Alpha decay half-lives of superheavy nuclei

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Abstract

Hartree-Fock calculations with the SKX Skyrme interaction are carried out to obtain alpha decay Q values for deformed nuclei above ^{208}Pb assuming axial symmetry. The results for even-even nuclei are compared with experiment and with previous calculations. Predictions are made for half-lives of superheavy nuclei using a global formula.

1 Introduction

Superheavy nuclei probe the extremes of nuclear structure with respect to the number of nucleons that can form a bound system. Their existence and decay properties are one of the most fundamental problems in nuclear physics [1, 2]. There are data which confirm the existence of $Z = 111$ and 112 and their connection to lighter decay chains [3]. The first data for $Z = 114$ and 116 also exist [4], with suggested $A = 288$ and 292, respectively, but the A values are not certain since the connection to lighter nuclei is not known.

Theoretical models for superheavy nuclei have evolved from macroscopic-microscopic models such as the finite-range droplet model with shell corrections [5] to fully microscopic deformed Hartree-Fock (HF) models [6, 7]. In addition to their importance for many-body nuclear structure, theoretical models for the prediction of the decay properties of the superheavy nuclei are important when designing experiments since the techniques used will depend on the half-life and decay mode.

Here we present a new set of HF results for alpha decay Q-values of superheavy nuclei. A global formula is used to calculate the half-lives. Our calculations are based upon the new Skyrme interaction SKX [8]. The reason for exploring results with another interaction is that the alpha decay Q-value systematics are sensitive to the spherical and deformed shell-effects which depend upon the underlying parameters of the hamiltonians. There are several modern Skyrme parameter sets available, each of them determined with a different weighting and emphasis on the nuclear structure properties.

The SLy4 parameters [9] used in [6] and the MSk7 parameters [7] take into account overall spacing of the single-particle states such as those in ^{208}Pb. However, the SKX interaction [8] explicitly incorporates most of the observed single-particle levels in ^{208}Pb (and lighter doubly magic nuclei) into the data set which was used to determine the parameter values. All of the Skyrme HF calculations have some disagreement with experimental single-particle energies, however, SKX has the best overall agreement.

In our deformed HF calculations we assume axial symmetry of the nuclei and expand the single-particle wave functions in a spherical basis [10]. The distribution of the single-particle energies for protons and neutrons in an alpha decay chain for constant $N-Z$ as a function of N shows clearly the transition between spherical nuclei (for the magic numbers $N = 126$ and $N = 184$) and well deformed nuclei around $N = 150$. Proton and neutron shell gaps, e.g. at $N = 162$, are readily identified in both spherical and deformed nuclei.

The binding energy of a nucleus with A nucleons and Z protons in its ground state is calculated from

$$BE(A,Z) = -(E_{mf} + E_{pair} - E_{cm} - E_{rot}) \tag{1}$$

with the mean-field contribution $E_{mf} = \int d^3r\, H(\vec{r})$ which is obtained by integrating the Skyrme-Hartree-Fock energy density $H(\vec{r})$ over the spatial coordinates. The pairing energy in the BCS approach is given by

$$E_{pair} = -\sum_q \frac{G_q}{4}\left(\sum_i \sqrt{w_{qi}(1-w_{qi})}\right)^2 \tag{2}$$

with occupation numbers w_{qi} and pairing strengths $G_{+1} = 1.9/\sqrt{A}$ MeV for protons and $G_{-1} = 1.2/\sqrt{A}$ MeV for neutrons, respectively. These values were obtained from a fit to experimental pairing gaps of $N = 146$ isotones and $Z = 92$ isotopes. The correction for the center-of-mass motion E_{cm} is the same harmonic oscillator approximation as for spherical nuclei in the SKX parametrization [8]. The rotational correction is approximated by $E_{rot} = \langle\psi|J_x^2|\psi\rangle/(2\mathcal{I}_x)$ where ψ is the many-body wave function of the nucleus in the BCS ground state. The moment of inertia $\mathcal{I}_x$ for the rotation around the x-axis is calculated in the cranking model.

2 Alpha decay Q-values and half-lives

From the binding energies we calculate the alpha decay Q-value, $Q_\alpha = BE(A-4, Z-2) + BE(4,2) - BE(A,Z)$. The results for even-even nuclei are shown in Fig. 1. The points are connected in this figure for a given $N - Z$ value in order to emphasize how the Q-values changes in a given decay chain. The purpose is to compare with the measured Q-values as well as to compare with the results of the finite-range droplet model (FRDM) [5] and to the deformed HF-BCS calculations based on the MSk7 Skyrme interaction [7]. The comparison shows that the results for MSk7 and SKX are remarkably similar even though they are based upon Skyrme parameter sets which are determined completely independently. Both show good overall agreement with experimental Q-values [11] to within a rms deviation of a few hundred keV. We also show in Fig. 1 the comparison with experimental Q_α values (cross-filled circles) from the sug-

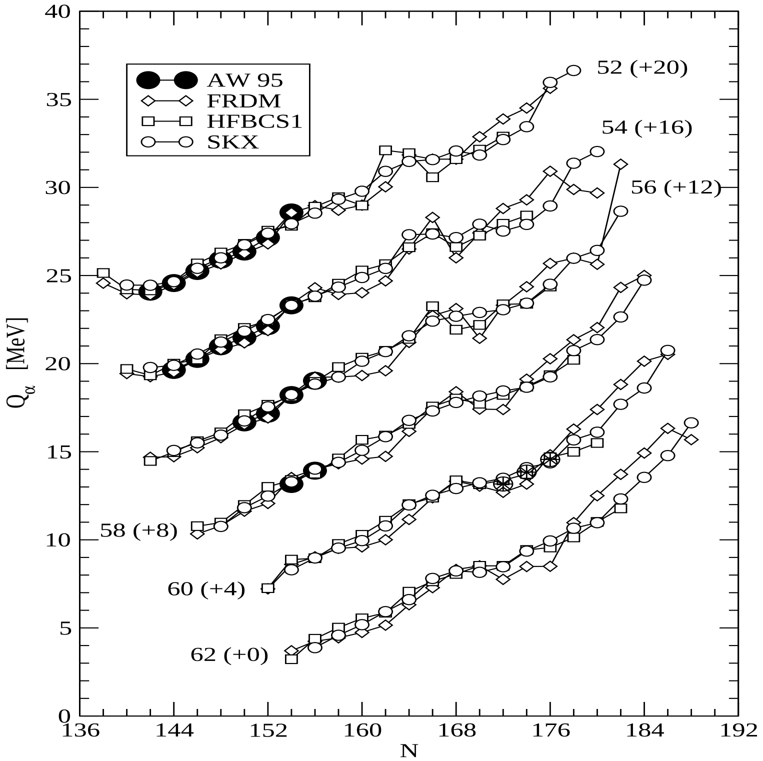

Fig. 1: Q-value for α-decay as a function of the neutron number N for even-even nuclei. Predictions from the finite range droplet model (open diamonds: FRDM), and two Skyrme Hartree-Fock parametrizations (open squares: MSk7 and open circles: SKX) are compared with the experimental data (solid circles). Different decay chains with the same value of $N - Z$ (indicated by the numbers) are connected by solid lines and shifted vertically by the amount (in MeV) shown in parentheses.

gested placement of the $Z = 116$ decay chain [4]. These also agree well with theory. The FRDM results are similar to the HF in the region where data are available but become more different for the extrapolation to heavier nuclei.

The alpha decay half-life is important for determining how the alpha decay of superheavy nuclei competes with fission. The extrapolated half-lives are also important for choosing the type of experimental techniques used for their identification. To calculate the half-lives we use the empirical result obtained in [12]

$$\log_{10}\left[T_{1/2}/\mathrm{s}\right] = 9.54(Z-2)^{0.6}/\sqrt{Q_\alpha/\mathrm{MeV}} - 51.37\,. \tag{3}$$

Comparing the half-life calculated from Eq. (3) with the experimental Q-values with experimental half-lives [13] we find an excellent agreement between experiment and theory. It shows that the systematics implied by Eq. (3) are adequate for a determination of the alpha decay half-life to within about a factor of three.

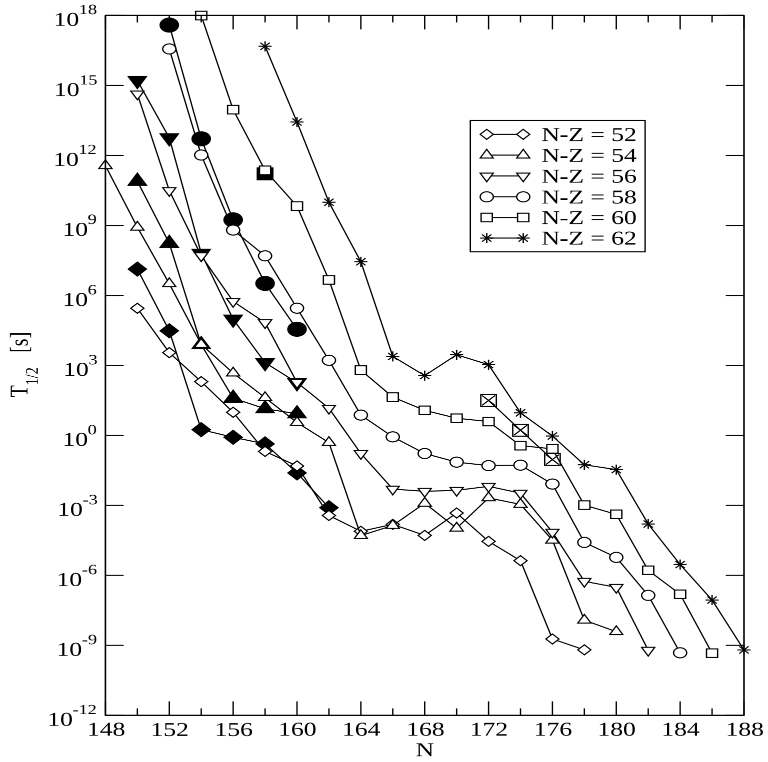

Fig. 2: Half-lives of even-even nuclei as a function of the neutron number N. Open (solid) symbols indicate half-lives calculated with Q_α values from the SKX parametrization (experiment). Decay chains with constant $N - Z$ value are connected by solid lines. The experimental half-lives from the suggested placement of the $^{292}116$ decay chain are shown by the cross-filled boxes.

The predictions for the half-lives of heavier nuclei based upon the theoretical Q_α values from our SKX calculations are shown in Fig. 2. The agreement with experiment is satisfactory except near $N = 152$ where the kink in the experimental half-lives is not reproduced by the theory. The experimental half-lives for the suggested placement of the $Z = 116$ decay chain [4] are also in reasonable agreement with theory. One observes an island of relative stability starting at $N = 164$ where the half-lives for $Z \approx 53$ remain at the msec level or longer until $N \approx 174$ where they start to become shorter.

Much of the data for the superheavy nuclei are for odd-even decay chains. These are more difficult to calculate and compare with experiment since the deformed level density is high and the observed nuclei may be in isomeric states. These must be considered carefully. For this paper we compare with the Q-values observed for the recently confirmed decay chain for $N - Z = 53$ starting at $^{277}112$ in Fig. 3. In the calculation we assume that the nucleus is in its lowest energy deformed single-particle state. The results are also compared to the FRDM and MSk7 models. As in Fig. 1, the SKX and MSk7 results are close to each other and both are close to experiment, with perhaps SKX being in best agreement with experiment. The FRDM results do not agree as well in detail with experiment. In the deformed HF the jump in Q-value between $N = 161$ and $N = 163$ observed in Fig. 3 comes from a deformed shell gap at $N = 162$ and $Z = 108$. These deformed gaps are also found with the

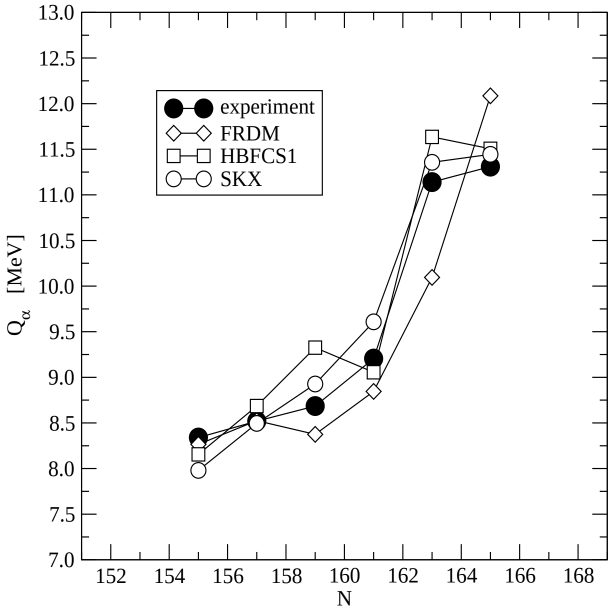

Fig. 3: Same as Figure 1 but for the nuclei with $N - Z = 53$.

SLy4 interaction [6].

3 Summary

We have presented a new calculation for the alpha decay Q values for superheavy nuclei based upon deformed Hartree-Fock calculations with the SKX Skyrme interaction. The Q values have been used to calculate alpha decay half-lives which are in reasonable agreement with theory. Deformed shell gaps at $N = 162$ and $Z = 108$ lead to jumps in the Q values which are consistent with experiment.

Acknowlegment

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