value of “trapping potentials” applied to the electrodes $\sim 100$ V.

Trapping time of up to 100 seconds was demonstrated by registration of secondary electron multiplier signal, corresponded to ions released from the trap. In Fig. 3, dependence of the ions number vs the time of their registration by secondary electron multiplier for different trapping times are presented.

Figure 3. Dependence of the ions number vs the time of their registration by secondary electron multiplier, for different trapping times.
Maximum number of ions are registered about 0.3 ms. The appearance of slower ions at long trapping times ~ 1 s can be explained by ions interaction with gas molecules in a vacuum chamber evacuated at a pressure of ~ $10^{-7}$ Torr.

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