

Bayesian inference correlation: From α -particle preformation factor to α -decay properties in heavy and superheavy nuclei

Xiao-Yan Zhu,^{1,*} Wei Gao,² Liqiang Zhu,³ Wen-Jing Xing,^{4,†} Xun Chen,^{4,‡} Wen-Bin Lin^{1,§} and Xiao-Hua Li^{4,||}

¹*School of Mathematics and Physics, University of South China, Hengyang 421001, China*

²*School of Physical Science and Technology, Southwest Jiaotong University, Chengdu 610031, China*

³*Key Laboratory of Quark and Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan 430079, China*

⁴*School of Nuclear Science and Technology, University of South China, Hengyang 421001, China*



(Received 7 April 2025; revised 15 June 2025; accepted 29 July 2025; published 29 August 2025)

In this study, we propose a novel Bayesian inference framework combined with the two-potential approach (TPA) to systematically investigate the α -particle preformation factors and decay properties of heavy and superheavy nuclei. By employing Markov chain Monte Carlo (MCMC) sampling, we globally calibrate the adjustable parameters of phenomenological α preformation factors, while incorporating experimental uncertainties in decay energies and half-lives. Our results reveal a significant correlation between the parameters, and the nuclear shell effects near neutron magic numbers $N = 126, 152$, and 162 play a key role. The 95% posterior confidence levels provided by the Bayesian method significantly enhance the reliability of parameter estimation, which is superior to traditional least-squares optimization. Notably, the derived preformation factors exhibit systematic deviations near shell closures, highlighting the necessity of explicitly incorporating nuclear structure effects. This work not only advances the precision of α -decay predictions but also offers a deeper understanding of shell evolution and collective effects in superheavy nuclei.

DOI: [10.1103/x53t-7fb8](https://doi.org/10.1103/x53t-7fb8)

I. INTRODUCTION

Since 1928, when Gamow [1] and Condon and Gurney [2] successfully explained the phenomenon of α decay through quantum tunneling effect, α decay has become one of the primary decay models for heavy and superheavy nuclei. This discovery not only provided a crucial probe for the study of unstable nuclei [3,4], neutron-deficient nuclei [5,6], and superheavy nuclei [7,8], but also offered a key method for the synthesis and identification of new elements [9,10]. Moreover, the phenomenon of α decay has provided a wealth of information for uncovering nuclear structural features such as the nuclear shell effects [11], energy level structures [12], coexistence of nuclear forms [13], and so on [14–16].

In recent years, with the development of particle accelerators and detection technologies, scientists have successfully synthesized several superheavy nuclei using both “hot fusion”

and “cold fusion” techniques [17–25]. At present, through the collision and fusion of the light projectile nucleus (^{48}Ca) and the heavy actinide target nucleus (^{249}Cf), the superheavy element with atomic number $Z = 118$ has been successfully synthesized [26]. It is through these experimental advancements that the synthesis of superheavy nuclei is propelled and theoretical investigations into their structural configurations and decay mechanisms are advanced, positioning this dual progress at the forefront of nuclear physics research.

In the process of α decay, the α preformation factor P_α reflects the relative probability of an α cluster forming either on the surface or within the interior of the decaying parent nucleus. Given that the α preformation factor is closely related to the structure and state of both the parent and daughter nuclei, it is serves as a critical probe for studying nuclear structure [27–34]. Although the structure of heavy and superheavy nuclei has been extensively studied, a major bifurcation between the theoretical half-lives of α decay and the experimental ones remains how to accurately calculate the α preformation factor. Due to the structural complexity of quantum many-body systems, it is difficult for many microscopic theories to effectively calculate the α preformation factor for nuclei heavier than ^{212}Po , as in the microscopic wave function approach [35–38], the density-dependent cluster model [39,40], the R -matrix method [41,42], and so on [43–46]. Furthermore, assuming a constant α preformation factor in the cluster model fails to adequately reflect the microscopic nuclear structure information. Therefore, there is often a significant deviation between the α decay calculated

*Contact author: xyzhu0128@163.com

†Contact author: wenjing.xing@mails.ccnu.edu.cn

‡Contact author: chenxun@usc.edu.cn

§Contact author: lwb@usc.edu.cn

||Contact author: lixiaohuaphysics@126.com

half-lives and experimental ones by using this model. Currently, the magic numbers of heavy and superheavy nuclei are uncertain, which makes it difficult to generalize certain formulas to the study of superheavy nuclei.

To this end, there is a pressing need to establish a new approach that more accurately describes the microscopic mechanisms of the α preformation factor. In a recent study by [47], an analytical formula with five effective parameters was proposed by combining experimental data of decay energy and half-life and using the least-squares (LS) method to study the α preformation factors of heavy and superheavy nuclei. Additionally, this study further uncovered the properties of nuclei near the neutron magic numbers $N = 126, 152$, and 162 [33]. While this approach is effective, its parameter estimation based on the least-squares method has certain limitations, mainly in the selection of model parameters and error handling. Therefore, a scheme combining Bayesian inference and the two-potential approach (TPA) model is proposed in this study. Compared with the traditional least-squares optimization method, using the global fitting method, Bayesian inference provides a confidence for each parameter by considering the uncertainty of experimental data and combining the error bars from the lattice preformation factor data, thus enhancing the reliability and robustness of parameter estimation. This approach not only addresses the uncertainty of the data better, but also provides more accurate estimation of the preformation factors, so as to improve the accuracy of the theoretical prediction, and then provides more intensive theoretical support for the structure and decay properties of superheavy nuclei.

The structure of this article is organized as follows. Section II gives a brief introduction of the theoretical framework. Section III presents Bayesian inference in phenomenological models. In Sec. IV, the detailed calculations and discussions are presented. Finally, Sec. V provides a concise summary.

II. THEORETICAL FRAMEWORK

The α decay half-life within the two-potential approach framework can be generally defined as

$$T_{1/2} = \frac{\hbar \ln 2}{\Gamma}, \quad (1)$$

where Γ denotes the α -decay width, which is given by

$$\Gamma = \frac{\hbar^2 F P P_\alpha}{4\mu}, \quad (2)$$

where $\hbar$ and μ are the Planck constant and reduced mass of the α particle and daughter nucleus, respectively. F represents the normalization factor, an essential physical quantity associated with collision probability or impact frequency. P denotes the penetration probability, which characterizes the quantum tunneling effect through a potential barrier and is calculated using the semiclassical Wentzel-Kramers-Brillouin (WKB) approximation. The expressions for F and P are given as [48]

$$F \int_{r_1}^{r_2} \frac{1}{2k(r)} dr = 1, \quad (3)$$

$$P = \exp\left(-2 \int_{r_2}^{r_3} k(r) dr\right). \quad (4)$$

Here, $k(r) = \sqrt{\frac{2\mu}{\hbar^2} |V(r) - Q_\alpha|}$ represents the wave number of the α particle, with r being the center-of-mass distance between the daughter nucleus and preformed α particle. Q_α and $V(r)$ are the α -decay energy and total interaction potential, respectively. r_1 , r_2 , and r_3 are the classical turning points, which satisfy the conditions $V(r_1) = V(r_2) = V(r_3) = Q_\alpha$.

In general, the total potential $V(r)$ consists of three components: the nuclear potential $V_N(r)$, Coulomb potential $V_C(r)$, and centrifugal potential $V_l(r)$. In this work, the centrifugal potential is defined as $V_l(r) = \frac{\hbar^2(l+\frac{1}{2})^2}{2\mu r^2}$, where l is the angular momentum. The nuclear potential $V_N(r)$ is chosen as the cosh type parametrized form, which can be described as

$$V_N(r) = -V_0 \frac{1 + \cosh(R/a_0)}{\cosh(r/a_0) + \cosh(R/a_0)}, \quad (5)$$

where V_0 is the depth of the nuclear potential well, and a_0 represents its surface diffuseness parameter [49]. The Coulomb potential is approximated as a that of a uniformly charged sphere,

$$V_C(r) = \begin{cases} \frac{Z_\alpha Z_d e^2}{2R} \left(3 - \frac{r^2}{R^2}\right), & r \leq R, \\ \frac{Z_\alpha Z_d e^2}{r}, & r > R, \end{cases} \quad (6)$$

where $R = 1.28A^{1/3} - 0.76 + 0.8A^{-1/3}$, Z_α and Z_d are the proton numbers of α particle and daughter nucleus, respectively. In this work, for the α -particle preformation factor P_α , a phenomenological analytic expression proposed by Ref. [47], which is expressed as

$$\log_{10} P_\alpha = aZQ_\alpha^{-1/2} + bA^{1/3} + c + dl + h, \quad (7)$$

where A and Z represent the mass and proton number of parent nucleus, while a , b , c , d , and h are the adjustable parameters, respectively.

III. BAYESIAN INFERENCE IN PHENOMENOLOGICAL MODELS

The efficacy of Bayesian inference method in heavy-ion collision studies [50–61] will motivate its extension to α decay systematics. In this study, we implement Markov Chain Monte Carlo (MCMC) sampling to globally calibrate the adjustable parameters $\theta = (a, b, c, d, h)$ of the phenomenological model for the α -particle preformation factor, using the experimental decay half-lives and decay energies of superheavy nuclei.

Based on Bayes's theorem, our model calibration for the parameter set, denoted as θ , is given by

$$P(\theta|\text{data}) \propto P(\text{data}|\theta)P(\theta), \quad (8)$$

where $\theta = (a, b, c, d, h)$ represents a five-dimensional vector related to the parameters. $P(\theta|\text{data})$ denotes the posterior distribution of the parameter set conditioned on the experimental data. $P(\theta)$ is the prior distribution of θ in the absence of data. $P(\text{data}|\theta)$ is the likelihood function expressing the probability that the current data set is observed given the parameter set θ . In this work, assuming that the data follow a normal

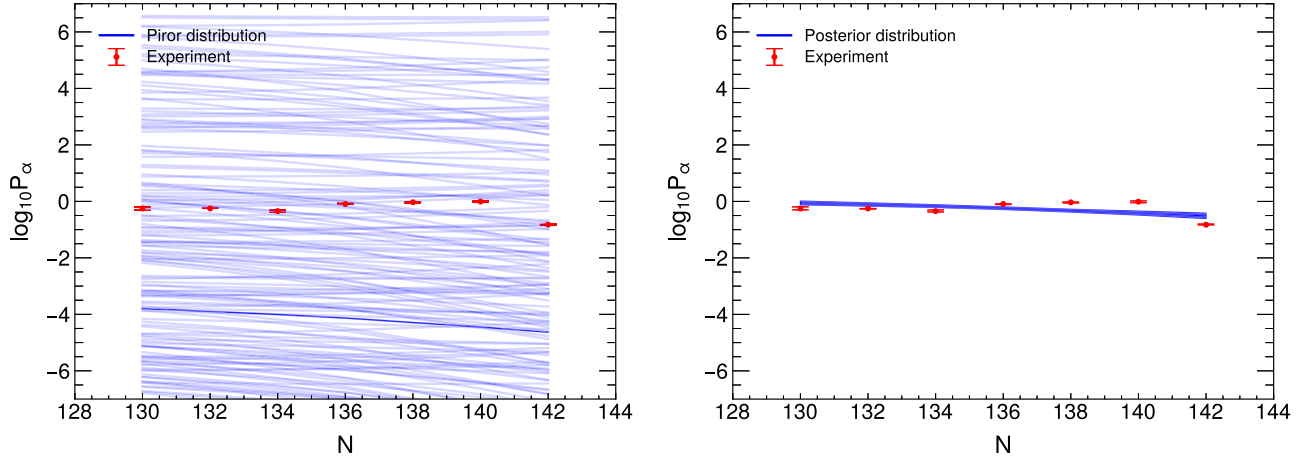


FIG. 1. Prior and posterior distributions of $\log_{10} P_\alpha$ for even-even Th isotopes. Left: blue curves denote prior distributions, while red balls with uncertainty bars denote experimental ones. Right: posterior distributions (blue bands: 95% credible intervals).

distribution, the likelihood function is defined as

$$P(\text{data}|\theta) = \prod_i \frac{1}{\sqrt{2\pi}\sigma_i} e^{-[y_i(\theta) - y_i^{\text{exp}}]^2 / (2\sigma_i^2)}, \quad (9)$$

where $y_i(\theta)$ denotes the model output at the i th data point, while y_i^{exp} and σ_i represent the mean value and error of experimental observations at point i , respectively. The experimental data uncertainty are incorporated in the analysis.

As for the prior distribution $P(\theta)$, each parameter is constrained within a finite design range, which limits the predictive capability of the Gaussian process emulator within these ranges. Therefore, in this work, the prior probability density function is defined as

$$P(\theta) \propto \begin{cases} 1, & \theta \in \prod_i [\theta_i^{\min}, \theta_i^{\max}], \\ 0, & \text{otherwise,} \end{cases} \quad (10)$$

where $\prod$ denotes the Cartesian product of parameter intervals, enforcing hard constraints on the Gaussian process-based surrogate model. The uniform prior distributions for parameters $\theta = (a, b, c, d, h)$ are constructed based on physical constraints and empirical knowledge from previous studies. For instance, the range of parameter a is designed to encompass the least-squares estimate $a_{\text{LS}} = -0.021$ reported in Ref. [47] with a safety margin of ± 0.1 , ensuring coverage of potential variations in $ZQ_\alpha^{-1/2}$ scaling. The bounds on d account for angular momentum suppression effects up to $l = 6\hbar$, as higher partial waves are typically forbidden in α decay of superheavy nuclei due to prohibitive centrifugal barriers [62]. The negative prior range for h aligns with the systematic reduction of P_α in odd- A and odd-odd nuclei observed in experimental systematics [33,63]. We adopt uniform priors to avoid injecting subjective biases, a practice consistent with Bayesian studies in heavy-ion collisions [50] and nuclear mass modeling [64]. A sensitivity analysis (see Fig. 1) confirms that posterior estimates are robust against alternative prior choices, including Gaussian distributions centered on literature values.

IV. RESULTS AND DISCUSSION

This work is mainly based on Bayesian inference to investigate the decay properties of superheavy nuclei ($90 \leq Z \leq 118$) by calibrating the adjustable parameters of phenomenological α preformation factors. The types of nuclei studied in this paper are entirely consistent with those listed in Tables 1–3 and Tables 2–5 of Refs. [47] and [33]. In the calculation process, we systematically include the measurement uncertainties of experimental half-life and decay energy for each nucleus, with the corresponding uncertainties directly quoted from Ref. [63]. First, a uniform prior distribution, $P(\theta)$, is assumed for the parameters within the ranges $a \in (-0.15, 0.05)$, $b \in (-3.0, -1.0)$, $c \in (4.0, 16.0)$, $d \in (-0.25, 0.67)$, and $h \in (-0.8, -0.1)$. These ranges are sufficiently wide to ensure that our model outputs encompass all experimental data. To accelerate the calibration process, a Gaussian process (GP) emulator [65] is employed for model-to-data comparison while scanning the five-dimensional input parameter space with $\theta = (a, b, c, d, h)$. The model output y is $\log_{10} P_\alpha$. We select a set of training points θ , run the model at each of these points, and observe the corresponding output y in order to identify functions that can interpolate all the effective training data pairs (θ, y) . By applying these prior ranges to Eq. (7), theoretical predictions for $\log_{10} P_\alpha$ in superheavy nuclei are consequently derived. A key concern in Bayesian analysis is whether results are unduly influenced by prior assumptions. We confirm this by comparing prior and posterior predictions of the Th isotopic chain, as shown in Fig. 1. The blue curve in the left figure of Fig. 1 represents the prior distribution of $\log_{10} P_\alpha$, and the red dots denote the experimental values of $\log_{10} P_\alpha$ with uncertainty. The blue band in the right figure of Fig. 1 represents the posterior distribution of $\log_{10} P_\alpha$ with 95% confidence interval. From the figure, we can see that the prior spans orders of magnitude, and the posteriors converge to a narrow band, closely tracking experimental data. This dramatic contraction confirms that the likelihood function Eq. (9) overrides unphysical prior regions, ensuring posteriors reflect empirical constraints rather than subjective assumptions. Meanwhile, the original prior bounds

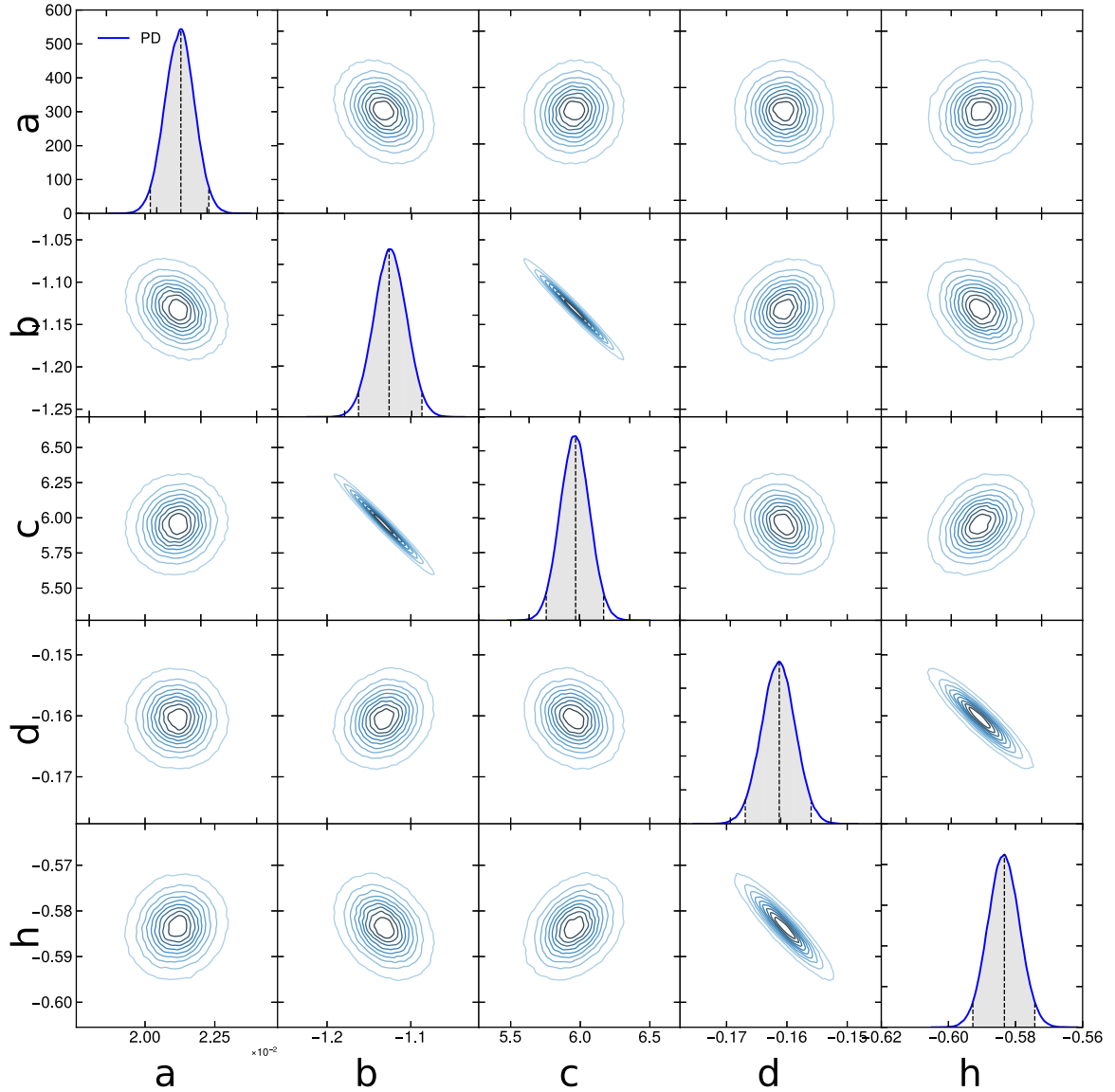


FIG. 2. Posterior distributions of model's global parameters (diagonal panels) and their correlations (off-diagonal panels) extracted from Eq. (7) using the original uncertainties of the experimental data, which are obtained from the latest evaluated atomic mass table AME2020 [67,68].

are sufficiently wide to avoid truncating physically meaningful posterior regions.

Next, it is shown that the independent likelihood function of α preformation factors is calculated for even-even (ee), odd-A (oa), and odd-odd (oo) nuclei in superheavy nuclei.

TABLE I. Global parameter estimates with posterior 95% confidence levels (CL) and MAP values for parameters in Eq. (7).

Parameter	95% CL	MAP
a	(0.020, 0.023)	0.021
b	(-1.179, -1.085)	-1.134
c	(5.670, 6.240)	5.962
d	(-0.167, -0.154)	-0.160
h	(-0.593, -0.574)	-0.583

We then construct a joint likelihood function as the product of individual likelihood, which is expressed as

$$P(\text{data}|\theta) = P(\text{data}_{\log_{10}P_{\alpha}^{\text{ee}}}|\theta)P(\text{data}_{\log_{10}P_{\alpha}^{\text{oa}}}|\theta)P(\text{data}_{\log_{10}P_{\alpha}^{\text{oo}}}|\theta). \quad (11)$$

In the following, using Eqs. (8), (9), and (11), we implement Markov chain Monte Carlo (MCMC) sampling via the Metropolis-Hastings algorithm [66]. Each iteration updates the parameter values based on a Gaussian transition kernel centered at the current position in the parameter space. To enhance sampling efficiency, we initialize 150 walkers, each starting from a random position within the parameter space. A burn-in phase of 5000 steps is conducted to ensure adequate convergence to the target posterior distribution. Subsequently, an additional 10 000 steps are performed to generate posterior

TABLE II. Local parameters respectively estimate posterior 95% confidence levels (CL) and MAP values for 65 even-even, 87 odd- A and 28 odd-odd nuclei in Eq. (7).

Parameter	Even-even		Odd- A		Odd-odd	
	95% CL	MAP	95% CL	MAP	95% CL	MAP
a	(0.018, 0.022)	0.020	(0.028, 0.033)	0.030	(−0.145, −0.119)	−0.132
b	(−1.186, −1.054)	−1.120	(−1.393, −1.226)	−1.308	(−1.879, −1.515)	−1.695
c	(5.531, 6.314)	5.917	(5.856, 7.157)	6.547	(12.191, 14.932)	13.675
d	(−0.227, 0.645)	0.446	(−0.180, −0.166)	−0.173	(0.465, 0.530)	0.495
h	(−0.782, −0.117)	−0.483	(−0.783, −0.118)	−0.695	(−0.783, −0.118)	−0.629

samples, providing a sufficiently large dataset for constructing smooth histogram visualizations.

Upon completion of MCMC sampling, the marginal posterior distributions for all parameters within the set

$\theta = (a, b, c, d, h)$ are analytically derived. Table I summarizes the globally inferred parameter constraints, starting from a random position of the 95% highest posterior density (PD) credible intervals and maximum *a posteriori* (MAP) estimates

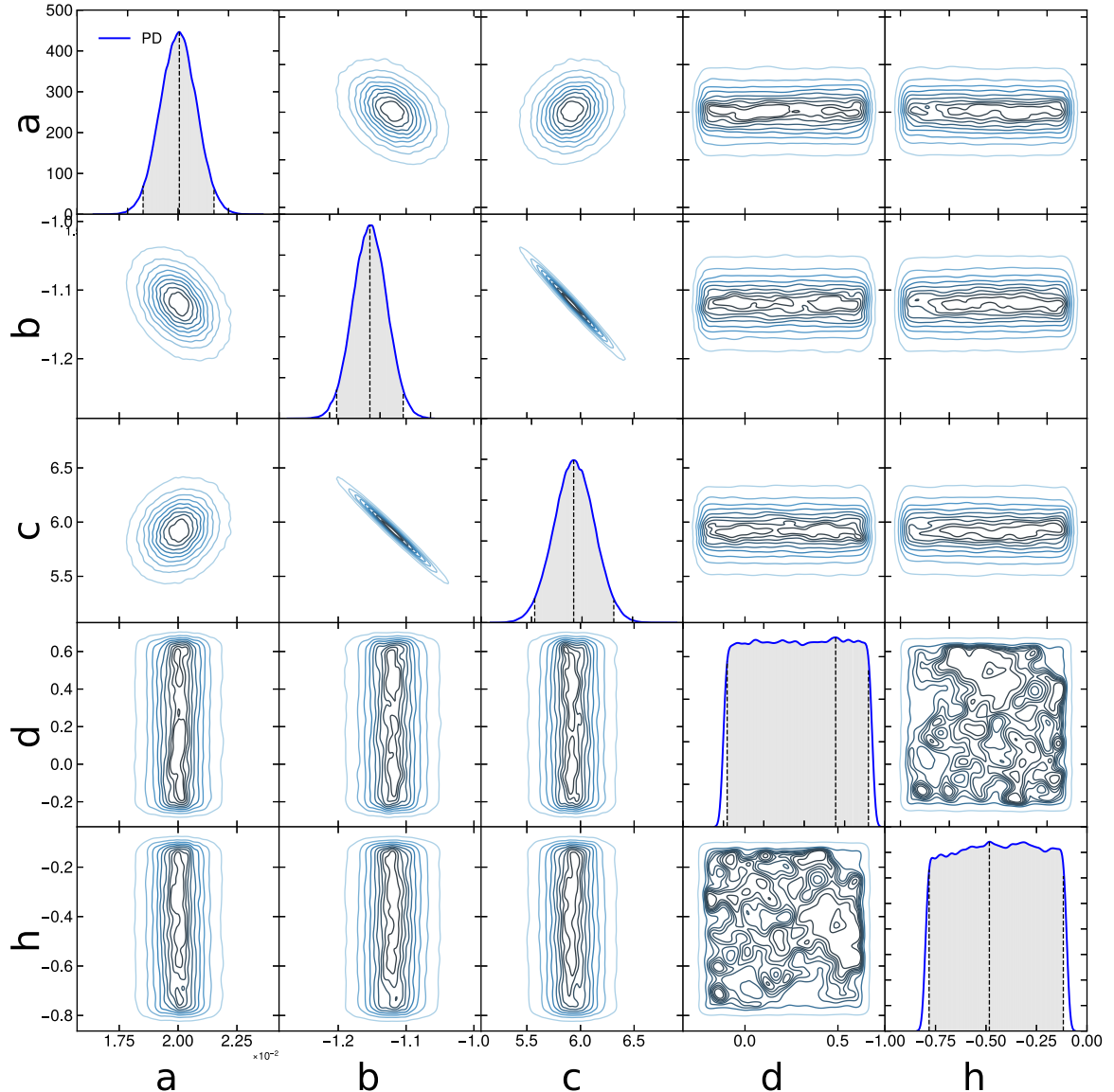


FIG. 3. Posterior distributions of the model's local parameters for 65 even-even nuclei, obtained from the latest evaluated atomic mass table AME2020 [67,68].

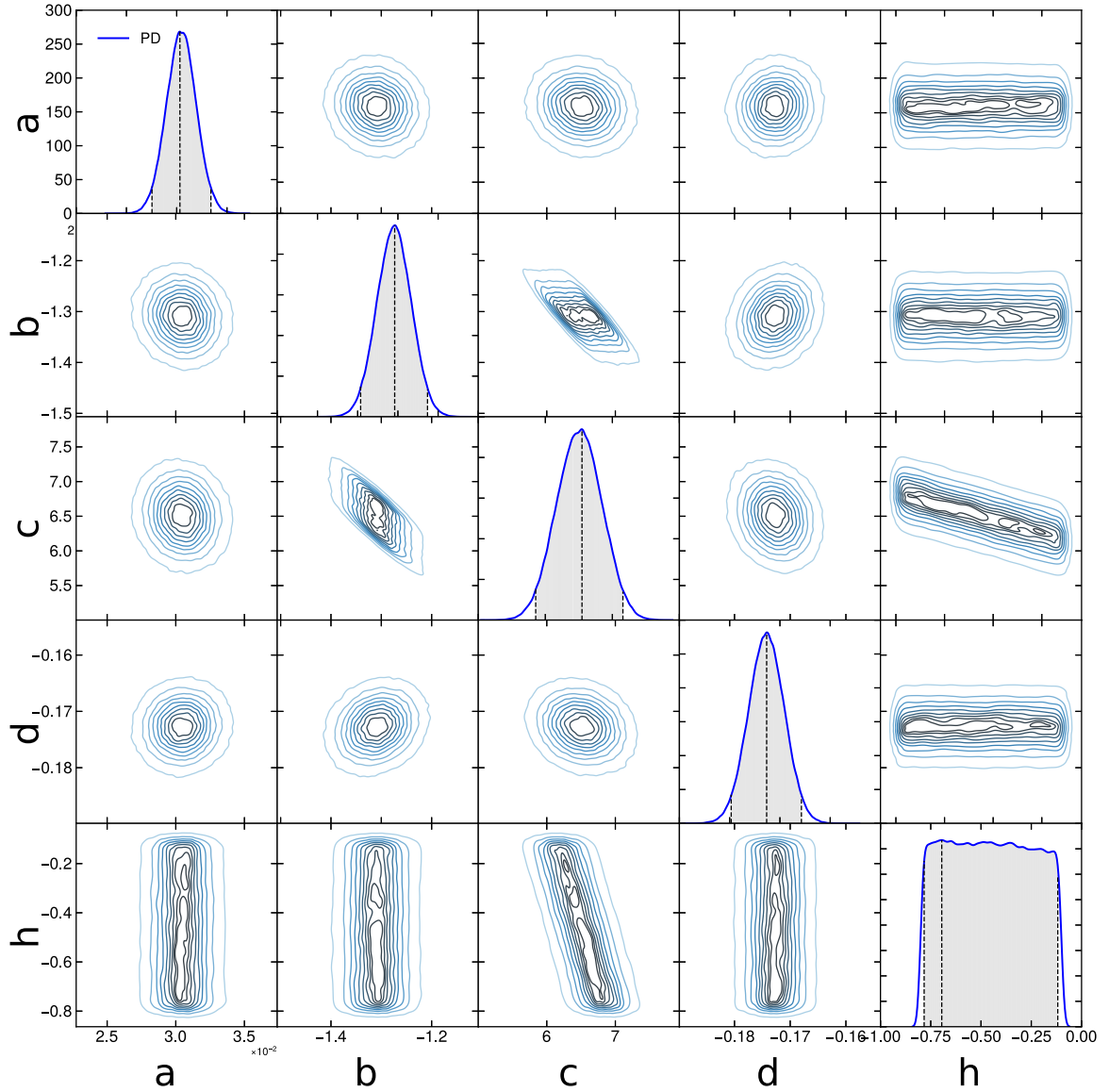


FIG. 4. Same as Fig. 3 but for 87 odd-A nuclei.

extracted from the MCMC chains. The posterior distributions are visualized in Fig. 2 using a corner plot, a canonical tool in Bayesian analysis for exploring high-dimensional parameter spaces, comprising both diagonal and off-diagonal subplots. Figure 2 presents a corner plot of the posterior distributions for global parameters, comprehensively displaying the multidimensional probability density distributions of five parameters (a , b , c , d , h) derived from Bayesian inference, along with their interdependencies. In the diagonal subplots, each displays the parameter's value range on both axes and the normalized probability density on the vertical axis. For instance, the distribution of parameter a spans a range of (0.018, 0.024), with its vertical axis representing probability density. In off-diagonal subplots, the joint distributions of parameter pairs are shown, such as the a - b subplot with a on the horizontal axis and b on the vertical axis. The diagonal subplots reflect the marginal distributions of parameters (a ,

b , c , d , h): Parameter a , the coefficient of the $ZQ_\alpha^{-1/2}$ term, exhibits a sharply peaked unimodal distribution with a 95% confidence level (CL) of (0.020, 0.023) and a MAP value of 0.021. Its narrow distribution indicates stringent experimental constraints on the Z and Q_α dependence, reflecting the synergistic effect of Z and Q_α on the preformation factor [69,70]. Parameter b , the coefficient of the $A^{1/3}$ term, is centered at -1.134 , with a range of $(-1.179, -1.085)$. The negative value indicates that an increase in $A^{1/3}$ suppresses the preformation probability, likely due to the increased nuclear density making α -particle formation more difficult [71]. Parameter c , the constant term, spans (5.670, 6.240) with a MAP of 5.962. The relatively large constant compensates for the negative contributions of other terms, reflecting the base contribution of collective motion outside the shell effects to the preformation factor [72,73]. Parameter d , the coefficient of the angular momentum l , ranges $(-0.167, -0.154)$ with a

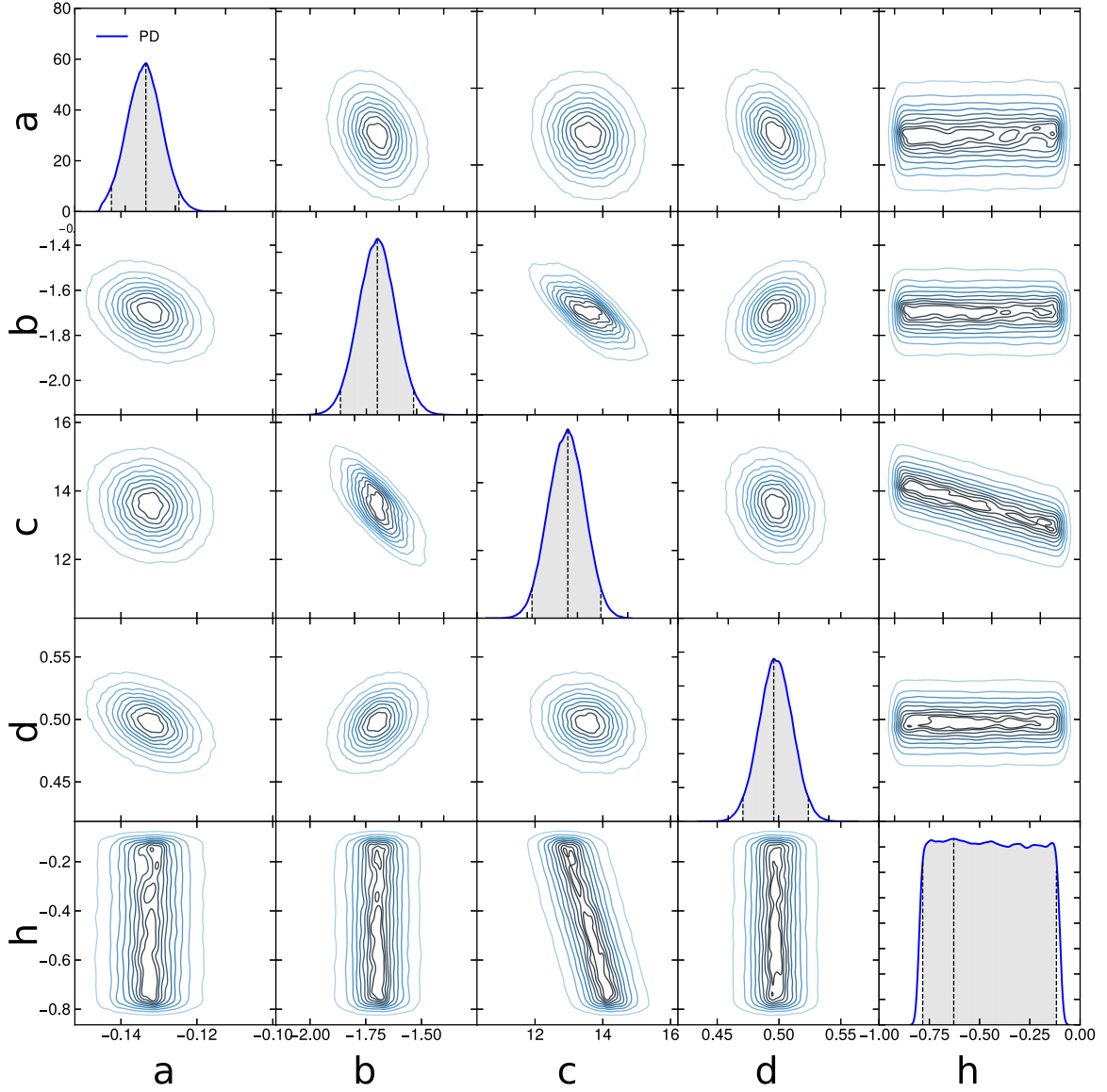


FIG. 5. Same as Fig. 3 but for 28 odd-odd nuclei.

MAP of -0.160 . The negative coefficient confirms that high angular momentum states ($l \neq 0$) significantly suppress the preformation, consistent with the physical picture of increased centrifugal potential barriers leading to reduced tunneling probabilities. Parameter h , the odd-even effect term, has a range of $(-0.593, -0.574)$, with MAP $= -0.583$. Its negative value indicates that the preformation factor for odd- A and odd-odd nuclei is lower than for even-even nuclei, aligning with the blocking effect of unpaired nucleons in odd nuclei. The off-diagonal subplots highlight parameter correlations: a - b show a negative correlation, where the $ZQ_\alpha^{-1/2}$ and $A^{1/3}$ exhibit a negative covariance. It implies a competitive balance between charge-driven facilitation and mass-dependent suppression of α preformation factor. c - d present a weak correlation, where the constant term and the angular momentum term are independent, indicating that the shell collective effect and centrifugal barrier influence are decoupled in the model.

h is independent of the other parameters, indicating that the joint distribution of the odd-even effect term is not significantly skewed, suggesting that it does not strongly adjust other parameters, thus it independently represents structural differences in odd nuclei [48,74,75]. Evidently, Bayesian inference not only quantifies model uncertainty through posterior distributions (narrow constraints on a and b in Fig. 2) but also resolves limitations of least-squares fitting by rigorously propagating experimental errors and capturing parameter correlations.

Following Bayesian calibration, we first calculate the preformation factors of superheavy nuclei ($90 \leq Z \leq 118$) [47] using global parameters drawn from MAP values of their posterior distributions. To validate the robustness of these global parameters, we also extract the local parameters separately for even-even, odd- A , and odd-odd nuclei using Bayesian inference. The 95% confidence levels and maximum *a posteriori*

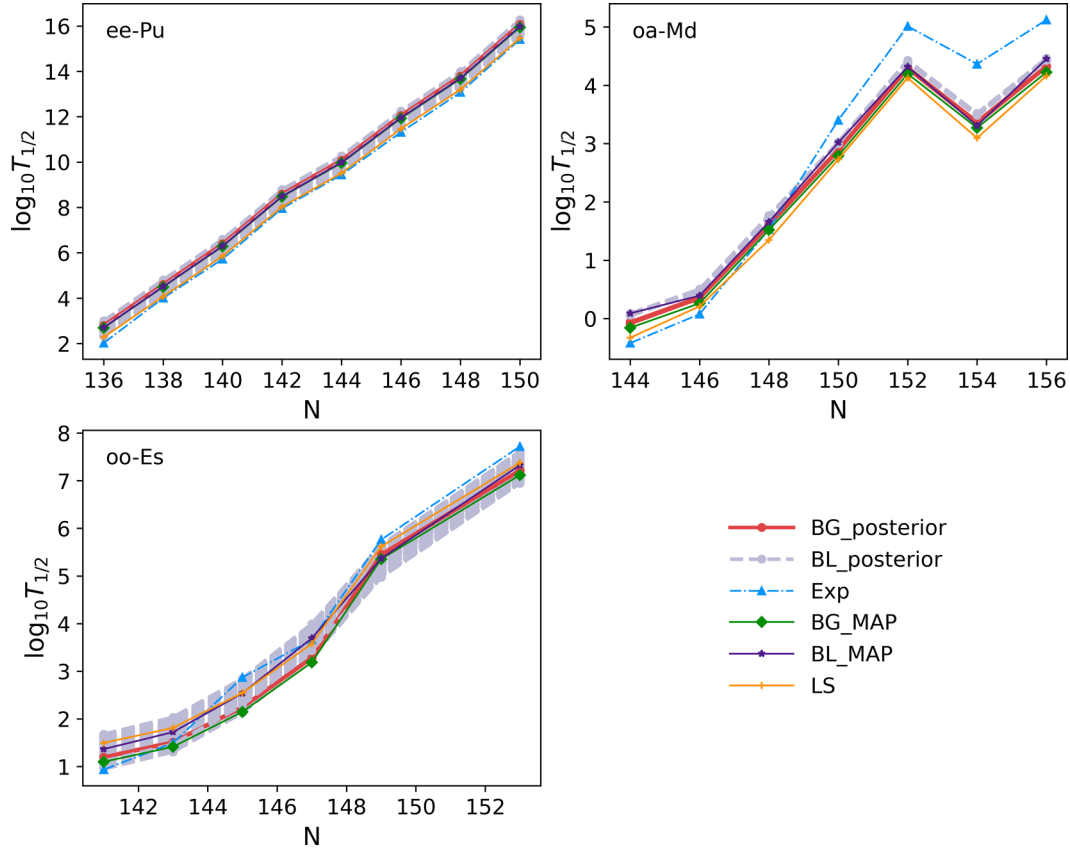


FIG. 6. Comparison of half-lives for even-even, odd-A, and odd-odd nuclei calculated by the posterior distributions and MAP values of BG, BL, and LS and experimental half-lives, respectively.

(MAP) estimates of the localized parameters for each nuclear category are listed in Table II, while their marginal posterior distributions are visualized in Figs. 3–5. Figure 3 shows the posterior distribution of the local parameters for even-even nuclei. In Figure 3, parameters a – c are strongly correlated: The $ZQ_\alpha^{-1/2}$ term exhibits a significant positive correlation with the constant term, indicating a synergistic adjustment of charge effects and base shell contributions for even-even nuclei. This likely reflects coupling between charge distribution and collective motion in deformed nuclei [76,77]. Parameter d has a wide distribution: The angular momentum term shows a marginal distribution spanning $(-0.227, 0.645)$ with a MAP of 0.446. Its positive sign suggests enhanced preformation probability in high- l states of even-even nuclei, potentially arising from spatial anisotropy of α preformation probability sites in deformed nuclei [78,79]. Deformation-induced spatial localization of α preformation probability may allow centrifugal barriers and shell effects to act cooperatively. Bayesian posteriors reveal that this phenomenon should be captured by parameter covariance, which univariate optimization in traditional methods might overlook. Figure 4 represents the odd-A nuclei posterior distributions. In this figure, parameter h has low sensitivity: The odd-even term spans $(-0.783, -0.118)$, consistent with even-even nuclei, but its joint distribution reveals a weak negative correlation with d . Unpaired nucleons in odd nuclei may simultaneously influence angular

momentum states and odd-even corrections. Parameters c and d are negatively correlated: The negative covariance between c and d implies competition between shell effects and angular momentum [80,81]. The structural complexity in odd nuclei introduces nonlinear parameter dependencies, which Bayesian joint distributions explicitly resolve, providing constraints for microscopic model construction [64,82].

Figure 5 is the odd-odd nuclei posterior distributions. In this figure, parameter c is shifted significantly to the right: MAP = 13.675, indicating that odd-odd nuclei require a large constant term to compensate for the suppressive effects of other terms. This reflects the strong blocking effect of unpaired protons and neutrons in doubly odd nuclei [62,83]. Parameter d is positively correlated: the MAP of d is 0.495. The extreme odd-even effects (h) and deformation effects ($d > 0$) in double-odd nuclei combine actions, leading to a preformation factor significantly lower than that in even-even nuclei [84]. The anomalous increase in c in the Bayesian posterior reveals that traditional formulas are insufficient in describing double-odd nuclei and require the introduction of additional structural terms. The complex dependence between α preformation factor parameters can be seen by Bayesian angular plot analysis: Z and A effects need to be dynamically balanced to describe the shell sensitive region. The unpaired nucleon effect interacts with nuclear deformation. In the global model, $d < 0$ is consistent with centrifugal

TABLE III. The α -particle preformation factors and half-lives of nuclei around neutron magic numbers $N = 126, 152, 162$ are calculated using BG, BL, and LS. The experimental α -decay energies and half-lives are taken from Refs. [47,63,67,68].

α transition	Q_{α}^{Expt}	$\log_{10} T_{1/2}^{\text{Expt}}$	P_{α}^{BG}	P_{α}^{BL}	P_{α}^{LS}	$\log_{10} T_{1/2}^{\text{BG}}$	$\log_{10} T_{1/2}^{\text{BL}}$	$\log_{10} T_{1/2}^{\text{LS}}$
$^{194}\text{Rn} \rightarrow ^{190}\text{Po}$	7.8620 ± 0.0100	$-3.1079^{+0.0810}_{-0.0997}$	0.2874	0.3663	1.0328	-2.5515	-2.6568	-3.1071
$^{196}\text{Rn} \rightarrow ^{192}\text{Po}$	7.6170 ± 0.0090	$-2.3279^{+0.0913}_{-0.1158}$	0.2794	0.3559	1.0079	-1.8117	-1.9169	-2.3689
$^{198}\text{Rn} \rightarrow ^{194}\text{Po}$	7.3490 ± 0.0040	$-1.1596^{+0.0107}_{-0.0109}$	0.2727	0.3472	0.9901	-0.9568	-1.0617	-1.5168
$^{200}\text{Rn} \rightarrow ^{196}\text{Po}$	7.0434 ± 0.0021	$0.0736^{+0.0595}_{-0.0689}$	0.2678	0.3406	0.9824	0.0976	-0.0069	-0.4669
$^{202}\text{Rn} \rightarrow ^{198}\text{Po}$	6.7738 ± 0.0018	$1.0947^{+0.0045}_{-0.0045}$	0.2625	0.3337	0.9716	1.0848	0.9807	0.5166
$^{204}\text{Rn} \rightarrow ^{200}\text{Po}$	6.5467 ± 0.0018	$2.0125^{+0.0080}_{-0.0081}$	0.2566	0.3259	0.9561	1.9283	1.8245	1.3571
$^{206}\text{Rn} \rightarrow ^{202}\text{Po}$	6.3837 ± 0.0016	$2.7393^{+0.0128}_{-0.0132}$	0.2491	0.3163	0.9303	2.6127	2.5090	2.0406
$^{208}\text{Rn} \rightarrow ^{204}\text{Po}$	6.2607 ± 0.0017	$3.3723^{+0.0025}_{-0.0025}$	0.2409	0.3058	0.8987	3.0918	2.9882	2.5200
$^{210}\text{Rn} \rightarrow ^{206}\text{Po}$	6.1590 ± 0.0022	$3.9542^{+0.0177}_{-0.0185}$	0.2324	0.2950	0.8650	3.5243	3.4207	2.9536
$^{212}\text{Rn} \rightarrow ^{208}\text{Po}$	6.3851 ± 0.0026	$3.1565^{+0.0036}_{-0.0036}$	0.2148	0.2732	0.7737	2.4980	2.3936	1.9414
$^{214}\text{Rn} \rightarrow ^{210}\text{Po}$	9.2080 ± 0.0090	$-6.5867^{+0.0050}_{-0.0051}$	0.1553	0.2003	0.4579	-6.3523	-6.4627	-6.8218
$^{216}\text{Rn} \rightarrow ^{212}\text{Po}$	8.1980 ± 0.0060	$-4.5376^{+0.0561}_{-0.0645}$	0.1606	0.2064	0.4951	-3.7777	-3.8867	-4.2666
$^{218}\text{Rn} \rightarrow ^{214}\text{Po}$	7.2625 ± 0.0019	$-1.4717^{+0.0019}_{-0.0019}$	0.1676	0.2146	0.5434	-0.8783	-0.9856	-1.3891
$^{220}\text{Rn} \rightarrow ^{216}\text{Po}$	6.4047 ± 0.0001	$1.7451^{+0.0008}_{-0.0008}$	0.1766	0.2251	0.6062	2.3514	2.2458	1.8157
$^{222}\text{Rn} \rightarrow ^{218}\text{Po}$	5.5904 ± 0.0003	$5.5187^{+0.0000}_{-0.0000}$	0.1890	0.2398	0.6944	6.1110	6.0076	5.5458
$^{202}\text{Ra} \rightarrow ^{198}\text{Rn}$	7.8800 ± 0.0070	$-2.3872^{+0.1032}_{-0.1357}$	0.2419	0.3086	0.8464	-1.8860	-1.9918	-2.4300
$^{204}\text{Ra} \rightarrow ^{200}\text{Rn}$	7.6370 ± 0.0070	$-1.2218^{+0.0607}_{-0.0706}$	0.2356	0.3004	0.8278	-1.1319	-1.2374	-1.6776
$^{206}\text{Ra} \rightarrow ^{202}\text{Rn}$	7.4150 ± 0.0040	$-0.6198^{+0.0348}_{-0.0378}$	0.2293	0.2922	0.8085	-0.4298	-0.5352	-0.9772
$^{208}\text{Ra} \rightarrow ^{204}\text{Rn}$	7.2730 ± 0.0050	$0.1058^{+0.0173}_{-0.0180}$	0.2215	0.2822	0.7798	0.0410	-0.0643	-0.5057
$^{210}\text{Ra} \rightarrow ^{206}\text{Rn}$	7.1510 ± 0.0030	$0.6021^{+0.0107}_{-0.0110}$	0.2136	0.2722	0.7502	0.5119	0.4066	-0.0336
$^{214}\text{Ra} \rightarrow ^{210}\text{Rn}$	7.2726 ± 0.0026	$0.3871^{+0.0028}_{-0.0029}$	0.1911	0.2440	0.6497	-0.0060	-0.1121	-0.5373
$^{216}\text{Ra} \rightarrow ^{212}\text{Rn}$	9.5260 ± 0.0070	$-6.7645^{+0.0173}_{-0.0180}$	0.1492	0.1924	0.4372	-6.3966	-6.5071	-6.8635
$^{218}\text{Ra} \rightarrow ^{214}\text{Rn}$	8.5400 ± 0.0120	$-4.5865^{+0.0023}_{-0.0024}$	0.1536	0.1975	0.4692	-3.9256	-4.0347	-4.4105
$^{220}\text{Ra} \rightarrow ^{216}\text{Rn}$	7.5940 ± 0.0050	$-1.7423^{+0.0279}_{-0.0298}$	0.1599	0.2049	0.5130	-1.1790	-1.2866	-1.6853
$^{222}\text{Ra} \rightarrow ^{218}\text{Rn}$	6.6780 ± 0.0040	$1.5263^{+0.0051}_{-0.0052}$	0.1689	0.2155	0.5748	2.1220	2.0163	1.5902
$^{224}\text{Ra} \rightarrow ^{220}\text{Rn}$	5.7889 ± 0.0002	$5.4966^{+0.0002}_{-0.0002}$	0.1820	0.2310	0.6656	6.1087	6.0052	5.5456
$^{226}\text{Ra} \rightarrow ^{222}\text{Rn}$	4.8707 ± 0.0003	$10.7032^{+0.0019}_{-0.0019}$	0.2037	0.2566	0.8217	11.3447	11.2443	10.7390
$^{208}\text{Th} \rightarrow ^{204}\text{Ra}$	8.2000 ± 0.0300	$-2.6198^{+0.1761}_{-0.3010}$	0.2090	0.2671	0.7071	-2.1325	-2.2390	-2.6619
$^{210}\text{Th} \rightarrow ^{206}\text{Ra}$	8.0960 ± 0.0060	$-1.7959^{+0.0881}_{-0.1107}$	0.2008	0.2567	0.6761	-1.8298	-1.9363	-2.3569
$^{212}\text{Th} \rightarrow ^{208}\text{Ra}$	7.9580 ± 0.0050	$-1.4989^{+0.0175}_{-0.0182}$	0.1937	0.2476	0.6504	-1.4394	-1.5460	-1.9654
$^{214}\text{Th} \rightarrow ^{210}\text{Ra}$	7.8270 ± 0.0050	$-1.0605^{+0.0473}_{-0.0530}$	0.1869	0.2389	0.6256	-1.0437	-1.1502	-1.5683
$^{216}\text{Th} \rightarrow ^{212}\text{Ra}$	8.0720 ± 0.0040	$-1.5804^{+0.0026}_{-0.0027}$	0.1739	0.2226	0.5660	-1.8328	-1.9401	-2.3454
$^{218}\text{Th} \rightarrow ^{214}\text{Ra}$	9.8490 ± 0.0090	$-6.9136^{+0.0174}_{-0.0182}$	0.1433	0.1849	0.4174	-6.3977	-6.5082	-6.8620
$^{220}\text{Th} \rightarrow ^{216}\text{Ra}$	8.9730 ± 0.0110	$-4.9914^{+0.0126}_{-0.0130}$	0.1459	0.1878	0.4397	-4.4080	-4.5174	-4.8870
$^{222}\text{Th} \rightarrow ^{218}\text{Ra}$	8.1326 ± 0.0029	$-2.6498^{+0.0058}_{-0.0059}$	0.1497	0.1921	0.4690	-2.0752	-2.1834	-2.5711
$^{224}\text{Th} \rightarrow ^{220}\text{Ra}$	7.2990 ± 0.0060	$0.0170^{+0.0083}_{-0.0084}$	0.1554	0.1987	0.5102	0.6335	0.5268	0.1174
$^{226}\text{Th} \rightarrow ^{222}\text{Ra}$	6.4525 ± 0.0010	$3.2653^{+0.0004}_{-0.0004}$	0.1643	0.2092	0.5720	3.9587	3.8539	3.4169
$^{228}\text{Th} \rightarrow ^{224}\text{Ra}$	5.5202 ± 0.0002	$7.7807^{+0.0002}_{-0.0002}$	0.1802	0.2280	0.6823	8.4925	8.3903	7.9142
$^{230}\text{Th} \rightarrow ^{226}\text{Ra}$	4.7700 ± 0.0015	$12.3765^{+0.0017}_{-0.0017}$	0.1979	0.2489	0.8158	13.1189	13.0194	12.5038
$^{232}\text{Th} \rightarrow ^{228}\text{Ra}$	4.0816 ± 0.0014	$18.6452^{+0.0031}_{-0.0031}$	0.2221	0.2773	1.0116	18.4739	18.3774	17.8154
$^{238}\text{Cf} \rightarrow ^{234}\text{Cm}$	8.1300 ± 0.3000	$-0.0737^{+0.0260}_{-0.0276}$	0.1184	0.1516	0.3722	0.9786	0.8712	0.4810
$^{240}\text{Cf} \rightarrow ^{236}\text{Cm}$	7.7110 ± 0.0040	$1.6119^{+0.0096}_{-0.0098}$	0.1183	0.1512	0.3794	2.3726	2.2659	1.8664
$^{242}\text{Cf} \rightarrow ^{238}\text{Cm}$	7.5170 ± 0.0040	$2.5356^{+0.0183}_{-0.0191}$	0.1156	0.1477	0.3723	3.0719	2.9654	2.5639
$^{244}\text{Cf} \rightarrow ^{240}\text{Cm}$	7.3290 ± 0.0018	$3.1931^{+0.0110}_{-0.0113}$	0.1130	0.1443	0.3655	3.9113	3.8050	3.4014
$^{246}\text{Cf} \rightarrow ^{242}\text{Cm}$	6.8616 ± 0.0010	$5.1090^{+0.0060}_{-0.0061}$	0.1146	0.1461	0.3819	5.6988	5.5935	5.1761
$^{248}\text{Cf} \rightarrow ^{244}\text{Cm}$	6.3610 ± 0.0050	$7.4596^{+0.0349}_{-0.0379}$	0.1176	0.1494	0.4066	7.9375	7.8334	7.3986
$^{250}\text{Cf} \rightarrow ^{246}\text{Cm}$	6.1285 ± 0.0002	$8.6160^{+0.0030}_{-0.0030}$	0.1166	0.1480	0.4087	9.1162	9.0126	8.5714
$^{252}\text{Cf} \rightarrow ^{248}\text{Cm}$	6.2170 ± 0.0000	$7.9352^{+0.0013}_{-0.0013}$	0.1101	0.1399	0.3783	8.6031	8.4990	8.0669

TABLE III. (Continued.)

α transition	Q_{α}^{Expt}	$\log_{10} T_{1/2}^{\text{Expt}}$	P_{α}^{BG}	P_{α}^{BL}	P_{α}^{LS}	$\log_{10} T_{1/2}^{\text{BG}}$	$\log_{10} T_{1/2}^{\text{BL}}$	$\log_{10} T_{1/2}^{\text{LS}}$
$^{254}\text{Cf} \rightarrow ^{250}\text{Cm}$	5.9270 ± 0.0050	$9.2269^{+0.0014}_{-0.0014}$	0.1103	0.1400	0.3873	10.0828	9.9793	9.5374
$^{244}\text{Fm} \rightarrow ^{240}\text{Cf}$	8.5500 ± 0.2000	$-0.5058^{+0.0110}_{-0.0113}$	0.1026	0.1316	0.3105	0.3272	0.2189	-0.1539
$^{246}\text{Fm} \rightarrow ^{242}\text{Cf}$	8.3790 ± 0.0050	$0.2181^{+0.0111}_{-0.0114}$	0.0998	0.1280	0.3023	0.8511	0.7429	0.3696
$^{248}\text{Fm} \rightarrow ^{244}\text{Cf}$	7.9950 ± 0.0080	$1.5378^{+0.0148}_{-0.0154}$	0.0993	0.1272	0.3060	2.1139	2.0063	1.6252
$^{250}\text{Fm} \rightarrow ^{246}\text{Cf}$	7.5570 ± 0.0080	$3.2695^{+0.0151}_{-0.0157}$	0.0998	0.1276	0.3146	3.6928	3.5860	3.1943
$^{252}\text{Fm} \rightarrow ^{248}\text{Cf}$	7.1537 ± 0.0010	$4.9610^{+0.0007}_{-0.0007}$	0.1003	0.1281	0.3236	5.2575	5.1515	4.7489
$^{254}\text{Fm} \rightarrow ^{250}\text{Cf}$	7.3073 ± 0.0010	$4.0671^{+0.0003}_{-0.0003}$	0.0942	0.1205	0.2969	4.6075	4.5009	4.1091
$^{256}\text{Fm} \rightarrow ^{252}\text{Cf}$	7.0253 ± 0.0019	$5.0658^{+0.0036}_{-0.0036}$	0.0935	0.1194	0.2987	5.7514	5.6452	5.2469
$^{252}\text{No} \rightarrow ^{248}\text{Fm}$	8.5490 ± 0.0050	$0.5622^{+0.0028}_{-0.0028}$	0.0889	0.1141	0.2639	1.0171	0.9086	0.5446
$^{254}\text{No} \rightarrow ^{250}\text{Fm}$	8.2260 ± 0.0080	$1.7550^{+0.0034}_{-0.0034}$	0.0879	0.1128	0.2642	2.0590	1.9509	1.5812
$^{256}\text{No} \rightarrow ^{252}\text{Fm}$	8.5820 ± 0.0050	$0.4663^{+0.0074}_{-0.0075}$	0.0812	0.1044	0.2356	0.8785	0.7695	0.4161
$^{260}\text{Sg} \rightarrow ^{256}\text{Rf}$	9.9010 ± 0.0100	$-1.7678^{+0.0280}_{-0.0300}$	0.0706	0.0911	0.1932	-1.5116	-1.6222	-1.9488
$^{266}\text{Hs} \rightarrow ^{262}\text{Sg}$	10.3460 ± 0.0160	$-2.4037^{+0.0792}_{-0.0969}$	0.0618	0.0799	0.1635	-2.0245	-2.1359	-2.4469
$^{268}\text{Hs} \rightarrow ^{264}\text{Sg}$	9.7600 ± 0.1000	$0.1461^{+0.2518}_{-0.6690}$	0.0622	0.0802	0.1683	-0.4946	-0.6053	-0.9269
$^{270}\text{Hs} \rightarrow ^{266}\text{Sg}$	9.0700 ± 0.0400	$0.9542^{+0.1597}_{-0.2553}$	0.0635	0.0817	0.1775	1.5000	1.3904	1.0535
$^{270}\text{Ds} \rightarrow ^{266}\text{Hs}$	11.1170 ± 0.0280	$-3.6882^{+0.0914}_{-0.1159}$	0.0553	0.0716	0.1405	-3.2431	-3.3556	-3.6483
$^{282}\text{Ds} \rightarrow ^{278}\text{Hs}$	9.1500 ± 0.4200	$2.4014^{+0.2518}_{-0.6690}$	0.0508	0.0656	0.1363	1.8656	1.7551	1.4374

inhibition, while $d > 0$ may reflect the spatial selectivity of the α preformation factor caused by deformation in even-even and odd-odd nuclei.

Figure 6 quantitatively and stochastically presents the decay half-lives of even-even Pu, odd-A Md, and odd-odd Es isotopes in calculated superheavy nuclei ($90 \leq Z \leq 118$), derived from the local parameter (BL) and global parameter (BG) posterior distributions and MAP values calculated by Bayesian inference. Comparative analyses against experimental results are included, along with parameters fitted by the genetic algorithm from Ref. [47] (LS). Notably, the confidence bands calculated using the BG posterior distribution exhibit significantly narrower ranges than those obtained through BL. It shows that the uncertainty of parameters

is strictly limited, which reflects the strong constraint of experimental data on the model. As the BG systematically incorporates experimental uncertainties into the likelihood function, Eq. (11). Through posterior distribution propagation, the resulting confidence band width directly quantifies the model's sensitivity to input errors, demonstrating rigorous uncertainty quantification. BL independently optimizes parameters for different even-even, odd-A and odd-odd nuclei, which makes the local model overfit specific nuclear structural features, resulting in a wide confidence band. LS determines the parameters only by minimizing the sum of squares of residuals, ignoring the parameter covariance and experimental error propagation. In the region of superheavy nuclei, the extrapolated uncertainty of confidence intervals becomes crucial.

TABLE IV. The predicted α -particle preformation factors and half-lives of nuclei around neutron magic number $N = 162$ are calculated using BG, BL, and LS with the Q_{α} values extracted from the WS4 mass model [47].

α transition	Q_{α}^{WS4}	P_{α}^{BG}	P_{α}^{BL}	P_{α}^{LS}	$\log_{10} T_{1/2}^{\text{BG}}$	$\log_{10} T_{1/2}^{\text{BL}}$	$\log_{10} T_{1/2}^{\text{LS}}$
$^{262}\text{Sg} \rightarrow ^{258}\text{Rf}$	9.65	0.0691	0.0891	0.1898	-0.8520	-0.9624	-1.2911
$^{264}\text{Sg} \rightarrow ^{260}\text{Rf}$	9.05	0.0699	0.0899	0.1972	0.8730	0.7634	0.4224
$^{266}\text{Sg} \rightarrow ^{262}\text{Rf}$	8.44	0.0712	0.0914	0.2073	2.7953	2.6867	2.3310
$^{268}\text{Sg} \rightarrow ^{264}\text{Rf}$	7.98	0.0717	0.0919	0.2141	4.4439	4.3362	3.9691
$^{270}\text{Sg} \rightarrow ^{266}\text{Rf}$	8.56	0.0646	0.0831	0.1829	2.3580	2.2487	1.9061
$^{272}\text{Sg} \rightarrow ^{268}\text{Rf}$	8.42	0.0629	0.0809	0.1780	2.8448	2.7356	2.3930
$^{272}\text{Hs} \rightarrow ^{268}\text{Sg}$	9.53	0.0584	0.0753	0.1570	0.1057	-0.0051	-0.3239
$^{274}\text{Hs} \rightarrow ^{270}\text{Sg}$	9.50	0.0562	0.0725	0.1498	0.1365	0.0256	-0.2896
$^{276}\text{Hs} \rightarrow ^{272}\text{Sg}$	9.05	0.0562	0.0724	0.1527	1.4971	1.3869	1.0630
$^{272}\text{Ds} \rightarrow ^{268}\text{Hs}$	10.38	0.0560	0.0725	0.1466	-1.4824	-1.5940	-1.8999
$^{274}\text{Ds} \rightarrow ^{270}\text{Hs}$	10.87	0.0518	0.0671	0.1307	-2.6962	-2.8088	-3.0982
$^{276}\text{Ds} \rightarrow ^{272}\text{Hs}$	10.88	0.0497	0.0644	0.1240	-2.7412	-2.8540	-3.1387
$^{278}\text{Ds} \rightarrow ^{274}\text{Hs}$	10.25	0.0501	0.0648	0.1280	-1.2395	-1.3515	-1.6472
$^{280}\text{Ds} \rightarrow ^{276}\text{Hs}$	9.43	0.0516	0.0666	0.1371	1.0379	0.9271	0.6133

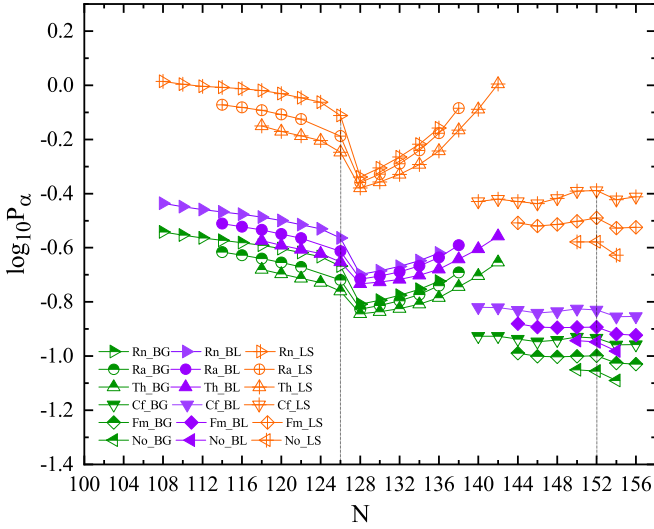


FIG. 7. The α -decay properties of nuclei around the neutron magic numbers $N = 126$ and 152 . For the variations of the preformation factors against the neutron number of parent nuclei for Rn, Ra, Th, Cf, Fm, and No isotopes, respectively.

Magic numbers serve as vital indicators of nuclear shell structures. It is of great significance to investigate the α -decay properties of nuclei near neutron magic numbers in heavy

and superheavy nuclei to understand shell effects and stability under extreme conditions. To this end, by combining the two-potential model from Ref. [47] with globally optimized parameters derived from Bayesian inference, we systematically calculate the α preformation factors and half-lives of nuclei near the neutron magic numbers $N = 126$, 152 , and 162 . By analyzing the α -decay properties of these isotope chains, such as the relationship between preformation factors and half-lives, the shell evolution and collective effects of nuclei in extreme neutron number regions are further revealed.

Meanwhile, we perform a quantitative comparison between the preformation factors and corresponding half-lives obtained with LS, BL, and BG in this work. Detailed calculation results are listed in Tables III and IV. In Table III, the first column lists α transitions. The second and third columns are the experimental decay energies and half-lives with uncertainty respectively. The fourth to sixth columns correspond to the preformation factors of BG, BL, and LS based on experimental data containing uncertainty. The seventh to ninth columns list the superheavy nuclear half-lives calculated from the previous three columns of preformation factors. In Table IV, the first column is still the α transition. The second column is the Q_α obtained by the WS4 mass model. Columns 3 to 8 corresponds to columns 4 to 9 of Table III, but show predicted results. From these tables, it can be seen that the half-lives calculated by BG are in the agreement with the

Pearson Correlation Coefficients for α Decay Systems

Color scale: light blue (anti-correlation) to grey (correlation)

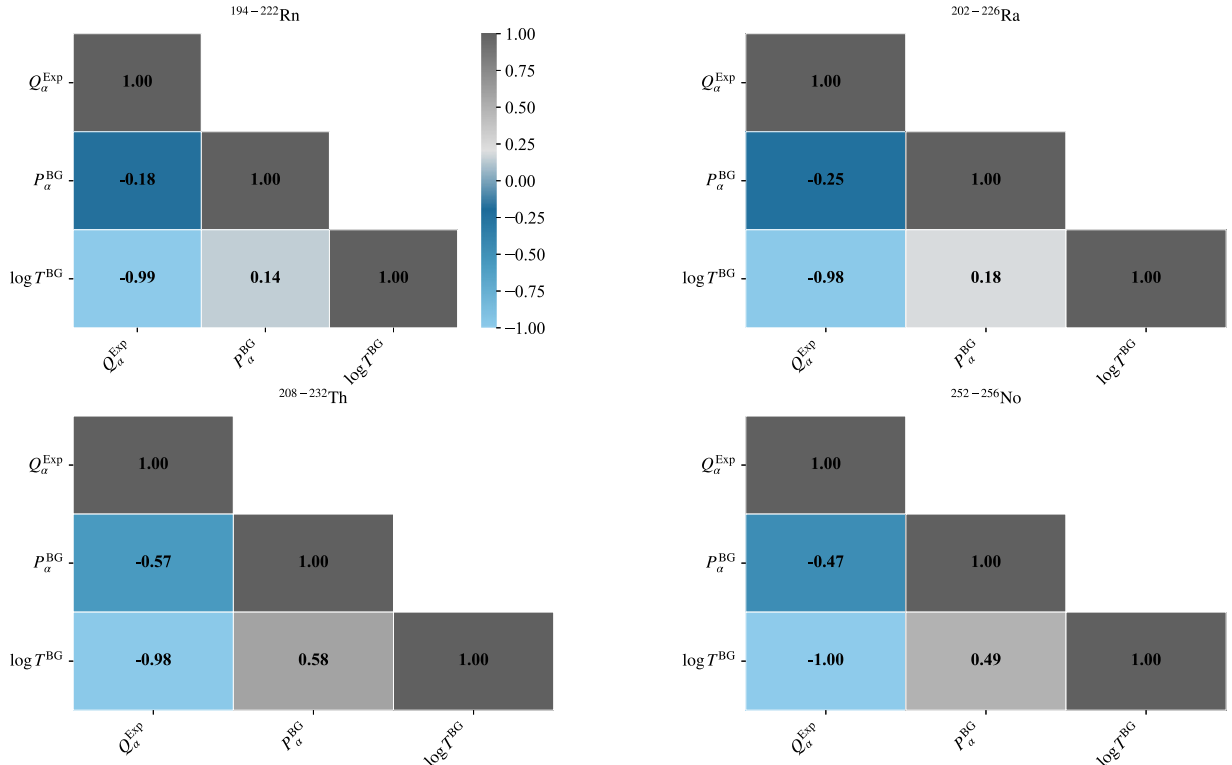


FIG. 8. Correlation between Q_α , P_α^{BG} , and $\log_{10} T_{1/2}^{\text{BG}}$ in α -decay systems using Pearson's correlation analyses for isotopes Rn, Ra, Th, and No.

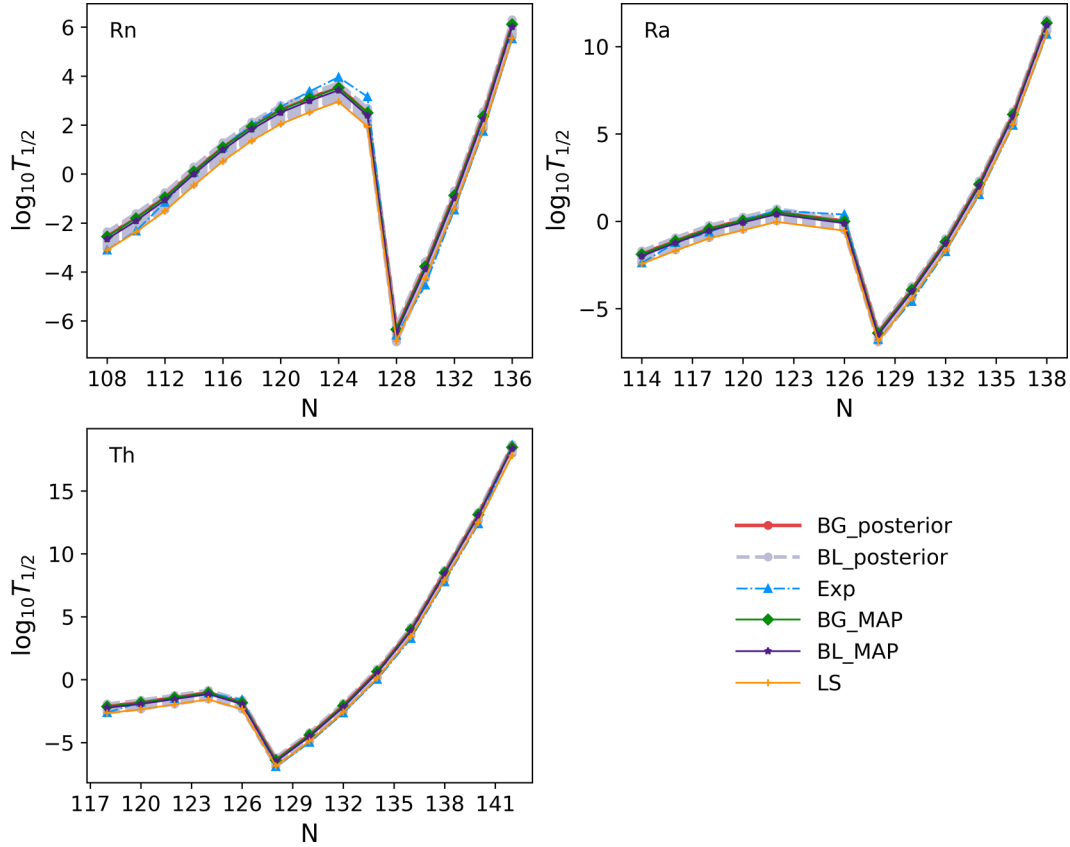


FIG. 9. The α -decay properties of nuclei around the neutron magic number $N=126$: The variations of the half-lives against the neutron number of parent nuclei for Rn, Ra, and Th isotopes, respectively.

experimental ones, and only a single set of adjustable parameters is required compared with BL and LS. In order to further intuitively present the differences, compared results for the preformation factors and half-lives are shown in Figs. 7–11, respectively. Figure 7 shows that, at neutron shell closures ($N = 126, 152, 162$), P_α exhibits distinct minima, a signature of nuclear structure effects. Notably, the P_α calculated via BG are systematically lower than those from BL and LS. This reduction stems from Gaussian prior constraints in our Bayesian inference, which restrict parameter ranges, thereby suppressing preformation factors. It can be seen from the analysis in Fig. 8, showing the Pearson correlation among Q_α , P_α^{BG} , and $\log_{10} T_{1/2}^{\text{BG}}$ that taking the isotopes $^{202-226}\text{Ra}$ as the example, Q_α is strongly negatively correlated with $\log_{10} T_{1/2}^{\text{BG}}$ (Pearson coefficient $\rho = -0.98$), P_α^{BG} and $\log_{10} T_{1/2}^{\text{BG}}$ exhibit a weak positive correlation ($\rho = 0.18$), while Q_α is weakly negative correlated with P_α^{BG} ($\rho = -0.25$). While Fig. 8 confirms a significant correlation between Q_α and $\log_{10} T_{1/2}^{\text{BG}}$, the specific correlation between Q_α and P_α^{BG} varies across chains. It can be seen that, even after taking into account the Q dependence, the local minimum value at the magic number still remains stable. This demonstrates that shell effects dominate α -cluster suppression at closures, modulating P_α independently of the broad correlation trends observed in individual isotopes. It can be clearly seen from Figs. 9–11 that for isotopes $^{194-222}\text{Rn}$, $^{202-226}\text{Ra}$, $^{208-232}\text{Th}$, $^{238-254}\text{Cf}$, $^{244-256}\text{Fm}$, and $^{252-256}\text{No}$, there is an obvious plummeting trend near

the neutron magic numbers $N = 126$ and 152 . And when $N < 126$, The half-lives calculated by BG are obviously highly consistent with the experimental ones, which indicates that the experimental data are abundant, the uncertainty of parameter estimation is low, and the analytical model of preformation factor (7) has a strong ability to capture the shell effect in this region. The observed precision diminishes in the $N = 152$ region, where BG and BL confidence bands notably widen compared to those near $N = 126$. Additional uncertainty may be introduced due to sparse experimental data, deformation shell effect, and collective motion competition. The wide confidence band reflects the structural complexity of superheavy nuclei, but the Bayesian method still captures the shell effect through prior constraints and global fitting. The confidence band is also wider near the predicted magic number $N = 162$. Due to the lack of experimental data, the model relies on the Q input of the WS4 quality model, which leads to the increase of parameter extrapolation uncertainty. The systematic suppression of P_α observed near neutron magic numbers $N = 126, 152, 162$, evident in Figs. 9–11 and Tables III and IV, originates from fundamental nuclear structure effects. At shell closures, the large energy gaps significantly reduce configuration mixing and collective excitations within the parent nucleus. This rigidity hinders the dynamic, cooperative motion of four nucleons required to form an α -like cluster configuration prior to decay [35,37,72]. The diminished wave function overlap between the parent and daughter nucleus

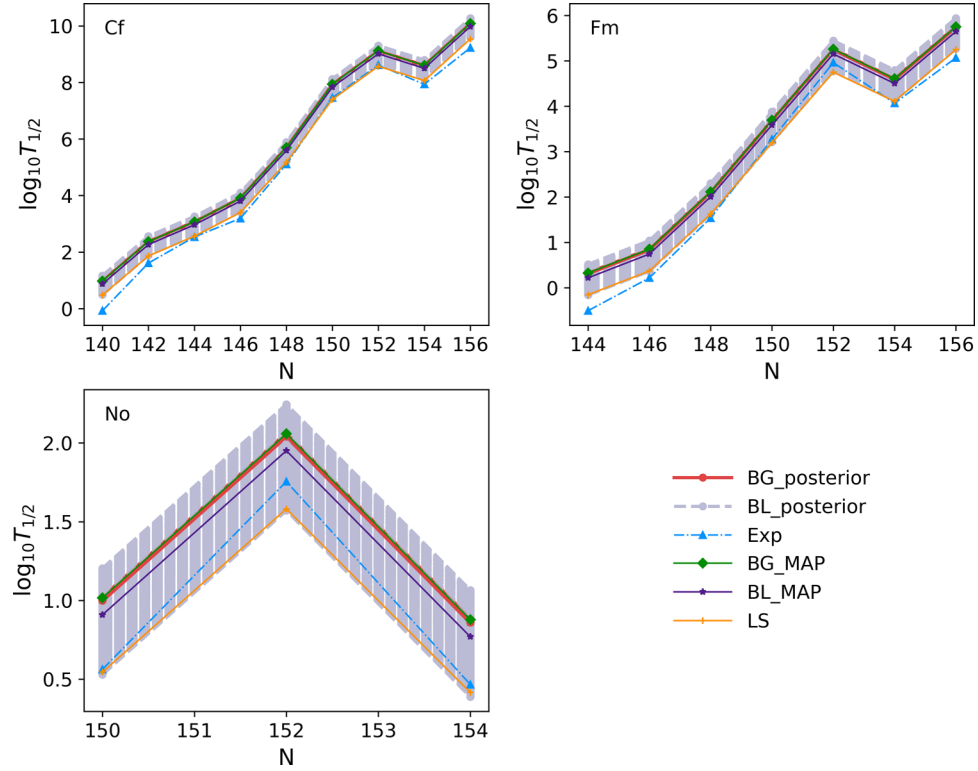


FIG. 10. The α -decay properties of nuclei around the neutron magic number $N = 152$: The variations of the half-lives against the neutron number of parent nuclei for Cf, Fm, and No isotopes, respectively.

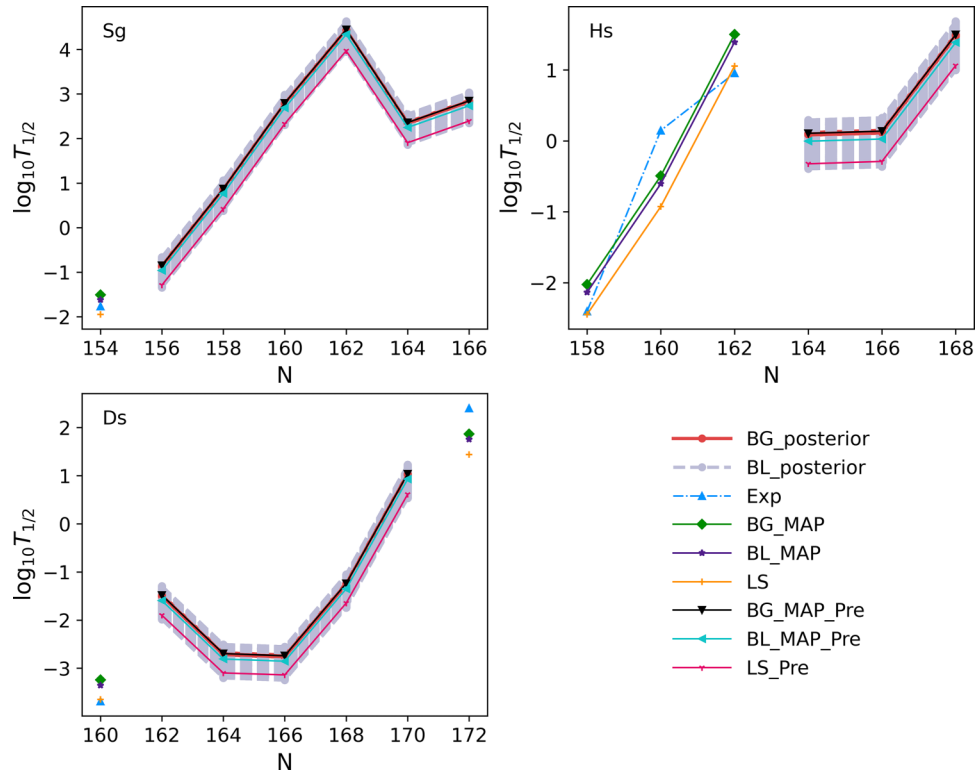


FIG. 11. The α -decay properties of nuclei around the neutron magic number $N = 162$: The variations of the predicted half-lives against the neutron number of parent nuclei for Sg, Hs, and Ds isotopes, respectively.

system near closed shells directly suppresses the preformation probability [27]. Furthermore, the spherical shape associated with magic numbers minimizes surface fluctuations and rotational degrees of freedom, which are known to enhance cluster formation probabilities in deformed nuclei [76,78]. The pronounced minima at $N = 126$ and $N = 152$ reflect this reduced collectivity [33,47]. For the predicted magic number $N = 162$ in superheavy nuclei, the observed suppression supports the existence of a substantial shell gap driven by enhanced spin-orbit coupling and central potential effects in this region [81,82]. The Bayesian framework quantitatively captures these underlying physics through the correlated adjustments of parameters b and c in the posterior distributions, demonstrating its ability to phenomenologically encode complex quantum many-body behavior beyond the reach of traditional fitting methods. These results show that by global parameter calibration and covariance analysis, Bayesian inference can still reveal the trend of shell effects and quantify the uncertainty in the sparse data region, providing a reliable framework for exploring the structure of extreme neutron number nuclei while embedding key physical drivers behind the statistical trends.

V. SUMMARY

This work establishes a Bayesian inference framework integrated with the two-potential approach to systematically

optimize the α -particle preformation factors for heavy and superheavy nuclei $90 \leq Z \leq 118$. By globally calibrating five phenomenological parameters governing P_α via MCMC sampling, we rigorously quantified posterior distributions with associated confidence intervals, effectively circumventing the inherent limitations of conventional least-squares methods in error propagation and covariance estimation. MAP estimates reveal moderate interparameter correlations, underscoring the superior capability of Bayesian methodology to constrain experimental uncertainties. Furthermore, shell effect analysis elucidates pronounced suppression of P_α at neutron shell closures $N = 126, 152, 162$, while the BG systematically reduced P_α in superheavy regions compared to BL and LS, highlighting the constraining effect of prior distributions on parameter extrapolation in the superheavy region. These results provide theoretical support for the exploration of nuclear structures beyond $Z > 118$.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China (Grants No. 12175100, No. 11975132, and No. 12405154).

DATA AVAILABILITY

The data that support the findings of this article are openly available [47,63,67,68].

-
- [1] G. Gamow, *Z. Phys.* **51**, 204 (1928).
 - [2] R. W. Gurney and E. U. Condon, *Nature (London)* **122**, 439 (1928).
 - [3] R. J. Carroll *et al.*, *Phys. Rev. Lett.* **112**, 092501 (2014).
 - [4] D. S. Delion, R. J. Liotta, and R. Wyss, *Phys. Rev. C* **92**, 051301(R) (2015).
 - [5] S. M. S. Ahmed, R. Yahaya, and S. Radiman, *Rom. Rep. Phys.* **65**, 1281 (2013).
 - [6] D. Ni and Z. Ren, *Ann. Phys.* **358**, 108 (2015).
 - [7] W. M. Seif, M. Shalaby, and M. F. Alrakshy, *Phys. Rev. C* **84**, 064608 (2011).
 - [8] Y. Ren and Z. Ren, *Phys. Rev. C* **85**, 044608 (2012).
 - [9] S. Hofmann and G. Munzenberg, *Rev. Mod. Phys.* **72**, 733 (2000).
 - [10] A. N. Andreyev *et al.*, *Phys. Rev. Lett.* **110**, 242502 (2013).
 - [11] X. J. Bao, S. Q. Guo, H. F. Zhang, and J. Q. Li, *Phys. Rev. C* **95**, 034323 (2017).
 - [12] H. F. Zhang and G. Royer, *Phys. Rev. C* **77**, 054318 (2008).
 - [13] J. Dong, W. Zuo, J. Gu, Y. Wang, and B. Peng, *Phys. Rev. C* **81**, 064309 (2010).
 - [14] S. Guo, X. Bao, Y. Gao, J. Li, and H. Zhang, *Nucl. Phys. A* **934**, 110 (2015).
 - [15] X. Bao, H. Zhang, H. Zhang, G. Royer, and J. Li, *Nucl. Phys. A* **921**, 85 (2014).
 - [16] Y. Z. Wang, S. J. Wang, Z. Y. Hou, and J. Z. Gu, *Phys. Rev. C* **92**, 064301 (2015).
 - [17] Y. T. Oganessian *et al.*, *Phys. Rev. C* **83**, 054315 (2011).
 - [18] J. Khuyagbaatar *et al.*, *Phys. Rev. Lett.* **112**, 172501 (2014).
 - [19] L. Ma *et al.*, *Phys. Rev. Lett.* **125**, 032502 (2020).
 - [20] Y. T. Oganessian *et al.*, *Phys. Rev. C* **63**, 011301(R) (2000).
 - [21] S. M. Saleh Ahmed, R. Yahaya, S. Radiman, and M. Samudi Yasir, *J. Phys. G* **40**, 065105 (2013).
 - [22] A. Dumitrescu and D. S. Delion, *At. Data Nucl. Data Tabl.* **145**, 101501 (2022).
 - [23] Z. Y. Zhang *et al.*, *Phys. Rev. Lett.* **126**, 152502 (2021).
 - [24] J. H. Hamilton, S. Hofmann, and Y. T. Oganessian, *Annu. Rev. Nucl. Part. Sci.* **63**, 383 (2013).
 - [25] J.-G. Deng and H.-F. Zhang, *Phys. Lett. B* **816**, 136247 (2021).
 - [26] Y. T. Oganessian, *Radiochim. Acta* **99**, 429 (2011).
 - [27] J. Dong, H. Zhang, J. Li, and W. Scheid, *Eur. Phys. J. A* **41**, 197 (2009).
 - [28] W. Yong-Jia, Z. Hong-Fei, Z. Wei, and L. Jun-Qing, *Chin. Phys. Lett.* **27**, 062103 (2010).
 - [29] C. Qi, D. S. Delion, R. J. Liotta, and R. Wyss, *Phys. Rev. C* **85**, 011303(R) (2012).
 - [30] Y. Wang, J. Gu, and Z. Hou, *Phys. Rev. C* **89**, 047301 (2014).
 - [31] J.-G. Deng and H.-F. Zhang, *Phys. Rev. C* **102**, 044314 (2020).
 - [32] Y.-Z. Wang, F.-Z. Xing, J.-P. Cui, Y.-H. Gao, and J.-Z. Gu, *Chin. Phys. C* **47**, 084101 (2023).
 - [33] M. Li, C.-X. Chen, L.-F. Xiao, Y. Zhang, S. Luo, and X.-H. Li, *Nucl. Sci. Tech.* **36**, 1 (2025).
 - [34] D. Deng and Z. Ren, *Phys. Rev. C* **93**, 044326 (2016).
 - [35] G. Röpke, P. Schuck, Y. Funaki, H. Horiuchi, Z. Ren, A. Tohsaki, C. Xu, T. Yamada, and B. Zhou, *Phys. Rev. C* **90**, 034304 (2014).
 - [36] C. Xu, Z. Ren, G. Röpke, P. Schuck, Y. Funaki, H. Horiuchi, A. Tohsaki, T. Yamada, and B. Zhou, *Phys. Rev. C* **93**, 011306(R) (2016).

- [37] S. Yang, C. Xu, G. Röpke, P. Schuck, Z. Ren, Y. Funaki, H. Horiuchi, A. Tohsaki, T. Yamada, and B. Zhou, *Phys. Rev. C* **101**, 024316 (2020).
- [38] C. Xu, G. Röpke, P. Schuck, Z. Ren, Y. Funaki, H. Horiuchi, A. Tohsaki, T. Yamada, and B. Zhou, *Phys. Rev. C* **95**, 061306(R) (2017).
- [39] C. Xu and Z. Ren, *Nucl. Phys. A* **760**, 303 (2005).
- [40] I. Tonozuka and A. Arima, *Nucl. Phys. A* **323**, 45 (1979).
- [41] K. Varga, R. G. Lovas, and R. J. Liotta, *Phys. Rev. Lett.* **69**, 37 (1992).
- [42] G. Dodig-Crnkovic, F. A. Janouch, and R. J. Liotta, *Nucl. Phys. A* **501**, 533 (1989).
- [43] K. Varga, R. G. Lovas, and R. J. Liotta, *Nucl. Phys. A* **550**, 421 (1992).
- [44] D. S. Delion, A. Sandulescu, and W. Greiner, *Phys. Rev. C* **69**, 044318 (2004).
- [45] D. S. Delion, R. J. Liotta, and R. Wyss, *Phys. Rev. C* **76**, 044301 (2007).
- [46] R. G. Lovas, R. Liotta, A. Insolia, K. Varga, and D. Delion, *Phys. Rep.* **294**, 265 (1998).
- [47] S. Luo, D.-M. Zhang, L.-J. Qi, X. Chen, P.-C. Chu, and X.-H. Li, *Chin. Phys. C* **48**, 044105 (2024).
- [48] S. A. Gurbitz and G. Kälbermann, *Phys. Rev. Lett.* **59**, 262 (1987).
- [49] X.-D. Sun, P. Guo, and X.-H. Li, *Phys. Rev. C* **93**, 034316 (2016).
- [50] J. Novak, K. Novak, S. Pratt, J. Vredevogd, C. E. Coleman-Smith, and R. L. Wolpert, *Phys. Rev. C* **89**, 034917 (2014).
- [51] S. Pratt, E. Sangaline, P. Sorensen, and H. Wang, *Phys. Rev. Lett.* **114**, 202301 (2015).
- [52] J. E. Bernhard, P. W. Marcy, C. E. Coleman-Smith, S. Huzurbazar, R. L. Wolpert, and S. A. Bass, *Phys. Rev. C* **91**, 054910 (2015).
- [53] J. E. Bernhard, J. S. Moreland, S. A. Bass, J. Liu, and U. Heinz, *Phys. Rev. C* **94**, 024907 (2016).
- [54] Y. He, L.-G. Pang, and X.-N. Wang, *Phys. Rev. Lett.* **122**, 252302 (2019).
- [55] J. E. Bernhard, J. S. Moreland, and S. A. Bass, *Nat. Phys.* **15**, 1113 (2019).
- [56] D. Everett *et al.* (JETSCAPE Collaboration), *Phys. Rev. Lett.* **126**, 242301 (2021).
- [57] S. Cao *et al.* (JETSCAPE Collaboration), *Phys. Rev. C* **104**, 024905 (2021).
- [58] H. Mäntysaari, B. Schenke, C. Shen, and W. Zhao, *Phys. Lett. B* **833**, 137348 (2022).
- [59] Y. Xu, J. E. Bernhard, S. A. Bass, M. Nahrgang, and S. Cao, *Phys. Rev. C* **97**, 014907 (2018).
- [60] W.-J. Xing, S. Cao, and G.-Y. Qin, *Phys. Lett. B* **850**, 138523 (2024).
- [61] L. Zhu, X. Chen, K. Zhou, H. Zhang, and M. Huang, *Phys. Rev. D* **112**, 026019 (2025).
- [62] R. K. Sheline and B. B.-M. Bossinga, *Phys. Rev. C* **44**, 218 (1991).
- [63] X.-Y. Zhu, S. Luo, W. Gao, L.-J. Qi, M. Li, X.-H. Li, and W.-B. Lin, *Chin. Phys. C* **48**, 074102 (2024).
- [64] L. Neufcourt, Y. Cao, W. Nazarewicz, and F. Viens, *Phys. Rev. C* **98**, 034318 (2018).
- [65] N. J. McMillan, J. Sacks, W. J. Welch, and F. Gao, *J. Biopharm. Stat.* **9**, 145 (1999).
- [66] D. Foreman-Mackey, D. W. Hogg, D. Lang, and J. Goodman, *Publ. Astron. Soc. Pac.* **125**, 306 (2013).
- [67] W. J. Huang, M. Wang, F. G. Kondev, G. Audi, and S. Naimi, *Chin. Phys. C* **45**, 030002 (2021).
- [68] M. Wang, W. J. Huang, F. G. Kondev, G. Audi, and S. Naimi, *Chin. Phys. C* **45**, 030003 (2021).
- [69] J.-G. Deng, H.-F. Zhang, and G. Royer, *Phys. Rev. C* **101**, 034307 (2020).
- [70] D. Ni and Z. Ren, *Phys. Rev. C* **82**, 024311 (2010).
- [71] J. S. Zheng, N. Y. Wang, Z. Y. Wang, Z. M. Niu, Y. F. Niu, and B. Sun, *Phys. Rev. C* **90**, 014303 (2014).
- [72] D. S. Delion, *Theory of Particle and Cluster Emission*, Lecture Notes in Physics Vol. 819 (Springer, Berlin, 2010).
- [73] M. Warda and J. L. Egido, *Phys. Rev. C* **86**, 014322 (2012).
- [74] M. Ismail, A. Y. Ellithi, M. M. Botros, and A. Adel, *Phys. Rev. C* **81**, 024602 (2010).
- [75] M. Huang, Z. Zhang, Z. Gan, X. Zhou, J. Li, and W. Scheid, *Phys. Rev. C* **84**, 064619 (2011).
- [76] H. A. Bethe, *Phys. Rev.* **103**, 1353 (1956).
- [77] R. V. Jolos, E. A. Kolganova, and G. Nikoghosyan, *Int. J. Mod. Phys. E* **32**, 2350042 (2023).
- [78] C. Xu and Z. Ren, *Phys. Rev. C* **74**, 014304 (2006).
- [79] D. Ni and Z. Ren, *Phys. Rev. C* **81**, 024315 (2010).
- [80] L. A. Malov and V. G. Soloviev, *Nucl. Phys. A* **270**, 87 (1976).
- [81] S. G. Nilsson, C. F. Tsang, A. Sobiczewski, Z. Szymanski, S. Wycech, C. Gustafson, I.-L. Lamm, P. Moller, and B. Nilsson, *Nucl. Phys. A* **131**, 1 (1969).
- [82] K. Nomura, T. Nikšić, and D. Vretenar, *Phys. Rev. C* **94**, 064310 (2016).
- [83] J. Sethi *et al.*, *J. Phys. G* **43**, 015103 (2016).
- [84] V. Prassa and K. Karakatsanis, *HNPS Adv. Nucl. Phys.* **30**, 75 (2024).