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Impact of the ionization of the atomic shell on the lifetime of the ^{229m}Th isomer

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Abstract

Recent experimental data are analyzed, concerning the half-lives of the ^{229m}Th isomer in neutral atoms and various ions. Calculation is performed on the united platform of interplay of traditional and subthreshold resonance conversion. General agreement with experiment is obtained in the cases of Th I and Th III, a prediction is made concerning half-life in Th IV. Most critical is the case of Th II, where experimental data can be explained by interplay of various factors. A new physics is proposed, based on dependence of the nuclear lifetime on the ambient conditions, such as atmospheric pressure. This must be taken into account in future experiments and their interpretation.

Keywords: Internal conversion; BIC; Resonance conversion; Nuclear excitation in electronic transition; Nuclear isomers; Electronic bridges

1. Introduction

The idea of the combined atomic-nuclear transitions experienced a period of strong development during the past decades. Making use of the resonance properties of the electron shell opens the way of manipulating the nuclei. A possible practical realization of this way is the creation of the optical-nuclear clock based on a few-eV nuclear isomer of ^{229}Th, with the relative accu-

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racy up to 10^{-19}–10^{-21} [1,2]. For this purpose, more detailed information concerning the isomer properties is still needed, including the exact value of the isomer energy and its half-life time.

Indirect evidence of the presence of the isomeric level is known for decades. However, nobody could detect the isomer or its decay directly. Only recently, its decay through internal conversion (IC) was finally discovered [3]. Nevertheless, information about characteristic properties of the isomer, including its precise energy and lifetime, remains extremely scarce. Thus, the estimate of its energy varies in time. An energy of 3.5 eV was considered for a long time [4]. Sometimes, a value of 5.5 eV was also used [5]. Most recent measurements resulted in a higher value of 7.6 ± 0.5 eV [6]. However, other values are also checked and cannot be excluded (e.g., [3,7] and refs. cited therein). For the present purposes, we are oriented to this value as the latest data.

Moreover, the isomer half-life was measured for the first time. Its value of 7 μs was obtained in neutral atoms [7], in coincidence with the theoretical estimate [8]. In neutral atoms, the isomer energy is higher than the ionization potential $I_a = 6.3$ eV [9]. Therefore, decay occurs via IC. Let us start with consideration of this basic process in more detail.

2. Decay of the isomer through internal conversion in neutral atoms

The decay width is described by

$$\Gamma = (1 + \alpha(M1))\Gamma_\gamma^{(n)} , \tag{1}$$

with $\alpha(M1)$ being the internal conversion coefficient (ICC), and $\Gamma_\gamma^{(n)}$ — the radiative nuclear width. Ground state electronic configuration is $(7s)^2(6d_{3/2})^2$. With the calculated ICC value in the 7s electronic shell, $\alpha(M1) = 1.1 \times 10^9$ [8], Eq. (1) allows one to conclude on the radiative nuclear half-life to be $T_{1/2} \approx 2$ h.

It is didactic to trace how the estimation of the lifetime depends on the energy of the isomer. Let us consider Fig. 2 in [8]. The ICC is exactly inversely proportional to ω^{-3}, where ω is the transition energy. On the other hand, the nuclear radiative width $\Gamma_\gamma^{(n)}$ is proportional to ω^3. Thus the expected lifetime, which is inversely proportional to ICC times $\Gamma_\gamma^{(n)}$, holds with respect to variations of the supposed isomer energy. A change in the lifetime could be brought about by switching-on the next $6s$ shell to IC. But onset of the $6s$ shell would occur only at 37 eV in neutral atoms, and 56 eV — in the singly charged ions. Currently such energies are not under discussion.

In the ionized atoms of ^{229}Th, IC becomes energetically closed. However, its mechanism remains effective in the form of bound internal conversion (BIC), also called resonance conversion because of its resonance character. Let us consider this process in more detail.

3. Transition to the subthreshold region of BIC in the ions

In the case of singly charged ions, the ionization potential is $I_a = 12.1$ eV [9], and the IC channel is energetically closed. However, deexcitation occurs mainly through many electronic bridges. For the first time this was shown in [10] for the 76-eV ^{235}U isomer, and in [11] in the case of neutral atoms of ^{229}Th, under assumption of an isomer energy of 3.5 eV. Calculations for singly charged ions of ^{229}Th were performed in ref. [12]. More detailed calculations for the neutral atoms of ^{229}Th, taking into account mixing of the electronic configurations, were undertaken in refs. [8,13]. The results show that the main contribution comes from a few electronic transitions, in spite of the high fragmentation of the single-electron levels. For this reason, BIC

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