β-decay half-life of Th and U isotopes

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Introduction

In simple quantum mechanical view α-decay is a quantum tunneling through Coulomb barrier, which is forbidden by the classical mechanics. In the superheavy region of the nuclear chart, the prominent modes are the α-decay and spontaneous fission along the β-stability line. Due to quantum mechanical tunneling approach, the probabilities for ^{216}Th and ^{218}U are relatively high, because of the large width as compared to its barrier height. So, it is easier for the α-particle to escape the turning points. As we increase the number of neutrons in the nucleus, the Coulomb force becomes weak due to the hindrance of the repulsive among the protons. In such cases, the width of the two turning points is very large and the barrier height is small. Thus, the probability of α-decay with N>150 for Th and U isotopes is almost infinity and this types of nuclei are stable against α- or cluster-deacy. In such isotopes, the possible decay mode is the β-decay. The life time of these nuclei predicted to be tens of second against β-decay. If these nuclei utilize before their decay time, a lots of energy can be produced within the help of multi-fragmentation fission. Also, these nuclei have a great implication in astrophysical point of view. Here, we calculated the β-decay half-life of Th and U isotopes using the empirical formula of Fiset and Nix [1].

Formalism

In present manuscript, we used the axially deformed relativistic mean field formalism to calculate various nuclear phenomena. The meson-nucleon interaction is given by [2]

$$
\begin{aligned}
\mathcal{L} \;=\; & \overline{\psi_i}\{i\gamma^\mu\partial_\mu - M\}\psi_i + \frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 \\
& -\frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4 - g_s\overline{\psi_i}\psi_i\sigma - \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} \\
& +\frac{1}{2}m_w^2V^\mu V_\mu + \frac{1}{4}c_3(V_\mu V^\mu)^2 - g_w\overline{\psi}_i\gamma^\mu\psi_i V_\mu \\
& -\frac{1}{4}\vec{B}^{\mu\nu}.\vec{B}_{\mu\nu} + \frac{1}{2}m_\rho^2\vec{R}^\mu.\vec{R}_\mu - g_\rho\overline{\psi}_i\gamma^\mu\vec{\tau}\psi_i.\vec{R}^\mu \\
& -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - e\overline{\psi}_i\gamma^\mu\frac{(1-\tau_{3i})}{2}\psi_i A_\mu. \qquad (1)
\end{aligned}
$$

Where, ψ is the Dirac spinor and meson fields are denoted by σ,V^μ and R^μ for σ,ω and $\rho-$ meson respectively. The electromagnetic interaction between the proton is denoted by photon field A^μ. g_s, g_ω, g_ρ and $\frac{e^2}{4\pi}$ are the coupling constants for the σ,ω and $\rho-$ meson and photon field respectively.

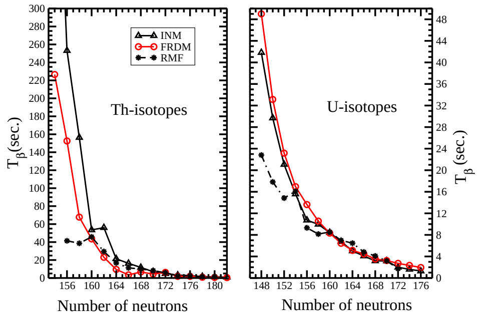

FIG. 1: The β-decay half life for Th and U isotopes are calculated using the formula of Fiset and Nix [1] [eq. (2)]. The ground state binding energies are taken from FRDM [4], INM [3] and RMF models.

β-decay half-life

Actually, the β-decay life time should be evaluated in a microscopic level, but in this

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paper, it is beyond the scope. Here we have used the empirical formula of Fiset and Nix [1], which is defined as:

$$T_\beta = (540 \times 10^{5.0}) \frac{{m_e}^5}{\rho_{d.s.}({W_\beta}^6 - {m_e}^6)} sec. \quad (2)$$

Similar to the α-decay, we evaluate the Q_β-value for Th and U series using the relation $Q_\beta = BE(Z+1, A) - B(Z, A)$ and $W_\beta = Q_\beta + {m_e}^2$. Here, $\rho_{d.s.}$ is the average density of states in the daughter nucleus ($e^{-A/290}$ $\times$ number of states within 1 MeV of ground state). To evaluate the bulk properties, such as binding energy of odd-Z nuclei, we used the Pauli blocking approximation, which restores the time-reversal symmetry. Here, we have taken BCS pairing for the calculations. The odd particle stays in one of these states, and its corresponding conjugate state remains empty. In principle, one has to block in turn different states around the Fermi level to find the one that gives the lowest energy configuration of the odd nucleus. For odd-odd nuclei, one needs to block both the odd neutron and odd proton.

The obtained results are displayed in Fig. 1 for both Th and U isotopes. From the figure, it is clear that for neutron-rich Th and U nuclei, the prominent mode of decay is β-decay. This means, once the neutron-rich thermally fissile isotope is formed by some artificial mean in laboratory or naturally in supernovae explosion, immediately it undergoes β-decay. In our rough estimation, the life time of ^{254}Th and ^{256}U, which are the nuclei of interest has tens of seconds. If this prediction of time period is acceptable, then in nuclear physics scale, is reasonably a good time for further use of the nuclei. It is worthy to mention here that thermally fissile isotopes of Th and U series are with neutron number N=154-172 keeping N=164 in the middle of the island. So, in case of the short life time of ^{254}Th and ^{256}U, one can choose a lighter isotope of the series for practical utility.

Conclusion

Our calculation predicts that the β-decay life time is about tens of seconds for ^{254}Th and ^{256}U and this time increases for nuclei with less neutron number, but thermally fissile. Finite life time of these thermally fissile isotopes could be very useful for energy production in nuclear reactor technology. If these neutron-rich nuclei use as nuclear fuel, the reactor will achieve critical condition much faster than the normal nuclear fuel, because of the release of large number of neutrons during the fission process.

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