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Discovery of New Isotopes ^{160}Os and ^{156}W: Revealing Enhanced Stability of the $N = 82$ Shell Closure on the Neutron-Deficient Side

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Using the fusion-evaporation reaction ^{106}Cd(^{58}Ni, $4n$)^{160}Os and the gas-filled recoil separator SHANS, two new isotopes $^{160}_{76}$Os and $^{156}_{74}$W have been identified. The α decay of ^{160}Os, measured with an α-particle energy of 7080(26) keV and a half-life of 201^{+58}_{-37} μs, is assigned to originate from the ground state. The daughter nucleus ^{156}W is a β^+ emitter with a half-life of 291^{+86}_{-61} ms. The newly measured α-decay data allow us to derive α-decay reduced widths (δ^2) for the $N = 84$ isotones up to osmium ($Z = 76$), which are found to decrease with increasing atomic number above $Z = 68$. The reduction of δ^2 is interpreted as evidence for the strengthening of the $N = 82$ shell closure toward the proton drip line, supported by the increase of the neutron-shell gaps predicted in theoretical models.

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The magic numbers of protons and neutrons, arising from the large energy gaps in the effective single-particle spectrum, are related to the stability of nucleus. However, the vanishing of traditional shell closures and the emergence of new magic numbers were viewed through the systematics of experimental observables, such as separation energies from atomic mass measurements, nuclear radius, energy of excited state, electromagnetic transition strength, etc. [1–3]. These changes of shell structure shed new light on nuclear forces [4]. In the neutron-deficient side, the study of α decay can provide an effective way to obtain information on shell structure. For example, the evolution of the $N = 126$ shell closure and its influence on the stability of uranium ($Z = 92$) and neptunium ($Z = 93$) isotopes were studied recently with the discovery of several new α-emitting isotopes [5–7]. According to these studies, it is recognized that the $N = 126$ shell effect is weakened when approaching the proton drip line but still exists in U and Np isotopes. Such a shell variation is one of the compelling issues in nuclear physics, and whether it will also take place at the $N = 82$ shell closure remains an open question worth investigating.

In analogy to the neutron shell closure at $N = 126$ which has a significant impact on the α-particle preformation probability [8–10], the $N = 82$ shell closure also strongly influences the α-decay process as evidenced by the abrupt change from α decay to β^+ decay when crossing the $N = 82$ shell toward lower neutron number. This is associated with the dramatic reduction in α-decay rates from $N = 84$ to 82, owing to the existence of the $N = 82$ shell gap. Consequently, no α emitter with $N = 61$–83 are found to date, and the $N = 84$ isotones become the lower limit of heavy nuclei to undergo α decay. As the $N = 84$ and 85 isotones are close to the $N = 82$ neutron shell, their α-decay systematics can provide hints on the change of this shell toward the proton drip line. Usually, the effort to establish the shell evolution of the $N = 82$ concentrates on neutron-rich nuclei around $^{132}_{50}$Sn [11–16], and less is known about this closure at the neutron-deficient side just due to the lack of experimental data on heavy $N = 80$–84 isotones.

In this Letter, we present the first identification of the nuclei ^{160}Os and ^{156}W, representing the most proton-rich $N = 84$ and 82 isotones to date. The new data obtained for ^{160}Os together with the literature values allow us to construct the tendency of the α-decay reduced widths (δ^2) for the $N = 84$ isotones up to Os. Based on the systematics of δ^2 values and neutron-shell gaps, a strengthening of the $N = 82$ shell closure near the proton drip line is inferred.

The experiment was performed at the Spectrometer for Heavy Atoms and Nuclear Structure (SHANS) [17]. The ^{160}Os nuclei were produced in the $^{106}\mathrm{Cd}(^{58}\mathrm{Ni}, 4n)^{160}\mathrm{Os}$ reaction, and the ^{156}W nuclei were populated via the α decay of ^{160}Os. The 335-MeV $^{58}\mathrm{Ni}^{19+}$ beam with a typical intensity of ∼10 pnA was delivered by the Sector Focusing Cyclotron of the Heavy Ion Research Facility in Lanzhou (HIRFL), China. Isotopically enriched (99.6%) ^{106}Cd targets with thickness of 365–415 $\mu\mathrm{g/cm}^2$ were mounted on a rocking frame which moves horizontally and periodically from side to side during the 163-h irradiation period. The evaporation residues were collected and separated by SHANS, and then implanted into three 300-μm-thick position-sensitive silicon strip detectors (PSSDs) surrounded by eight non-position-sensitive silicon detectors. All silicon detectors were cooled to a temperature of −37 °C using circulating ethanol. Energy resolution of individual strips of the PSSDs was about 30 keV (FWHM) for 5–9 MeV α particles, and vertical position resolution was better than 1.2 mm. In the case of protons or escaped α particles deposited less than 3-MeV energy in the PSSDs, the position resolution was deteriorated to be 3–5 mm. In order to distinguish the radioactive decay events from the implantation events, two multi-wire proportional counters were mounted in front of the PSSDs. To measure γ rays, two high-purity Ge detectors were used, which were mounted around the silicon detectors in close geometry. After they were amplified with preamplifiers, all detector signals were processed in a digital data acquisition system, where they were time stamped with a precision of 10 ns to allow flexible off-line data analysis. More details on the experimental setup and data analysis can be found in Refs. [17,18].

Based on the FRDM2012 mass model [19], ^{160}Os is expected to be the lightest α-emitting isotope in osmium, and its daughter nuclide ^{156}W with $N = 82$ would be a β^+ emitter. For clarity, the expected decay scheme of ^{160}Os as well as the subsequent decays is shown in Fig. 1. In order to isolate α decays of ^{160}Os from the large number of counts in the α-particle energy spectrum of Fig. 2(a), correlations were first sought with the proton decays of ^{156}Ta, populated via the β^+ decay of ^{156}W (see Fig. 1). Figure 2(b) shows the energy spectrum of the α particles that are followed within 1.2 s by a signal in the energy range of 975–1025 keV, which would correspond to possible proton decays of the

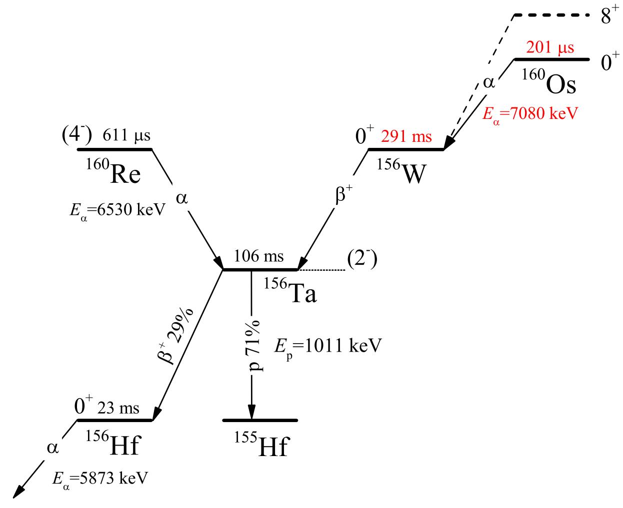

FIG. 1. The decay chain of ^{160}Os. Half-lives, decay energies and branching ratios are taken from Ref. [20] and this Letter (red color). The expected 8^+ isomeric state in ^{160}Os is indicated by a thick horizontal dashed line.

2^- state in ^{156}Ta [$E_p = 1011(5)$ keV, $T_{1/2} = 106(4)$ ms] [20]. More than ten peaks are viewed in Fig. 2(b), but most of them are due to random correlations of the known α-decay signals with escaped α particles falling within the proton energy gate. These background peaks can be identified in Fig. 2(c), for which the energy gate was shifted below the proton peak of ^{156}Ta but still included the background from escaping α particles. Clearly, two α peaks in Fig. 2(b) do not appear in Fig. 2(c) and hence they are attributed to real correlations. The significant peak at 6530(20) keV was identified to ^{160}Re [20] as ^{156}Ta could be fed directly by the α decay of ^{160}Re, see Fig. 1. The ^{160}Re was considered to be the product of the $1p3n$ reaction channel. The weak peak comprising ∼20 events at 7080 (26) keV was attributed to the α decay of the new isotope ^{160}Os, the half-life of which was determined to be 201^{+58}_{-37} μs using the method of maximum likelihood [21].

From the time intervals between the decays of ^{160}Os and ^{156}Ta, the half-life of ^{156}W was roughly estimated to be 291^{+86}_{-61} ms by assuming that the measured half-life for ^{156}Ta is consistent with the literature value of 106(4) ms [20]. The error bars include the uncertainty in the lifetime of ^{156}Ta. Notably, the deduced half-life of ^{156}W is approximate to that of its neighboring isotope ^{157}W [$T_{1/2} = 275(40)$ ms] [22], which is in compliance with the regularity that the half-lives of the $N = 82$ and 83 β-emitting isotopes above Gd ($Z = 64$) are always close to each other.

Considering the non-negligible β-decay branch of the 2^- state in ^{156}Ta as shown in Fig. 1, the α decay of ^{160}Os was then searched using correlations with the α decays of ^{156}Hf. The resultant spectra do not show a distinguishable peak at 7080 keV, owing to the anticipated factor of

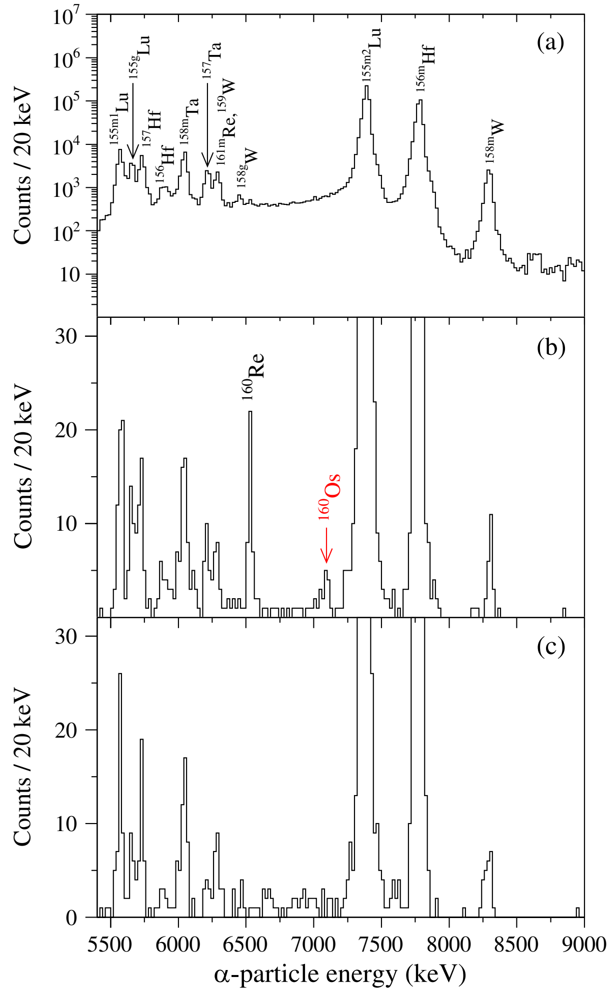

FIG. 2. (a) Energy spectrum of α particles occurring within 30–700 μs of the implantation of an evaporation residue into the same PSSD pixel. Known α-decay lines are labeled. (b) Alpha particles in (a) that were followed within 1.2 s by the proton decays of ^{156}Ta. The red arrow indicates the α peak attributed to the new isotope ^{160}Os. (c) The same as (b) except the energy gate selected for the second decay is below the proton peak.

3 statistical reduction in the number of ^{160}Os burying it below background. When the β-decay branch of ^{156}Ta is taken into account, the production cross section of ^{160}Os is estimated to be $5.4^{+1.2}_{-1.0}$ nb.

In addition, according to the energy level systematics (Fig. 6 in Ref. [23]) for the $N = 84$ isotones, a $\nu(f_{7/2} \otimes h_{9/2})8^+$ yrast trap isomer is expected to exist in ^{160}Os. However, no evidence for the isomer was found in the present work. Only the events observed in the correlations with the proton emissions from ^{156}Ta (2^-) were utilized to determine the decay properties of ^{160}Os and ^{156}W.

As illustrated in Fig. 3, the newly measured α-decay properties of ^{160}Os fit quite well into the systematics of α-decay energies (Q_α) and partial α-decay half-lives ($T^{\alpha}_{1/2}$) for the nearby even-Z isotopes, which implies that the

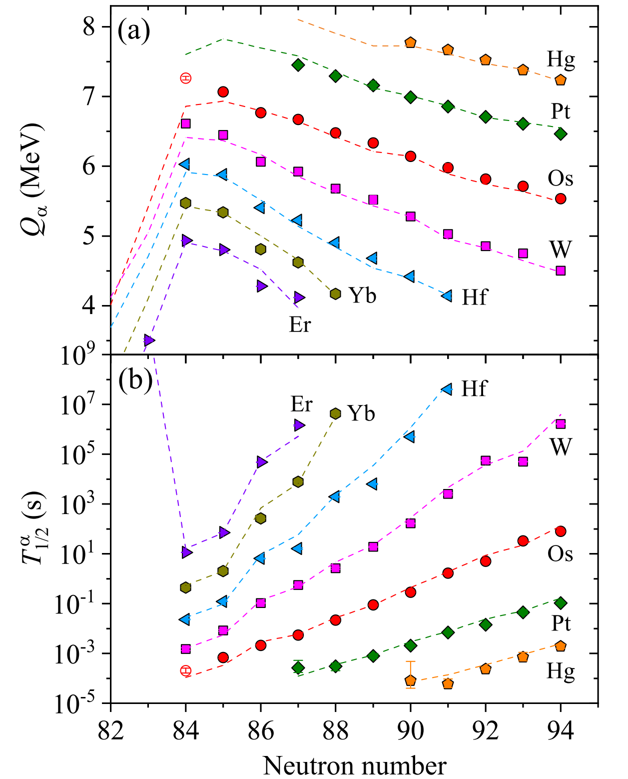

FIG. 3. The (a) Q_α and (b) $T^{\alpha}_{1/2}$ values of ground-state to ground-state transitions for neutron-deficient Er, Yb, Hf, W, Os, Pt, and Hg isotopes as a function of the neutron number N. Experimental data are taken from [25–27] and this Letter (open symbols). The corresponding theoretical values (dash lines) are taken from [28] or calculated using the Rasmussen method [24].

observed α decays originate from ground states. From the regular behavior of Q_α, one can deduce a general trend. For a given isotopic chain, Q_α increases as a function of decreasing neutron number, reaching its maximum value at $N = 84$. When $N = 84$ is crossed, a sudden decrease of about 2 MeV is expected, see Fig. 3(a). The general trend is a clear manifestation for the existence of the $N = 82$ shell closure. Accordingly, the Q_α value of ^{160}Os allows extending the trend for Os isotopes down to $N = 84$ smoothly, suggesting the possible persistence of the $N = 82$ shell closure up to $Z = 76$. To reach a firm conclusion, high-precision mass measurements of the $N = 83$ isotones above $Z = 68$ are necessary. Furthermore, the half-life obtained for ^{160}Os, together with the existing $T^{\alpha}_{1/2}$ values of other neutron-deficient Hf-Hg isotopes, is compared with the values calculated using the formalism of Rasmussen [24]. As shown in Fig. 3(b), the measured 201^{+58}_{-37} μs agrees with the calculated value of 109 μs within a factor of 2.

The α-decay reduced width δ^2 defined in Ref. [24] is related to the α-particle preformation probability and has been employed to obtain detailed information on nuclear structure successfully [5,9,29]. To explore the evolution of the $N = 82$ shell closure, the δ^2 values of the $N = 84$ and 85

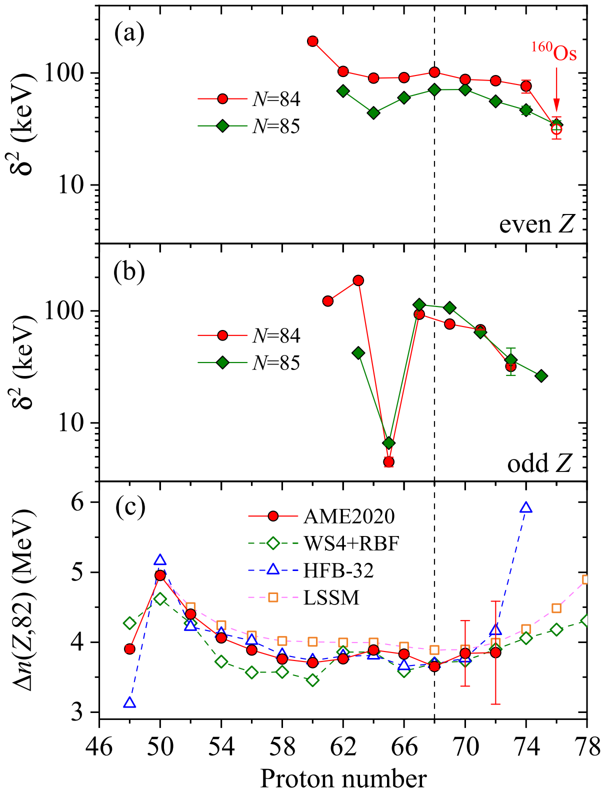

FIG. 4. Reduced α-decay widths δ^2 of (a) even-Z and (b) odd-Z $N = 84$, 85 isotones as a function of proton number. The datum of ^{160}Os is marked by an open symbol. (c) Experimental neutron-shell gaps of the $N = 82$ isotones from AME2020 [25] compared to the predictions of WS4 + RBF (open diamonds) [28,35], HFB-32 (open triangles) [36], and LSSM (open squares) [2,37,38] models.

α emitters were extracted from the experimental Q_α [25] and $T^{\alpha}_{1/2}$ [26,27,30] data. The deduced δ^2 values, which correspond to the ground-state to ground-state transitions, are plotted in Figs. 4(a) and 4(b) as a function of proton number Z, separately for even and odd atomic numbers. It is worth pointing out that the δ^2 value of ^{148}Gd ($Z = 64$, $N = 84$) in Fig. 4(a) was derived using the latest measured half-life of 86.9(39) years [30], and the observed small dip at $Z = 64$ is in agreement with the results reported in Refs. [31–33] rather than the result in [34], which clarifies an early debate about whether δ^2 values of the $N = 84$ α emitters show a dip at $Z = 64$. The δ^2 values of odd-Z isotones shown in Fig. 4(b) is similar in trend to that of even-Z isotones, except for the larger dips with a shift of one unit on proton number. This is usually attributed to the blocking effect of unpaired proton [32]. The comparison of the data in Figs. 4(a) and 4(b) implies that the odd proton blocking effect on δ^2 is more significant than that of odd neutron.

Furthermore, as shown in Figs. 4(a) and 4(b), the δ^2 values display systematic decreases above $Z = 68$. The value of ^{160}Os appears to continue the decreasing trend even with a larger drop from $^{158}_{74}$W to $^{160}_{76}$Os, which clearly indicates the enhanced stability of ^{160}Os against α decay. As the $N = 84$ and 85 isotones are close to the $N = 82$ shell closure, the variation of δ^2 values for the $N = 84$ and 85 isotones is considered to be closely related to the evolution of this shell, just as the increasing trend of δ^2 for the proton-rich $N = 124$–130 isotones was attributed to the weakening of the $N = 126$ shell effect when moving away from $Z = 82$ (see Fig. 5 in [5]). Therefore, the systematic decreasing behavior of δ^2 for the $N = 84$ and 85 isotones from $Z = 68$ to 76 evinces the enhanced stability of the $N = 82$ shell closure toward the proton drip line, which can be attributed to the proximity to the $Z = 82$ shell closure. The importance of the new experimental data reported here can be assessed by noticing that, in previous studies [31–34], the behavior of δ^2 for the $N = 84$ isotones above $Z = 68$ is uncertain just due to the lack of reliable experimental data on heavier isotones.

Further evidence for the enhanced $N = 82$ shell effect can be found in the behavior of the neutron-shell gap Δn. The procedure to extract the gap values involves the binding energies (B) of the $N = 82$ nuclei and its neighbors according to $\Delta n(Z,82) = 2B(Z,82) - B(Z,83) - B(Z,81)$ [39]. A nucleus with a closed (sub)shell has a relatively high binding energy among neighboring nuclei, resulting in an enhanced Δn value. The values extracted using the experimental or extrapolated AME2020 [25] masses are shown in Fig. 4(c), from which it can be seen that all Δn values from $Z = 48$ to 68 are larger than 3.5 MeV, indicating the strong $N = 82$ shell effect. The maxima at $Z = 50$ and 64 confirm the well established doubly magic character of $^{132}_{50}$Sn and $^{146}_{64}$Gd. However, the experimental information on Δn above $Z = 68$ is much more limited compared to that on δ^2. Therefore, in the nuclear region above Er, it is essential to inspect the behavior of Δn theoretically. To this end, we extracted the Δn values using the predicted masses of various theoretical models, WS4 + RBF [28,35], HFB-32 [36], FRDM2012 [40], HFBCS-1 [41], DZ28 [42], HFB-27 [43], KTUY05 [44], RMF [45], and large-scale shell model (LSSM) [2,37,38], and compared them to experimental data. The best agreements with the data are obtained by the WS4 + RBF, HFB-32, and LSSM models, which reproduce the experimental Δn values over a wide range of atomic numbers, see Fig. 4(c). Crucially, all of the three theoretical models predict an increasing trend of Δn above $Z = 68$, which yields a strong support for the above discussed strengthening of the shell closure inferred from the systematics of δ^2 values. The stronger shell effect toward higher Z can be explained in terms of the concept of mutually enhanced magicity [46], namely, a strong correlation of the $N = 82$ and $Z = 82$ shell strengths, implying that the hitherto unobserved ^{164}Pb could be a doubly magic nucleus with increased stability.

In conclusion, using the fusion-evaporation reaction ^{58}Ni + ^{106}Cd and the gas-filled recoil separator SHANS, the α-emitting isotope ^{160}Os and its β-emitting daughter ^{156}W have been identified for the first time. The measured α-particle energy and half-life values of ^{160}Os are 7080 (26) keV and 201^{+58}_{-37} μs, respectively. The half-life of ^{156}W was determined to be 291^{+86}_{-61} ms. Combining the newly measured α-decay properties with existing data, we obtained an updated systematics of α-decay reduced widths for the $N = 84$ and 85 isotones, from which a systematic decreasing behavior from $Z = 68$ to 76 were observed. We interpreted the observed feature as an evidence of the enhanced shell effect for the $N = 82$ neutron magic number toward the proton drip line. This finding was also supported by the increasing trend of the $N = 82$ shell gaps above $Z = 68$ predicted in three different theoretical models. To further investigate the evolution of the $N = 82$ shell closure at the neutron-deficient side, it would be very interesting to continue α-decay studies of even heavier $N = 84$, 85 isotones such as ^{161,162}Ir and ^{162,163}Pt to see whether they follow the δ^2 systematics. Moreover, high-precision mass measurements of the $N = 81$–83 isotones above $Z = 68$ are definitely desired.

Note added.—Recently, a parallel effort to discover ^{160}Os and ^{156}W [47] was published. We note that our results are in agreement with the reported data within the experimental accuracy.

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