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RESEARCH PAPER

Decay Modes and Half-Life of $^{265-282}$Ds Isotopes

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Abstract
The decay modes and half-lives of superheavy $^{265-282}$Ds isotopes have been investigated by using Relativistic Mean Field (RMF) model with density-dependent point-coupling and density-dependent meson-exchange functional. The potential energy surfaces as a funtion of deformation parameters (β, γ) for the considered Ds nuclei have been obtained by using a triaxially deformed RMF model calculations for the investigation of their ground-state shapes and binding energies. The computed ground-state binding energy values of given Ds isotopes have been used for calculations of Q values of the alpha (α), beta-plus/electron capture (β^+/EC), beta-minus (β^-) and spontaneous fission (SF) decay modes. The dominant decay modes and half-lives of $^{265-282}$Ds isotopes have been predicted by using the computed Q-values and some empirical formulas. The results of the present study demonstrate that the $^{265-282}$Ds isotopes are well deformed, with prolate configuration in their ground-states. Our estimations for decay modes and half-lives are consistent with available experimental data.

Keywords Ds isotopes · Decay modes · Half-life · Relativistic mean field theory · Superheavy nuclei

1 Introduction

Numerous radioactive elements spontaneously decay into stable or unstable elements, releasing a variety of particles and energies in the process. Alpha decay and spontaneous fission (SF) are the two most common forms of decay for superheavy elements (Sayedi and Alemdar Milan 2015). As a result of the Coulomb force generated by protons, heavy nuclei are unstable against SF, according to the liquid drop model (Khuyagbaatar et al. 2020). The quantum tunnelling effect is a phenomenon that both alpha decay and SF are theoretically associated with (Ismail et al. 2017; Nithya and Santhosh 2022). If we compare the scenario in SF to that of alpha decay, the matter is far more complicated because there are significant uncertainties in the fission process. On the basis of the liquid drop model, Bohr and Wheeler explained the mechanism of nuclear fission and determined a limit $Z^2/A = 48$ for SF, beyond which nuclei are unstable against SF (Kiren et al. 2012; Soylu 2019). In addition, SF half-lives of heavy and superheavy nuclei are influenced by the isospin effect $(N - Z)/(N + Z)$ (Nithya and Santhosh 2022). In reality, SF is a significant limiting factor in the stability of synthesized superheavy nuclei since it describes the stability of superheavy nuclei in their natural state (Soylu 2019).

In particular, the alpha decay event is of high importance for heavy elements. For a long period of time, physicists were fascinated by the mechanism of alpha emission from a uranium nucleus until Gamow provided an explanation (Kiren et al. 2012). Gamow, as well as Gurney and Condon, each independently, used quantum tunneling to explain the alpha decay process (Palenzuela et al. 2012). The Quantum tunneling phenomenon is interesting and significant because it differs from the principles of classical mechanics. Since a particle cannot go across a potential without the needed energy, tunneling occurs as a direct result of the quantum mechanical wave nature of the particles. In classical physics, however, a particle cannot cross a potential without the needed energy (Nithya and

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Santhosh 2022). The tunneling theory was utilized by George Gamow to compute the half-lives of alpha particle emissions (Binning and Rohrer 1986). Alpha decay of superheavy nuclei is achievable if the shell effect provides additional binding energy and raises the barrier height of fission (Poenaru et al. 2006; Kiren et al. 2012). Alpha decay half-lives can be predicted using a variety of models such as universal decay law (UDL), Viola–Seaborg semi-empirical(VSS), semiempirical based on fission theory (SemFIS), and Denisov–Khudenko (DEKH), each of which has its own set of limitations (Karpov et al. 2012). On the other hand, there are other conceivable decay modes for a superheavy nucleus that can occur as a result of the weak interaction occurring. However, because beta decay happens through weak contact, the process is slow and less favorable when compared to SF and alpha decay (Chhanda et al. 2007; Rather et al. 2016). Weak interaction decay, is the transformation of nucleons from one type to another within the nucleus (Sheng et al. 2014; Rajan et al. 2016, 2020). β^--decay, β^+-decay, and orbital electron capture (EC) are the three processes that are classed together as weak interaction decay.

Despite the common decay modes in superheavy nuclei are SF and alpha decay, their instability against β-decay is not identified yet. According to a recent prediction, an exciting even-even superheavy nuclei may fission after β-decay of an odd-odd superheavy nuclei (Forsberg et al. 2016). However, due to the intrinsic complexity of both weak interaction and strong interaction for atomic nuclei, calculating beta emission probabilities for the vast majority of situations continues to be a difficult and time-consuming task (Zhang et al. 2007).

Because of some limitations in the superheavy nuclei (SHN) synthesis via cold and hot fusion reactions, a large number of superheavy nuclei are produced far away from the predicted location of the most stable SHN (Oganessian 2006; Heenen et al. 2015). The theoretical predictions of the properties for decay modes and half-lives of superheavy nuclei are very significant to synthesize new elements, to examine predictions of different models of the nucleus, and, eventually, to understand the existence of the finite number of elements in nature (Bhuyan 2018). Because of this reason, we have investigated the decay mode and half-lives of $^{265-282}$Ds isotopes.

In this work, we have investigated the ground-state (g.s.) binding energies (BEs) of $^{265-282}$Ds isotopic chain using density-dependent point-coupling (DD-PC1) and meson-exchange versions of relativistic mean field (RMF) model. The potential energy surfaces (PESs) and g.s. BEs of the considered nuclei are obtained by applying the constrained triaxially symmetric RMF model calculations. The calculated BEs of $^{265-282}$Ds isotopes have been used in various half-lives formulas to predict decay modes and related half-lives of $^{265-282}$Ds isotopes.

2 Theoretical Formalism and Details of Calculations

In this section, density-dependent version of RMF models and solution of RMF equations to obtain g.s. properties of $^{265-282}$Ds are summarized. Also, Karpov's formula used for calculating the SF half-lives, modified Royer's formula for calculating the alpha decay half-lives and Fiset and Nix method for calculating the weak-interaction decay modes ($\beta^{\pm}$ and EC) half-lives are briefly explained.

2.1 RMF Model

The nucleons interact with each other via exchange of various mesons and photons in RMF model (Walecka 1974; Ring 1996). The mesons considered in the RMF model are scalar σ, vector ω and isovector vector ρ mesons. The scalar σ and vector ω mesons are responsible for attractive and repulsive parts of the interaction of nucleons, respectively, while the isovector vector ρ meson and photon are important for the description of isospin-dependent effects and the electromagnetic interaction in nuclei, respectively. Because the mesons do not interact among themselves in the simplest version of RMF model, it encountered an issue for describing incompressibility of nuclear matter. For solution of this problem, an addition of nonlinear self-interaction of the σ-mesons were proposed by Boguta and Bodmer (1977). This nonlinear version of the RMF model has been succesfully used for describing many nuclear phenomena and properties of nuclei (Ring 1996; Lalazissis et al. 1999; Meng et al. 2006; Bayram and Yılmaz 2013; Bayram and Akkoyun 2013; Nabi et al. 2021). There are RMF models with nonlinear self-interaction of the ω and ρ mesons, and also density-dependent meson–nucleon couplings which is an alternative approach for describing finite nuclei. In this work, we have used two covariant density functional forms of RMF theory, mainly: the density-dependent meson-exchange model and a density-dependent point-coupling model. For simplicity we will summarize the both versions of RMF model in this section. More details about RMF model versions could be found in Meng et al. (2006).

The starting point of density-dependent meson-exchange version of RMF model is a phenomenological Lagrangian density given by

$$\mathcal{L} = \mathcal{L}_{\mathrm{N}} + \mathcal{L}_{\mathrm{m}} + \mathcal{L}_{\mathrm{int}}. \tag{1}$$

In Eq. (1), $\mathcal{L}_{\mathrm{N}}$ is the Lagrangian for the free nucleon

$$\mathcal{L}_{\mathrm{N}} = \bar{\Psi}(i\gamma_{\mu}\partial^{\mu} - m)\Psi, \tag{2}$$

where ψ denotes the Dirac spinor and m is the nucleon mass. $\mathcal{L}_{\mathrm{m}}$ is the Lagrangian density for the free meson fields and electromagnetic field

$$\begin{aligned}\mathcal{L}_{\mathrm{m}} = &\frac{1}{2}\partial_{\mu}\sigma\partial^{\mu}\sigma - \frac{1}{2}m_{\sigma}^{2}\sigma^{2} - \frac{1}{2}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_{\omega}^{2}\omega_{\mu}\omega^{\mu} \\ &- \frac{1}{4}\vec{R}_{\mu\nu}.\vec{R}^{\mu\nu} + \frac{1}{2}m_{\rho}^{2}\vec{\rho}_{\mu}.\vec{\rho}^{\mu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}\end{aligned} \tag{3}$$

where m_{σ}, m_{ω} and m_{ρ} are the mass of σ, ω and ρ mesons, respectively. Arrows denote isovectors. $\Omega_{\mu\nu}$, $\vec{R}_{\mu\nu}$ and $F^{\mu\nu}$ are field tensors given by

$$\begin{aligned}\Omega_{\mu\nu} &= \partial_{\mu}\omega_{\nu} - \partial_{\nu}\omega_{\mu}, \\ \vec{R}_{\mu\nu} &= \partial^{\mu}\vec{\rho}_{\nu} - \partial_{\nu}\vec{\rho}_{\mu}, \\ F_{\mu\nu} &= \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}.\end{aligned} \tag{4}$$

The interaction term ($\mathcal{L}_{\mathrm{int}}$) in Eq. (1) is given by

$$\begin{aligned}\mathcal{L}_{\mathrm{int}} = &-g_{\sigma}\bar{\Psi}\Psi\sigma - g_{\omega}\bar{\Psi}\gamma^{\mu}\Psi\omega_{\mu} - g_{\rho}\bar{\Psi}\vec{\tau}\gamma^{\mu}\Psi.\vec{\rho}_{\mu} \\ &- e\bar{\Psi}\gamma^{\mu}\Psi A_{\mu}\end{aligned} \tag{5}$$

where the g_{σ}, g_{ω} and g_{ρ} are the coupling constants of the corresponding mesons. The density-dependent meson-exchange model has an explicit density dependence for the meson-nucleon vertices. The coupling constant dependence is defined by

$$g_i(\rho) = g_i(\rho_{\mathrm{sat}})f_i(x) \quad \text{for } i = \sigma, \omega. \tag{6}$$

where ρ_{sat} represents the baryon density at saturation in symmetric nuclear matter and

$$f_i(x) = a_i\frac{1 + b_i(x + d_i)^2}{1 + c_i(x + d_i)^2}, \tag{7}$$

is a function of $x = \rho/\rho_{\mathrm{sat}}$. The eight parameters in Eq. (6) are not independent, but constrained as follows: $f_i(1) = 1$, $f_{\sigma}(1)'' = f_{\omega}''(1)$ and $f_i''(0) = 0$. These constrains reduce the number of independent parameters for density dependence to three. For the ρ meson, density dependence is of exponential form and given by

$$g_{\rho}(\rho) = g_{\rho}(\rho_{\mathrm{sat}})e^{-a_{\rho}(x-1)} \tag{8}$$

where $\rho(\rho_{\mathrm{sat}})$ and a_{ρ} provide parametrization of the isovector channel. The meson-nucleon vertex functions can be fixed-on by tuning the parameters of the assumed phenomenological density dependence of the meson-nucleon couplings to generate the properties of symmetric and asymmetric nuclear matter and finite nuclei (Lalazissis et al. 2005).

The density-dependent point-coupling version of RMF model is in complete analogy to the meson-exchange version of RMF phenomenology (Nikšić et al. 2002). In this version the isoscalar-scalar σ meson, the isoscalar-vector ω meson, and the isovector-vector ρ meson build the minimal set of meson fields that is necessary for a description of bulk and single-particle nuclear properties. The effective density-dependent point-coupling model (Nikšić et al. 2008) that includes the isoscalar-scalar, isoscalar-vector and isovector-vector four-fermion interactions is given by the Lagrangian density

$$\begin{aligned}\mathcal{L} = &\bar{\Psi}(i\gamma.\partial - m)\Psi \\ &- \frac{1}{2}\alpha_S(\rho)(\bar{\Psi}\Psi)(\bar{\Psi}\Psi) - \frac{1}{2}\alpha_v(\rho)(\bar{\Psi}\gamma^{\mu}\Psi)(\bar{\Psi}\gamma_{\mu}\Psi) \\ &- \frac{1}{2}\alpha_{TV}(\rho)(\bar{\Psi}\vec{\tau}\gamma^{\mu}\Psi)(\bar{\Psi}\vec{\tau}\gamma_{\mu}\Psi) \\ &- \frac{1}{2}\delta_S(\partial_v\bar{\Psi}\Psi)(\partial^v\bar{\Psi}\mu\Psi) - e\bar{\psi}\gamma.A\frac{1 - \tau_3}{2}\Psi.\end{aligned} \tag{9}$$

It includes the free-nucleon term, the point-coupling interaction terms, and the term for coupling of the proton to the electromagnetic field. The derivative terms in Eq. (9) account for the leading effects of finite-range interactions. These are crucial for a quantitative description of the nuclear properties of nuclei. The following practical functional form of the couplings is chosen

$$\alpha_i = a_i + (b_i + c_i x)e^{-d_i x}, \quad (i = S, V, TV) \tag{10}$$

where $x = \rho/\rho_{\mathrm{sat}}$, and ρ_{sat} represents the nucleon density at saturation in symmetric nuclear matter. Details can be found in Nikšić et al. (2008).

In the present study, we have employed axially and triaxially deformed RMF model calculations for $^{265-282}$Ds using DIRHB packgage from Nikšić et al. (2014). Two different versions of density-dependent RMF interactions, namely meson-exchange DD-ME2 (Lalazissis et al. 2005) and point-coupling DD-PC1 (Nikšić et al. 2008) have been used in our calculations. The range of DD-ME2 interaction is finite and related to the mass of the meson. In the DD-PC1 interaction, the mesons are absent and thus uses a zero range interaction. They have been used very successfully for investigations of various ground-states and excited states properties of nuclei over the nuclidic chart (Nikšić et al. 2011; Abusara et al. 2012, 2017).

Pairing correlations are important for open-shell nuclei. Bardeen–Cooper–Schrieffer (BCS) approximation has been used for treatment of pairing correlations in this work. We have performed the constrained calculations by applying constraints on both axial and triaxial mass quadrupole moments. The potential energy surface (PES) study as a function of the quadrupole deformation parameter is

performed by the method of quadratic constrained. The method of quadratic constraints uses an unrestricted variation of the function

$$\langle \hat{H} \rangle + \sum_{\mu=0,2} C_{2\mu}(\langle \mathcal{Q}_{2\mu} \rangle - q_{2\mu})^2 \tag{11}$$

where $\langle \hat{H} \rangle$ is the total energy and $\langle \hat{Q} \rangle$ represents the expectation values of mass quadrupole operators,

$$\hat{Q}_{20} = 2z^2 - x^2 - y^2 \quad \text{and} \quad \hat{Q}_{22} = x^2 - y^2 \tag{12}$$

$q_{2\mu}$ is the constrained value of the multipole moment and $C_{2\mu}$ is the corresponding stiffness constant.

2.2 Spontaneous Fission and α-Decay

In this work, we have used Karpov's formula (Karpov et al. 2012) given in Eq. (13) for the calculations of SF decay half-lives of $^{265-282}$Ds nuclei.

$$\begin{aligned} \log_{10} T_{\mathrm{SF}} = {} & 1146.44 - 75.3153\frac{Z^2}{A} \\ & + 1.63792\left(\frac{Z^2}{A}\right)^2 - 0.0119827\left(\frac{Z^2}{A}\right)^3 \\ & + B_f\left(7.23613 - 0.0947022Z^2/A\right) \\ & + \begin{cases} 0, & Z \text{ and } N \text{are even} \\ 1.53897, & A \text{ is odd} \\ 0.80822, & Z \text{ and } N \text{ are odd.} \end{cases} \end{aligned} \tag{13}$$

where B_{f} and Z^2/A are the fission barrier heights and the fissility, respectively. It includes the even-odd corrections. In this equation, the B_{f} is estimated as a sum of the liquid-drop barrier $B_{\mathrm{f}}(\mathrm{LDM})$ which is obtained from Möller et al. (2016) and the ground-state shell correction δU (g.s.) from Karpov et al. (2012).

We have used the modified Royer formula (Akrawy and Poenaru 2017) given in Eq. (14) for calculation of α-decay half-lives of $^{265-282}$Ds isotopes.

$$\log_{10} T_\alpha(\mathrm{sec}) = \alpha + bA^{\frac{1}{6}}\sqrt{Z} + \frac{cZ}{\sqrt{Q}} + dI + eI^2 \tag{14}$$

In this equation, $I = (N - Z)/A$ and the constant parameters a, b, c, d and e have been taken from Akrawy and Poenaru (2017). The Q-values of the α-decay have been obtained by using the calculated BEs of $^{265-282}$Ds from our RMF calculations in the following equation:

$$Q_\alpha(Z, A) = \mathrm{BE}(Z - 2, A - 4) + \mathrm{BE}(2, 4) - \mathrm{BE}(Z, A) \tag{15}$$

where $\mathrm{BE}(2, 4)$ is the binding energy of ^{4}He nuclei taken to be 28.30 MeV.

2.3 $\beta^{\pm}$-Decay and Electron Capture

In a similar way to the Q-value calculation in alpha decay mode, we have calculated the Q-values for β^-, β^+ and EC-decays as follows:

$$Q_{\beta^-} = \mathrm{BE}(Z + 1, A) + \mathrm{BE}(Z, A) + M_n - M_H \tag{16}$$

$$\begin{aligned} Q_{\beta^+} = {} & \mathrm{BE}(Z - 1, A) + \mathrm{BE}(Z, A) \\ & + M_n - M_H - 2m_0c^2 \end{aligned} \tag{17}$$

$$\begin{aligned} Q_{\mathrm{EC}} = {} & \mathrm{BE}(Z - 1, A) + \mathrm{BE}(Z, A) \\ & + M_n - M_H - \mathrm{BE}(\mathrm{electron}) \end{aligned} \tag{18}$$

By applying the Fiset and Nix method (Fiset and Nix 1972), we have investigated the probability of $\beta^{\pm}$-decay and EC in this work. The inverse half-lives for $\beta^{\pm}$-decay and EC to the g.s. of the daughter nuclei are given in Eqs. (19) and (20), respectively.

$$T_\beta = \frac{540m_0^5}{\rho\left(W_\beta^6 - m_e^6\right)} \times 10^{5.0} s \tag{19}$$

The $W_\beta = Q_\beta + m_{\mathrm{e}}$ represents the total energy for emitted β-particles, where as the m_{e} stands for electron's rest mass energy. The nuclear states density ρ is calculated from $e^{-A/290} \times$ *number of states* within 1 MeV of g.s. for the daughter nucleus which are utilized from Seeger et al. (1965) results.

For the calculation of EC half-lives of considered Ds isotopes we have used the formula:

$$\begin{aligned} T_{\mathrm{EC}} = {} & \frac{9m_{\mathrm{e}}^2}{2\pi(\alpha Z_k)^{2s+1}\rho\left[Q_{\mathrm{EC}} - (1-s)m_{\mathrm{e}}\right]^3} \\ & \times \left(\frac{2R_0}{\frac{\hbar c}{m_{\mathrm{e}}}}\right)^{2-2s} \frac{\Gamma(2s+1)}{1+s} 10^{6.5} s. \end{aligned} \tag{20}$$

In Eq. (20), Z_K represents the parent nucleus' effective charge for an electron in the K-shell, which can be expressed as $Z_K = Z_{\mathrm{P}} - 0.35$. The Z_{P} stands for the proton number of parent nucleus, where as α and R_0 are the fine structure and nuclear radius, respectively.

3 Results and Discussion

One of the most important nuclear features of nuclei is deformation. Previous researchs predicted that SHNs are well deformed, with the exception of superheavy nuclei with shell closure (Ren et al. 2003). The present study was initially focused on predicting the ground-state form of $^{265-282}$Ds isotopes. We have employed triaxially symmetric constrained self-consistent RMF+BCS computations that

include both gamma and beta deformations. In our calculations both density-dependent DD-ME2 and the DD-PC1 interactions have been taken into account. The PESs of $^{265–282}$Ds isotopes in the $\beta-\gamma$ plane $(0 \leq \gamma \leq 60^{o})$ calculated with DD-ME2 are shown in Fig. 1. The binding energy is set to zero at the minimum of each surface, whereas the peripheral lines represent a step of 0.75 MeV. In each PES, the minimum energy configuration is obtained on the quadrupole deformation parameter (β_2) axes which means that a prolate shape configuration is predicted for all of the Darmstadtium isotopes under consideration. The PESs of $^{265–282}$Ds isotopes obtained by using DD-PC1 functional are not present here because they are similar to those of DD-ME2 functional.

The minimum energy of each PES obtained in our calculations is related with g.s. BE of nuclei. The predicted g.s. BEs of $^{265–282}$Ds nuclei obtained by using density-dependent DD-ME2 and DD-PC1 interactions are shown in Fig. 2. In addition, the results of RMF model calculation with nonlinear NL3* interaction (Bayram and Yılmaz 2013), Finite Range Droplet Model (FRDM) (Möller et al. 2016) and available experimental data (Wang et al. 2017) are also represented in Fig. 2 for comparison. As it can be seen in the figure, RMF model results obtained by using DD-ME2 and DD-PC1 functionals and the predictions of FRDM model for g.s. BE of $^{265–282}$Ds nuclei are in great harmony with experimental data rather than the results of RMF model with NL3* interaction. It should be indicated

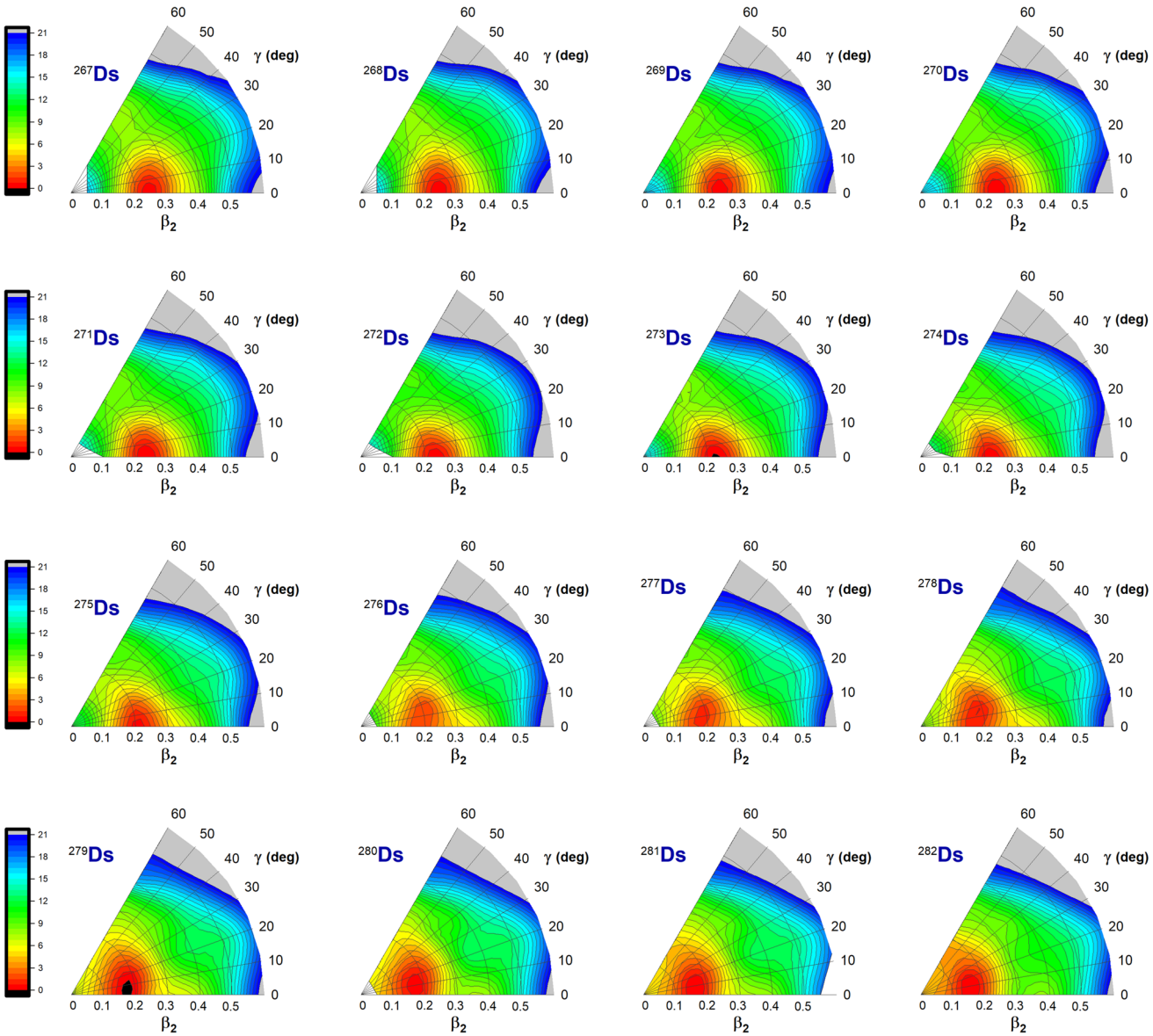


Fig. 1 The calculated PESs for $^{265–282}$Ds by using RMF model with DD-ME2 interaction

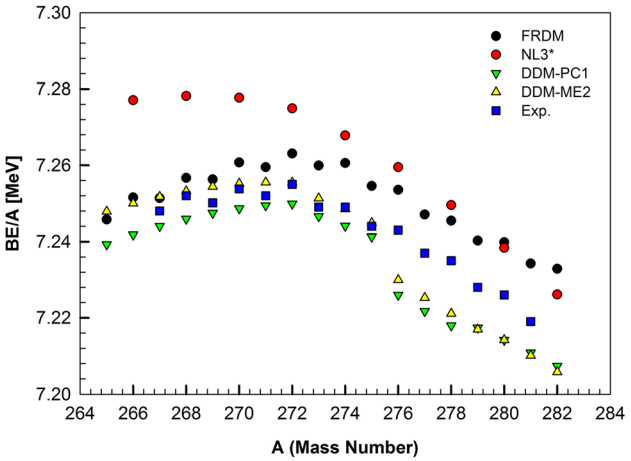


Fig. 2 The calculated and experimental binding energy per nucleon (BE/A) for isotopic chain of even-even Ds isotopes

that the RMF model with density-dependent forces which have small number of adjusted parameters predicts g.s. BE of $^{265-282}$Ds isotopes well. As a result, the RMF model with DD-ME2 and DD-PC1 functional is effective for predicting g.s. BE of Ds isotopes as FRDM which is known to be the best model to estimate BE through nuclidic chart.

The calculated BEs of $^{265-282}$Ds isotopes and the reults of FRDM have been used in Eqs. (15–18) for the calculations of Q-values of α, β^-, β^+ and EC-decays. Differences of calculated and experimental Q-values of α, β^-, β^+ and EC-decays are shown in Fig. 3. The calculations for Fig. 3(a) and (b) have been done by using the BE predictions of RMF model with DD-ME2 and DD-PC1 interactions, respectively. Furthermore, the calculated root-mean-square error (RMSE) values of Q-values for α, β^-, β^+ and

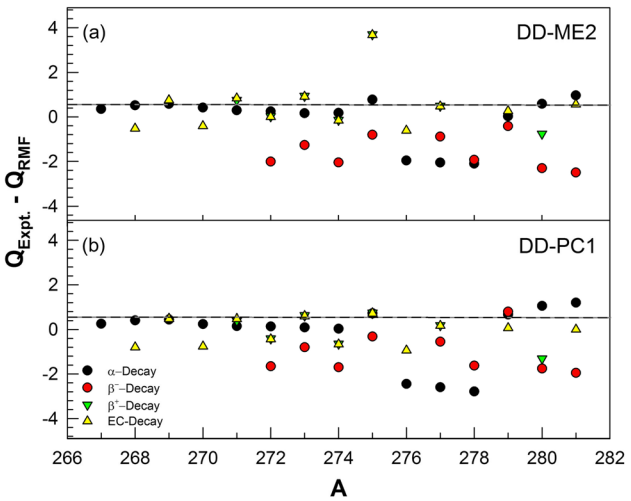


Fig. 3 Difference of calculated and experimental (NNDC 2022) Q-values for α, β^- and β^+/EC-decays

Table 1 Root-mean-square error (RMSE) values of α, β^- and β^+/EC-decay Q values for Ds isotopes

Decay	FRDM	DD-PC1	DD-ME2
α	0.203	0.353	0.281
β^-	0.074	0.660	0.744
β^+	0.806	1.961	0.570
EC	0.108	2.830	0.344

EC-decays of $^{265-282}$Ds isotopes are listed in Table 1. As it can be seen from the table, small RMSE values for α and β^--decays have been obtained with FRDM, RMF model with DD-ME2 and RMF-PC1 functional.

We have employed the calculated Q-values obtained from RMF model with density-dependent forces and the equations given in Sect. 2 to calculate half-lives of α, $\beta^{\pm}$ and EC-decays for $^{265-282}$Ds nuclei by using Eqs. (14), (19) and (20), sequentially. The half-lives for SF have been calculated by using Eq. (13). The predicted half-lives for $^{265-282}$Ds isotopes with DD-ME2 and DD-PC1 functional are listed in Tables 2 and 3, respectively. The competence of decay modes and the most probable decay mode for each Ds nuclei are listed. Additionally, we have compared our predictions for decay modes and half-life of probable decay mode with available experimental data (NNDC 2022) in Tables 2 and 3 for validation of our results. For this comparison, only nuclei having a probability of more than 50 percent of any particular decay mode or similar decay modes were taken into account. As it can be understood from Tables 2 and 3, the density-dependent version of RMF models together with the phenomenological formulas are able to determine experimental decay modes of Ds isotopes.

4 Conclusions

The RMF model with density-dependent forces DD-ME2 and DD-PC1 were used to investigate the ground-state structure of $^{265-282}$Ds nuclei. PESs of the considered Ds isotopes were performed for this purpose, and well deformed prolate structure of the Ds isotopes in their g.s. was reported as consistent with prior reports. The predicted g.s. binding energies of $^{265-282}$Ds isotopes were found to be consistent with the experimental data. The Q-values of α, β^+/EC, β^- and SF-decay modes were computed from predicted BEs of $^{265-282}$Ds nuclei. The dominant decay modes and half-lives of $^{265-282}$Ds isotopes were predicted using the computed Q-values and some empirical formulas. The RMF model's predictions for decay modes and half-

Table 2 Comparison of decay-modes and half-lives obtained from RMF model with DD-ME2 and DD-PC1 interactions for Darmstadtium isotopes. Experimental decay modes and half-lives are taken from NNDC (2022)

Nuclei	$\log T_{\frac{1}{2}}$					Decay mode		$T_{\frac{1}{2}}$	
	$\log T_{\alpha}$	$\log T_{\beta^-}$	$\log T_{\beta^+}$	$\log T_{\mathrm{EC}}$	$\log T_{\mathrm{SF}}$	Predicted	Expt.	Predicted	Expt.
^{265}Ds	−3.53	0.30	0.74	1.62	−1.22	α/SF	–	2.9×10^{-4} s	–
^{266}Ds	−4.07	0.93	1.39	2.19	−2.58	α/SF	–	8.3×10^{-5} s	–
^{267}Ds	−3.19	0.56	1.04	1.76	−0.45	α	α	6.3×10^{-4} s	2.8×10^{-6} s
^{268}Ds	−3.18	1.19	1.69	2.332	−1.76	α/SF	α	6.6×10^{-4} s	–
^{269}Ds	−2.10	0.83	1.35	1.90	1.37	α	α	7.6×10^{-3} s	1.79×10^{-4} s
^{270}Ds	−2.12	1.4	2.08	2.51	1.54	α	α	7.5×10^{-3} s	1×10^{-4} s
^{271}Ds	−1.30	1.19	1.81	2.12	4.71	α	α	0.050 s	1.63×10^{-3} s
^{272}Ds	−1.54	1.89	3.70	3.23	4.58	α	SF	0.028 s	–
^{273}Ds	−2.81	2.41	3.21	2.74	6.87	α	–	1.5×10^{-3} s	1.7×10^{-4} s
^{274}Ds	−4.06	2.89	4.47	3.56	4.92	α	SF/α	8.5×10^{-5} s	–
^{275}Ds	−1.84	2.85	4.46	–	5.56	α	α	0.014 s	–
^{276}Ds	−7.16	5.46	4.92	3.74	2.98	α	SF/α	6.8×10^{-8} s	–
^{277}Ds	−6.40	3.44	4.84	3.40	3.51	α	–	3.9×10^{-7} s	4.1×10^{-4} s
^{278}Ds	−6.19	4.00	6.30	4.24	0.63	α	–	6.42×10^{-7} s	–
^{279}Ds	−0.14	3.62	6.53	3.94	2.54	α	SF/α	0.72 s	0.18 s
^{280}Ds	1.963	6.28	–	5.54	1.38	SF /α	–	0.3 s	–
^{281}Ds	4.57	6.75	–	6.22	3.67	SF	α/SF	77.9 min	13 s/9.6 s
^{282} Ds	6.08	–	–	–	2.61	SF	–	6.7 min	–

Table 3 The same as Table 2 but for density-dependent PC1 interaction

Nuclei	$\log T_{\frac{1}{2}}$					Decay mode		$T_{\frac{1}{2}}$	
	$\log T_{\alpha}$	$\log T_{\beta^-}$	$\log T_{\beta^+}$	$\log T_{\mathrm{EC}}$	$\log T_{\mathrm{SF}}$	Predicted	Expt.	Predicted	Expt.
^{265}Ds	−3.72	0.19	0.61	1.56	−1.22	α/SF	–	1.9×10^{-4} s	–
^{266}Ds	−4.26	0.81	1.25	2.12	−2.58	α/SF	–	5.4×10^{-5} s	–
^{267}Ds	−3.41	0.43	0.89	1.69	−0.45	α	α	3.8×10^{-4} s	2.8×10^{-6} s
^{268}Ds	−3.43	1.05	1.53	2.25	−1.76	α/SF	α	3.6×10^{-4} s	–
^{269}Ds	−2.43	0.69	1.19	1.83	1.37	α	α	3.6×10^{-3}	1.79×10^{-4} s
^{270}Ds	−2.53	1.34	1.86	2.41	1.54	α	α	2.9×10^{-3}	1×10^{-4} s
^{271}Ds	−1.65	1.00	1.55	2.00	4.71	α	α	0.02 s	1.63×10^{-3}s
^{272}Ds	−1.82	1.67	3.20	3.01	4.58	α	SF	0.01 s	–
^{273}Ds	− 2.98	2.01	2.84	2.58	6.87	α	α	1×10^{-3} s	1.7×10^{-4} s
^{274}Ds	− 4.38	2.59	3.74	3.25	4.92	α	–	4.1×10^{-5} s	–
^{275}Ds	− 1.99	2.37	3.78	2.98	5.56	α	α	0.01 s	–
^{276}Ds	−8.00	5.92	4.34	3.50	2.98	α	SF/α	9.9×10^{-9}s	–
^{277}Ds	−7.36	3.01	4.20	3.15	3.51	α	α	4.3×10^{-8} s	4.1×10^{-4} s
^{278}Ds	−7.44	3.60	4.21	3.45	0.63	α	α/SF	3.5×10^{-8} s	–
^{279}Ds	1.64	2.27	5.66	3.69	2.54	α	SF/α	43.7 s	0.18 s
^{280}Ds	3.41	4.86	7.02	4.44	1.38	SF	–	24.06 s	–
^{281}Ds	5.36	4.78	–	4.30	3.67	SF	α/SF	79.45 min	13 s/9.6 s
^{282}Ds	5.44	5.83	–	5.41	2.61	SF	–	6.9 min	–

lives with density-dependent forces DD-ME2 and DD-PC1 were tabulated.

Author Contributions TB executed literature research, designed the study and edited the paper. AH performed calculations and analyzed data. ŞŞ performed calculations. All authors read and approved the final manuscript.

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Declarations

Conflict of interest The authors declare that there is no conflict of interest.

References

Abusara H, Afanasjev AV, Ring P (2012) Fission barriers in covariant density functional theory: extrapolation to superheavy nuclei. Phys Rev C 85:024314

Abusara H, Ahmad S, Othman S (2017) Triaxiality softness and shape coexistence in mo and ru isotopes. Phys Rev C 95:054302

Akrawy DT, Poenaru DN (2017) Alpha decay calculations with a new formula. J Phys G Nucl Part Phys 44(10):105105

Bayram T, Akkoyun S (2013) An analysis of E(5) shape phase transitions in Cr isotopes with covariant density functional theory. Phys Scr 87(6):065201

Bayram T, Yılmaz AH (2013) Table of ground state properties of nuclei in the RMF model. Mod Phys Lett 28:1350068

Bhuyan M (2018) Probable decay modes at limits of nuclear stability of the superheavy nuclei. Phys At Nucl 81(1):15–23

Binning G, Rohrer H (1986) Scanning tunneling microscopy. IBM J Res Dev 30(4):355–369

Boguta J, Bodmer A (1977) Relativistic calculation of nuclear matter and the nuclear surface. Nucl Phys A 292(3):413–428

Chhanda S, Narayan Basu D, Chowdhury PR (2007) Quantum tunneling in ^{277}112 and its α-decay chain. J Phys Soc Jpn 76:124201

Fiset E, Nix J (1972) Calculation of half-lives for superheavy nuclei. Nucl Phys A 193(2):647–671

Forsberg U, Rudolph D, Andersson LL et al (2016) Recoil-α-fission and recoil-α–α-fission events observed in the reaction ^{48}Ca + ^{243}Am. Nucl Phys A 953:117–138

Heenen PH, Skalski J, Staszczak A et al (2015) Shapes and α- and β-decays of superheavy nuclei. Nucl Phys A 944:415–441

Ismail M, Seif W, Adel A et al (2017) Alpha-decay of deformed superheavy nuclei as a probe of shell closures. Nucl Phys A 958:202–210

Karpov AV, Zagrebaev VI, Martinez Palenzuela Y et al (2012) Decay properties and stability of heaviest elements. Int J Mod Phys E 21:1250013

Khuyagbaatar J, Albers HM, Block M et al (2020) Search for electron-capture delayed fission in the new isotope ^{244}Md. Phys Rev Lett 125(14):142504

Kiren OV, Gudennavar SB, Bubbly SG (2012) Alpha decay favoured isotopes of some superheavy nuclei: spontaneous fission versus alpha decay. Rom J Phys 57:1335–1345

Lalazissis GA, Raman S, Ring P (1999) Ground state properties of even-even nuclei in the relativistic mean-field theory. At Data Nucl Data Tables 71(1):1–40

Lalazissis GA, Nikšić T, Vretenar D et al (2005) Relativistic hartree-bogoliubov model with density-dependent meson-nucleon couplings. Phys Rev C 71:024312

Meng J, Toki H, Zhou S et al (2006) Relativistic continuum Hartree Bogoliubov theory for ground-state properties of exotic nuclei. Prog Part Nucl Phys 57(2):470–563

Möller P, Sierk A, Ichikawa T et al (2016) Nuclear ground-state masses and deformations: Frdm (2012). At Data Nucl Data Tables 109–110:1–204

Nabi JU, Bayram T, Daraz G et al (2021) The nuclear ground-state properties and stellar electron emission rates of ^{76}fe, ^{78}ni, ^{80}zn, ^{126}ru, ^{128}pd and ^{130}cd using rmf and pn-qrpa models. Nucl Phys A 1015:122278

Nikšić T, Vretenar D, Finelli P et al (2002) Relativistic hartree-bogoliubov model with density-dependent meson-nucleon couplings. Phys Rev C 66:024306

Nikšić T, Vretenar D, Ring P (2008) Relativistic nuclear energy density functionals: adjusting parameters to binding energies. Phys Rev C 78:034318

Nikšić T, Vretenar D, Ring P (2011) Relativistic nuclear energy density functionals: mean-field and beyond. Prog Part Nucl Phys 66:519–548

Nikšić T, Paar N, Vretenar D et al (2014) Dirhb-a relativistic self-consistent mean-field framework for atomic nuclei. Comput Phys Commun 185(6):1808–1821

Nithya C, Santhosh K (2022) Studies on the decay modes of superheavy nuclei with z = 120. Nucl Phys A 1020:122400

NNDC (2022) National nuclear data center. http://www.nndc.bnl.gov/ . Accessed on 2 Mar 2022

Oganessian Y (2006) Synthesis and decay properties of superheavy elements. Pure Appl Chem 78(5):889–904

Palenzuela Y, Ruiz L, Karpov A et al (2012) Systematic study of decay properties of heaviest elements. Bull Russ Acad Sci Phys 76:1165–1171

Poenaru DN, Plonski IH, Greiner W (2006) α-decay half-lives of superheavy nuclei. Phys Rev C 74:014312

Rajan MKP, Biju RK, Santhosh KP (2016) Studies on beta decay of isotopes in the heavy region. Paper presented at the 61. DAE Symposium on nuclear physics, 5–9 Dec 2016

Rajan MKP, Biju RK, Santhosh KP (2020) Beta decay studies of nuclides in the heavy region. J Nucl Phys Mat Sci Radiat Appl 8(1):43–53

Rather AA, Ikram M, Usmani AA et al (2016) Structural and decay properties of z = 132, 138 superheavy nuclei. Eur Phys J A 52:372

Ren Z, Chen DH, Tai F et al (2003) Ground state properties of odd-z superheavy nuclei. Phys Rev C 67(6):064302

Ring P (1996) Relativistic mean field theory in finite nuclei. Prog Part Nucl Phys 37:193–263

Sayedi M, Alemdar Milan S (2015) Estimation of alpha decay half lives for isotopes super heavy nuclei (even [z]-even [n]), (even-odd), (odd-even) and (odd-odd) the range atomic number z=104-118. Cumhur Sci J 36(3):1300–1949

Seeger PA, Fowler WA, Clayton DD (1965) Nucleosynthesis of heavy elements by neutron capture. Astrophys J 11:121

Sheng Z, Shu L, Meng Y et al (2014) Competition between alpha-decay and beta-decay for Heavy and superheavy nuclei. Chin Phys C 38(12):124101

Soylu A (2019) Calculations of spontaneous fission (sf) half-lives of superheavy nuclei in different models. BEU J Sci 57:72–76

Walecka J (1974) A theory of highly condensed matter. Ann Phys 83(2):491–529

Wang M, Audi G, Kondev FG et al (2017) The AME2016 atomic mass evaluation (II). tables, graphs and references. Chin Phys C 41(3):030003

Zhang X, Ren Z, Zhi Q et al (2007) Systematics of β^--decay half-lives of nuclei far from the β-stable line. J Phys G Nucl Part Phys 34(12):2611–2632

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