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α-decay lifetime in superheavy nuclei with $A > 282$

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Nuclei with $A > 282$ have been studied in the relativistic mean field approach using the force FSU Gold and a zero range pairing interaction. The Euler-Lagrange equations have been solved in the coordinate space. The α-nucleus potential has been constructed with the density-dependent M3Y interaction (DDM3Y1), which has an exponential density dependence, in the double folding model using the nucleon densities in the daughter nucleus and the α particle. Half-lives of α decay have been calculated for tunneling of the α particle through the potential barrier in the WKB approximation and assuming a constant preformation probability. The resulting values agree well with experimental measurements.

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Study of α decay in superheavy nuclei (SHN) presents a unique opportunity for probing the nuclear density in this mass region where other common methods such as scattering are not yet possible. α decay is known to take place through tunneling of the potential barrier by the α particle. The barrier itself depends on the density profile of the daughter nucleus. Thus, α-decay lifetime may provide a stringent test of the ability of nuclear structure theories to predict the nuclear density.

In the present work, we have followed the microscopic super-asymmetric fission model (SAFM) which uses WKB approximation to calculate the tunneling probability. The potential between the α particle and the daughter nucleus has been obtained in the double folding model by folding the proton and neutron densities in the α particle and the daughter nucleus with some suitable interaction. Usually the densities are obtained from phenomenological description. However, in the present work we utilize the microscopic densities obtained from the relativistic mean field (RMF) calculation. The shape of the barrier is known to be sensitively dependent on the density. For example, the height of the fission barrier in very heavy nuclei is known to change with the nucleon density [1]. Avrigeanu *et al.*. [2] investigated the effect of different phenomenological densities in the α nucleus scattering and found that some densities are more suited to describing the α-nucleus interaction. In the superheavy region, nucleon densities are not experimentally known, and theoretical densities may be used as a substitute.

We study the even-even and odd mass nuclei with $A > 282$ in the present report. A large number of calculations of half-life of SHN based on the SAFM are available in the literature, and we cite only a few recent ones. A number of nuclei in this mass region have been systematically studied using a phenomenological density profile and effective interaction by Mohr [3] and Roy Chowdhury *et al.* [4]. Gambhir *et al.* [5] have also calculated the half-life values of superheavy nuclei with densities obtained from the RMF calculation with the relativistic force NL3 [6] and the density-dependent interaction DDM3Y in the double folding approach. In the present brief report, we use a new Lagrangian density to calculate the density of the nuclei. We also employ an interaction with an exponential density dependence which reproduces the low-energy α scattering data very well. In contrast to most earlier works in the RMF, we perform our calculation in the coordinate space because obtaining exact values for density as a function of radius is of great importance in constructing the barrier.

RMF is now a standard approach used for studying low-energy nuclear structure. It can describe various features of stable and exotic nuclei including ground state binding energy, shape, size, properties of excited states, single-particle structure, neutron halo, etc. (see, e.g., Ref. [7]). In nuclei far from the stability valley, the single-particle level structure undergoes modifications in which the spin-orbit splitting plays an important role. In exotic nuclei, it is often difficult experimentally to obtain information about these changes. For example, in the nuclei studied in this work, almost nothing is known experimentally about the single-particle levels. Being based on the Dirac Lagrangian density, RMF is particularly suited to investigating these nuclei because it naturally incorporates the spin degrees of freedom. There are different variations of the Lagrangian density and also a number of different parametrizations in RMF. Recently, a new Lagrangian density has been proposed [8] which involves self-coupling of the vector-isoscalar meson as well as coupling between the vector-isoscalar meson and the vector-isovector meson. The corresponding parameter set is called FSU Gold [8]. This Lagrangian density has earlier been employed to obtain the proton nucleus interaction to successfully calculate the half-life for proton radioactivity [9] and cluster radioactivity [10]. In this work also, we have employed this force.

In the conventional RMF+BCS approach, the Euler-Lagrange equations are solved under the assumptions of classical meson fields, time reversal symmetry, no-sea contribution, etc. Pairing is introduced under the BCS approximation. Since the nuclear density as a function of radius is very important in our calculation, we have solved the equations in coordinate space. The strength of the zero range pairing force is taken as 300 MeV fm for both protons and neutrons. For the odd-mass nuclei also, we followed the same procedure, though the time

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reversal symmetry is not an exact symmetry for them. The main aim of the present work is to calculate density and use the results to predict the half-lives for α decay. We expect the density for the odd-mass nuclei calculated with time reversal symmetry to be nearly identical to the results when explicit breaking of symmetry is taken into account.

Rashdan [11] also used the RMF Lagrangian to consistently calculate nucleus-nucleus potential and obtained the cross sections for elastic scattering in halo nuclei. That work reproduces the work better than the DDM3Y force in the case of scattering of the halo nucleus ^{11}Li. However, we expect that in the nuclei that we have studied, the conventional DDM3Y potential may be adequate for calculating the α-daughter nucleus potential. Indeed, Rashdan [11] pointed out that the optical model potential has to be strongly reduced to explain the measured angular distribution, but such a large reduction cannot explain the total cross section. However, in our work, we have observed no renormalization except the effect that it may have on the spectroscopic factor. Thus we have used the DDM3Y interaction in our work.

The microscopic density-dependent M3Y interaction (DDM3Y) was obtained from a finite range nucleon interaction by introducing a density-dependent factor. This class of interactions has been employed widely in the study of nucleon-nucleus as well as nucleus-nucleus scattering, calculation of proton radioactivity, etc. In this work, we have employed the interaction DDM3Y1, which has an exponential density dependence

$$\begin{aligned} v(r, \rho_1, \rho_2, E) \\ = C[1 + \alpha \exp(-\beta(\rho_1 + \rho_2))](1 - 0.002E)u^{\mathrm{M3Y}}(r), \quad (1) \end{aligned}$$

used in Ref. [12] to study α-nucleus scattering. Here ρ_1 and ρ_2 are the densities of the α particle and the daughter nucleus, respectively, and E is the energy per nucleon of the α particle in MeV. It uses the direct M3Y potential $u^{\mathrm{M3Y}}(r)$ based on the G-matrix elements of the Reid [13] NN potential. The weak energy dependence was introduced [14] to reproduce the empirical energy dependence of the optical potential. The parameters used have been assigned the standard values, *viz.*, $C = 0.2845$, $\alpha = 3.6391$, and $\beta = 2.9605$ fm^2 in this work. This interaction has been folded with the theoretical densities of α particle and the daughter nucleus in their ground states using the code DFPOT [15] to obtain the interaction between them.

Once the α-nucleus interaction has been obtained, the barrier tunneling probability for the α particle is calculated in the WKB approximation. The assault frequency is calculated from the decay energy following Gambhir *et al.* [5]. All the lifetime values calculated are for $l = 0$ decays, i.e., assuming no centrifugal barrier. For odd-mass nuclei, it is possible that some of the decays involve non-zero l values. However, as no experimental evidence is available for the spin-parity of the levels involved in the decay, we have not included the centrifugal barrier.

We have assumed the nuclei studied to be spherical in shape. Other relativistic structure calculations have also suggested that nuclei in the vicinity of ^{286}114 are spherical in shape, as $N \sim 172$, $Z \sim 114$ behave like a closed core. Our results for binding energy and Q value of α decay for the different chains are presented in Table I. No experimental binding energy value is available for any of the nuclei studied. Except for the decay of ^{283}113 and ^{283}112, the Q values are close to experiment. For the above two nuclei, the Q-value predictions are poor, because the daughter nuclei in the two cases, ^{279}111 and ^{279}110, respectively, have been assumed to be spherical. In reality, they are more likely to be deformed, and hence the binding energies of the daughters are larger than predicted by spherical calculation.

TABLE I. Binding energy and α-decay Q values for the nuclei studied.

Nucleus	B.E./A (MeV)	Q_α (MeV)	
		Theo.	Expt.
^{294}118	7.107	11.453	11.81
^{290}116	7.146	10.979	11.00
^{286}114	7.186	9.830	10.345
^{282}112	7.222		
^{292}116	7.140	10.673	10.80
^{288}114	7.178	9.287	10.09
^{284}112	7.212		
^{287}115	7.170	10.535	10.74
^{283}113	7.208	8.226	10.26
^{279}111	7.240		
^{293}116	7.136	10.543	10.67
^{289}114	7.174	9.047	9.96
^{285}112	7.207	8.745	9.29
^{281}110	7.240		
^{291}116	7.143	10.805	10.89
^{287}114	7.182	9.568	10.16
^{283}112	7.217	6.597	9.76
^{279}110	7.243		

The density as a function of radius is very important in calculating the α-nucleus potential. In Fig. 1, the proton and neutron densities in two nuclei, ^{294}118 and ^{282}112, have been plotted. The densities for other nuclei studied in this work follow the same pattern.

A small change in Q value can lead to an order of magnitude change in the estimates of life time, and theoretically calculated Q values do not achieve such high accuracy. Following the

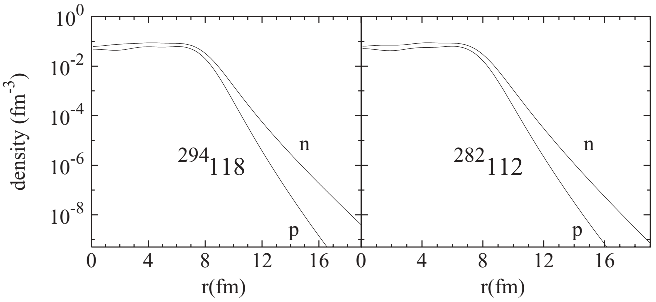

FIG. 1. Calculated neutron (n) and proton (p) densities in ^{294}118 and ^{282}112.

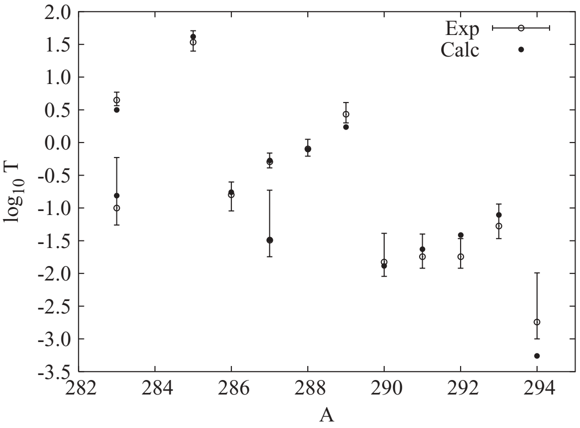

FIG. 2. Calculated and experimental half-life values in superheavy nuclei.

usual practice, the Q values (and the decay energies) were taken from experiment in the present work.

The spectroscopic factor in α decay was introduced to incorporate the preformation probability. It mainly contains the nuclear structure effects and may be thought of as the overlap between the actual ground state configuration of the parent and the configuration described by one α-particle coupled to the ground state of the daughter. Obviously, it is expected to be much less than unity, as there are contributions from many other configurations other than the one mentioned above. As we have considered only a small mass region, $283 \leqslant A \leqslant 294$, for the parent nuclei, we do not expect the spectroscopic factor to vary to any large extent. In the present work, we did not calculate the spectroscopic factor theoretically but instead took a constant value 1.4×10^{-2} for all the decays from a fit of the half-life values. This number is smaller than the values assumed usually. However, Mohr [3] showed that the spectroscopic factors are considerably small, and more so in the region above $A = 280$. Applying this value for the spectroscopic factor in all the decays, we obtain the half-life values.

Our results for half-life values are shown in Fig. 2. One can see that in most cases, the agreement is quite satisfactory. Only in the case of the decay of ^{294}118 do we have a significant departure. Of course, one must remember that the errors in the measured values are large because of the experimental difficulties and consequent poor statistics. The errors shown correspond to 1σ values. The excellent agreement over a range of over four orders of magnitude shows that the assumption that the nuclei under investigation are spherical in shape is fairly correct. It also shows that the densities are fairly well reproduced in the present calculation with the force FSU Gold.

To summarize, α-decay half-lives in SHN with $A > 282$ have been calculated in SAFM. The nuclear binding energy, Q value, and density have been obtained from the RMF approach in coordinate space using the force FSU Gold and a zero range pairing interaction. The α-nucleus potential has been constructed with the DDM3Y1 interaction, which uses an exponential density dependence, in the double folding model with the densities of the daughter nucleus and the α particle. Lifetimes of α decay have been calculated for tunneling of the α particle through the potential barrier in the WKB approach and assuming a constant preformation probability. The resulting values agree with experimental measurements.

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[1] J. F. Berger and K. Pomorski, Phys. Rev. Lett. **85**, 30 (2000).
[2] M. Avrigeanu, W. von Oertzen, A. J. M. Plompen, and V. Avrigeanu, Nucl. Phys. **A723**, 104 (2003).
[3] P. Mohr, Phys. Rev. C **73**, 031301(R) (2006).
[4] P. R. Chowdhury, C. Samanta, and D. N. Basu, Phys. Rev. C **73**, 014612 (2006).
[5] Y. K. Gambhir, A. Bhagwat, and M. Gupta, Phys. Rev. C **71**, 037301 (2005).
[6] G. A. Lalazissis, J. König, and P. Ring, Phys. Rev. C **55**, 540 (1997).
[7] P. Ring, Prog. Part. Nucl. Phys. **37**, 13 (1996).
[8] B. G. Todd-Rutel and J. Piekarewicz, Phys. Rev. Lett. **95**, 122501 (2005).
[9] M. Bhattacharya and G. Gangopadhyay, Phys. Lett. **B651**, 263 (2007).
[10] M. Bhattacharya and G. Gangopadhyay, Phys. Rev. C **77**, 027603 (2008).
[11] M. Rashdan, Phys. Rev. C **54**, 315 (1996).
[12] D. T. Khoa and W. von Oertzen, Phys. Lett. **B342**, 6 (1995).
[13] G. Bertsch, J. Borysowicz, H. McManus, and W. G. Love, Nucl. Phys. **A284**, 399 (1977).
[14] D. T. Khoa, W. von Oertzen, and H. G. Bohlen, Phys. Rev. C **49**, 1652 (1994).
[15] J. Cook, Comput. Phys. Commun. **25**, 125 (1982).