^{164}Pb: A possible heaviest $N = Z$ doubly magic nucleus[†]

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With the advent of accelerator facilities worldwide, the nuclear chart has been rapidly extended towards the regions where the neutron or proton number far exceeds that of naturally abundant nuclei. A fundamental question motivating such experimental challenges is "How far from the beta stability line nuclei can exist with a finite half-life?," which serves as a rigorous test for our understanding of the nuclear binding.

For each isotopic chain, the binding energy of the outermost valence neutron defines the limit of neutron excess. In contrast, the limit of proton excess remains ambiguous both experimentally and theoretically. This ambiguity arises because, in extremely proton-rich nuclei, proton orbitals with positive energy can be meta-stable with the assistance of the Coulomb barrier, allowing them to exist with finite half-lives that undergo charged-particle emission.

The decay lifetime of states confined by the Coulomb barrier depends exponentially on the difference between the Coulomb barrier height and the binding energy. If a shell gap exists in the proton orbitals, the decay lifetime should differ by orders of magnitude above and below the gap. Therefore, a double closed-shell nucleus likely represents the limit of the existence of proton-rich nuclei. In this sense, ^{164}Pb is a candidate for the last double closed nucleus following ^{100}Sn, and it could be the ultimate endpoint for proton-rich nuclei. However, it is not trivial whether the magic numbers remain intact in a mass region significantly different from ordinary nuclei.

Therefore, in this paper, to seek the possibility of a finite half-life of ^{164}Pb and whether $Z = N = 82$ magicity holds, we investigate this nucleus using the Skyrme Hartree-Fock-Bogoliubov (HFB) calculation with continuum. Since some protons occupy near or above the threshold, it is crucial to consider the pairing correlation coupling to the continuum. We use typical six Skyrme energy density functionals (EDF)—SLy4, SLy5, SkM*, UNEDF0, UNEDF1, and UNEDF2 and the volume-type pairing interaction.

The proton lowest unoccupied orbital is the $2f_{7/2}$, whose energy is approximately 8 MeV, and the pairing gap of ^{164}Pb is less than 10 keV. Hence, the $Z = 82$ shell gap is large enough. Furthermore, we confirmed that the $N = Z$ nuclei are calculated within the axial deformation. The systematics of Δ, S_{2p}, Q_α, and the deformation parameter β_2 also show that ^{164}Pb is a typical doubly magic nucleus. Therefore, we conclude that $Z = N = 82$ magicity still holds.

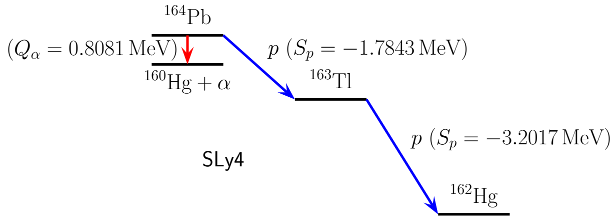

Fig. 1. Decay scheme of ^{164}Pb calculated with the SLy4 EDF.

Despite considerable neutron deficiency, the single-particle spectra are still similar to those of stable isotopes. The proton highest occupied single-particle orbital is the $3s_{1/2}$, which is not a standard shell structure. The proton single-particle orbitals of the *sdg*-shell behave similarly to the bound orbitals and are localized in $r \lesssim 10$ fm, inside the Coulomb barrier.

As all the EDFs yield $S_p < 0$, $S_{2p} < 0$, and $Q_\alpha > 0$, one- and two-proton emission, and the α decay channels should be open as summarized in Fig. 1. Since the proton highest single-particle orbital is the $3s_{1/2}$, the $1p$ emission from this orbital should dominate and $2p$-emission process is negligible.

Then, the half-life of the one-proton emission is estimated by using the Wentzel–Kramers–Brillouin (WKB) approximation. As discussed above, we assume that a $3s_{1/2}$ proton is emitted. The estimated half-lives range from the order of 0.1 ps to 10 ns, which is regarded as the uncertainty originates in an EDF. Especially, if $\epsilon_{\pi 3s_{1/2}}$ is small enough, as in the SLy4, SLy5, and SkM* cases, it is possible to measure properties of ^{164}Pb before its decay by accelerator experiments. In addition, we find that the half-life is roughly determined by only the single-particle energy of the proton $3s_{1/2}$ orbital. In turn, this means that the measurement of the half-life will provide an estimation of the proton single-particle energy $\epsilon_{\pi 3s_{1/2}}$.

Lastly, we estimate the α-decay half-life $T^\alpha_{1/2}$. We use a phenomenological formula proposed in Ref. 1). The estimated values of $T^\alpha_{1/2}$ are more than 10^{35} s; thus, we need not to consider the α decay of ^{164}Pb.

The recent experiment[2)] predicted that the $N = 82$ magic number is still robust in the neutron-deficient side. Our finding also supports this prediction, and the synthesis of ^{164}Pb at next-generation accelerator facilities is demanded.

References
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