Towards creation of the nuclear clock and frequency reference point: search for the optimal parameters today, accessorio of the future

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Creation of nuclear reference for the frequency, and nuclear clock on this basis, is a very topical problem at the contemporary research metrology. Simple estimates show that nuclear transitions are characterized with higher stability and narrower line widths. Basing on these principles, it is possible to create nuclear clock e.g. on the basis of $^{229}$Th nuclide with systematic error within $10^{-19} - 10^{-21}$. Such precision will allow one to solve a number of problems of fundamental research, as well as applied engineering. Thus, differences of the gravitation potential in various space points, or non-variation of the fundamental constants will be measured within narrower limits. For comparison, best facilities have errors at the level of $10^{-17}$ at the time being.

The idea of the new standard is founded on the cooperative atomic-nuclear transitions. Internal conversion transitions comprise a conventional class of the transitions of this type. They underlie nuclear spectroscopy, being used for decades. For the purpose of creation the nuclear CLOCK, subthreshold, or BOUND INTERNAL CONVERSION (BIC) becomes indispensable means. This also manifests itself a the Combined electronic-nuclear transitions: first, the energy of the laser photon is absorbed by the electron shells of the atoms. Then this energy is further transferred to the nuclei in non-radiative transitions.

**BIC and NEET**

In practice, while the nuclear energy is not known precisely, another method might be used in principle: resonance excitation of the atomic shell to a discrete atomic level. At first site, this method may look more convenient and feasible. It is supposed that afterwards, part of the absorbed photon energy may be transferred to the nucleus. The remaining energy must be taken away, e.g., by an emitted photon. With assumptions, the latter mechanism can be attributed as NEET. However, necessary presence of the second stage in the NEET method essentially diminishes the cross-section, by orders of magnitude, as the related vertex turns out to be small. For example, in the case of neutral, singly- and doubly-charged ions of $^{229}$Th, this vertex turns out to be electrical quadrupole or a two-photon one. In both cases, it brings the strong suppression factor.

**DEPENDENCE OF THE NUCLEAR LIFETIME ON THE AMBIENT CONDITIONS THROUGH BIC**

In spite of its very short lifetime, in Ref. [1,2] the authors first observed the decay of the isomer, which occurs via the internal conversion (IC) channel with the half-life of approximately $10\mu$s. Transportation of the isomeric nuclei from the place of formation to the detector needed more time. This “delay” became possible due to the fact that in the ions, the internal conversion channel is closed, and the lifetime is much longer. However, necessary presence of the second stage in the NEET method essentially diminishes the cross-section, by orders of magnitude, as the related vertex turns out to be small. For example, in the case of neutral, singly- and doubly-charged ions of $^{229}$Th, this vertex turns out to be electrical quadrupole or a two-photon one. In both cases, it brings the strong suppression factor.

In the case of BIC, expression for the decay width $\Gamma_{bic}$ reads as follows [3]:

$$\Gamma_{bic} = (1 + R)\Gamma_\gamma$$  \hspace{1cm} (1)

where, in turn, the BIC factor $R$ is expressed in terms of the analogue of internal conversion coefficient $\alpha_I$

$$R = \frac{\alpha_I(M1)}{\Delta^3 + (\Gamma / 2)^2}$$  \hspace{1cm} (2)

with

$$\Gamma = \Gamma_n + \Gamma_a \approx \Gamma_a$$

being the total nuclear and atomic decay widths of the intermediate state, and

$$\Delta = \omega_a - \omega_n$$

is its defect of the resonance. It is conventionally accepted that the nuclear properties, specially the radioactive decay constant, are essentially independent of the physical environment.

Turning to the concrete conditions of experiment [1,2], we know that $0.01\ s$ is just the time during which fresh atoms and ions of isomeric $^{229}$Th are kept in the stopping cell for the purpose of thermalization. The cell is filled by helium buffer gas at the pressure of $40\ mbar$. This comprises $1/10$ of a normal atmosphere pressure. Therefore, taking into account what is said above, the lifetime of the excited atomic state might be reduced by up to an order of magnitude. This must be taken into account in future experiments and their interpretation.