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

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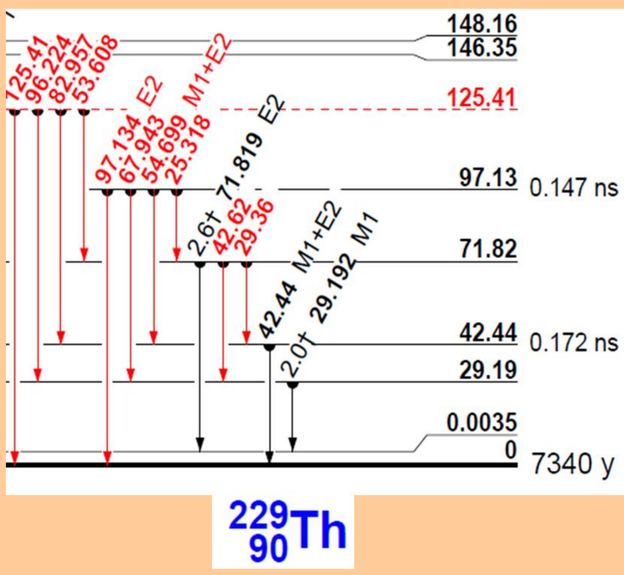
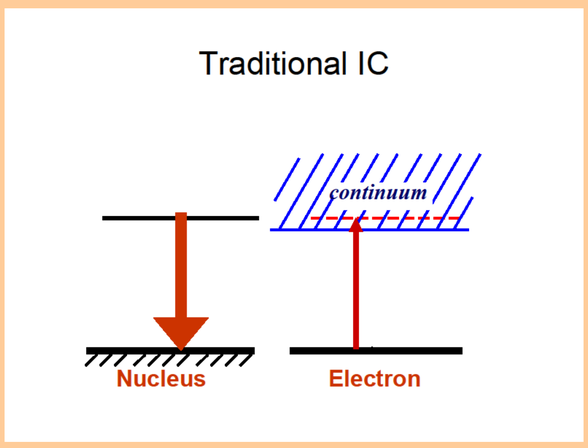
Creation of nuclear reference for the frequency, and nuclear clock on this basis, is a very topical problem at the contemporary research metrology. Simple estimates show that nuclear transitions are characterized with higher stability and narrower line widths. Basing on these principles, it is possible 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.

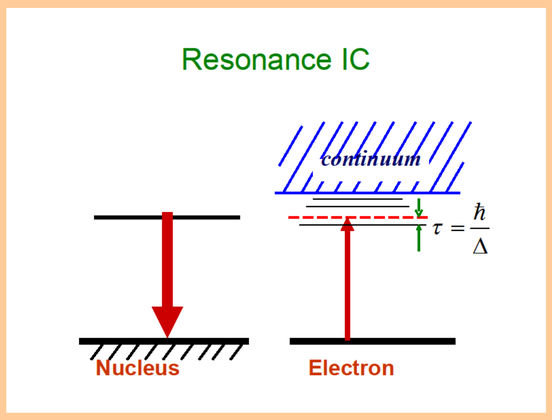
The idea of the new standard is founded on the cooperative atomic-nuclear transitions. Internal conversion transitions comprise a conventional class of the transitions of this type. They underlie nuclear spectroscopy, being used for decades. For the purpose of creation the nuclear CLOCK, subthreshold, 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.

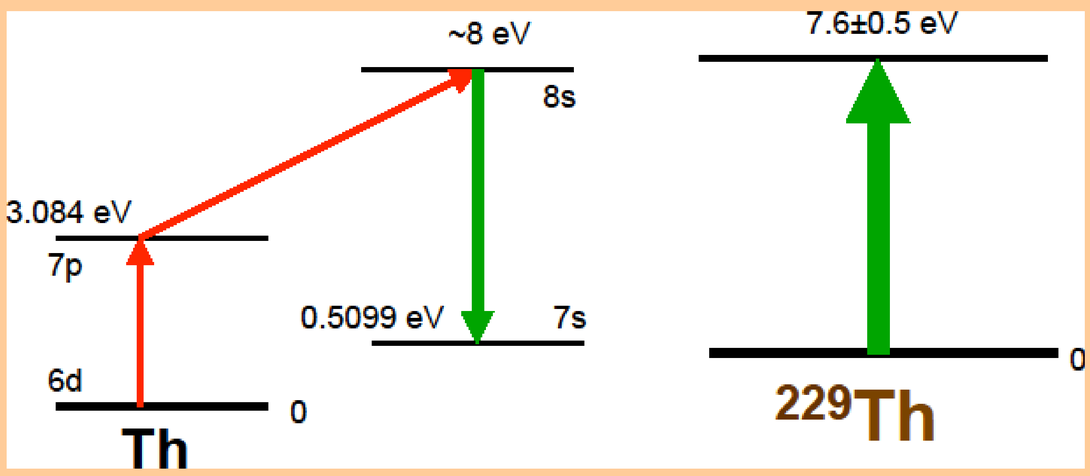


Consider ThII, whose experimental study was performed in PTB. Let ω_1 and ω_2 be the energies of the two laser photons. At the first step, atom absorbs photon ω_1 and transfers to the state 2. The ground-state configuration is $7s(6d)^2$, that of state 2 may be $(7s\ 7p\ 6d)J = 5/2$ with the energy of 24874 cm^{-1} = 3.084 eV. Absorbing then a second photon ω_2, the atom transfers to an intermediate state 3 with the energy $\hbar(\omega_1+\omega_2)$. Transferring part of the energy, $\hbar\omega_n$, to the nucleus, the atom comes to a state 4. Pursuing the reverse BIC mechanism, we derive interrelation

$$\hbar(\omega_1+\omega_2)= \hbar\omega_n+\varepsilon_4.$$







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 LIFETIE 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 μs. 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. It however remains much shorter than the radiative nuclear lifetime due to bound internal conversion (BIC). Thus, in singly charged ions the half-life is $\tau 1/2 < 0.01$ s. This is the first clear observation of BIC, which is based on interaction of the isomeric nuclei with the environment. This fact deserves the following comment

In the case of BIC, expression for the decay width Γ_{BIC} reads as follows [3]:

$$\Gamma_{BIC} = (1+R)\Gamma_\gamma^{(n)} \quad (1)$$

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

$$R = \frac{\alpha_d(M1)\Gamma/2\pi}{\Delta^2+(\Gamma/2)^2} \quad (2)$$

with

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

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

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

–| its defect of the resonance. It is conventionally accepted that the nuclear properties, specically 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 ^{229m}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.

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