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Relativistic mean field study of the newly discovered α-decay chain of $^{287}115$

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Abstract

The single particle structure of the low lying levels in the nuclei belonging to the newly observed α-decay chain starting from $^{287}115$ has been studied. Relativistic mean field calculation with two forces NL1 and NL3 has been performed in the blocked BCS approximation. Q-values for possible decay have been calculated and compared with experiment. Lifetime estimates obtained from phenomenological relations have also been compared.

1 Introduction

One of the most exciting fields in nuclear physics in recent times is the production and study of superheavy nuclei. It has been possible to synthesize nuclei up to Z=116 in the laboratory. The most recent additions are the nuclei $^{287,288}115$[1]. The odd nucleus $^{287}115$ has been observed to decay through α-emissions and most probably ending in the nucleus $^{267}105$. Superheavy nuclei present an exciting challenge to the existing nuclear theories as their very existence is a quantum effect, the liquid drop barrier being either absent or negligibly small. Theory plays a very important role also in the identification of nuclei in the superheavy region.

In any study of odd mass nuclei in the superheavy region the most important quantities are the binding energy and the Q_α value. In many cases, the binding energy is known from the Q_α values of the decays of the chain when the mass of any member of the chain is known previously, assuming the decay to be between the ground states of the parent and the daughter nuclei. However, decay from ground state to ground state may be hindered or forbidden due to

spin-parity selection rules. Thus it is important to study the one quasiparticle states near the ground state for possible decay paths. If the observed decay involves isomeric excited states, the Q_α value may differ considerably from that expected in ground state to ground state transition. Frequently the chain does not end in any previously known nucleus making the identification of the parent very difficult. The Q-values for α-decay and the lifetime estimates obtained from them using phenomenological relations are used for the identification. As already mentioned, the hindrance factors of α-decay, and hence lifetime values, depend crucially on the quantum numbers of the parent and daughter states involved. Theoretical ideas about the single particle structure are therefore crucial even for identification.

Relativistic mean field (RMF) calculations are known to give a good description of the structure of nuclei throughout the periodic table. In an odd nucleus, there is an additional complication as the last odd nucleon breaks the time reversal symmetry of the mean field. Hence, the space-like components of the meson fields, which are absent in even-even nuclei, contribute to the different nuclear properties in odd nuclei. However, it is well known that these contributions are very small in the case of bulk properties like binding energy or deformation and are important only in features like magnetic moment or moment of inertia which depend on only a few nucleons[2, 3]. We have neglected these contributions as we are primarily interested in only the binding energy. We have restored time reversal symmetry by using the blocking method in pairing [4].

Proton-odd neutron-even superheavy nuclei have not been extensively studied in the mean field formalism. Ren *et al* [5] have systematically studied the binding energy and deformation of odd Z superheavy nuclei using the relativistic forces TMA[6] and NLZ2[7]. Rashdan [8] have studied the nuclei $^{271}111$ using the force NLRA1. These calculations do not take the level occupied by last odd nucleon into account. Geng *et al* [9] have studied the the nuclei of the α-decay chain starting from $^{287}115$ using the TMA force and included the effect of the blocking by the odd proton. They have used both constant pairing and density dependent delta-function interaction.

In this work we have studied the structure of the nuclei belonging to the decay chain of $^{287}115$. First we investigate the heaviest proton-odd nuclei whose ground state spin parity values are known to check the ability of the theory to reproduce the experimental structure in superheavy region. Next we study the nuclei occurring in the α-decay chain of $^{287}115$ to find out the energy and spin-parity of the one quasiparticle levels near the ground state and hence the possible α-transitions. We have used the relativistic forces NL1[10] and NL3[11].

2 Results

The RMF theory is well known and will not be discussed here. Readers may find excellent descriptions of the theoretical method using the basis expansion method in refs [12, 13]. We have described the blocking procedure followed in RMF in an earlier calculation [14]. The levels are denoted by the Nilsson

quantum numbers. The number of oscillator shells used in both the fermion and the boson sectors is 22. Pairing has been included in the constant gap approximation with the gap being given by $\Delta_{n,p} = 11.2/\sqrt{A}$.

Table 1 presents the calculated binding energy and quadrupole deformation of the ground state and the excitation energy and spin-parity of the lowest one quasiparticle states obtained in three Md nuclei using the forces NL1 and NL3. These are the heaviest odd-proton nuclei whose ground state spin-parity values are experimentally known. The deformation parameters of the excited states are very close to that of the ground state and have not been shown. One can see that either the ground state spin is either correctly predicted or the state corresponding to the experimental ground state lies within approximately 0.5 MeV in all cases. This is comparable to the results we have obtained earlier in a lower mass region[14].

Next we study the odd-proton nuclei belonging to the chain $^{287}115$. These are the heaviest odd proton nuclei that have been experimentally observed. Nothing is known about the spin-parity of the low-lying levels in these nuclei. In table 2 the binding energy values calculated using the forces NL1 and NL3 for the lowest energy level i.e. ground state in different nuclei are given. In table 3 we present the results of our calculation for the lowest lying one quasiparticle levels. There are both normal negative parity states as well as positive parity states arising out of the intruder orbital in the low excitation energy region and a pattern of low-lying isomeric states are expected. For example, in $^{287}115$, the $\frac{11}{2}^+$ state is expected to be an isomeric state in both the calculations. Similarly, in ^{267}Db, the lowest lying negative-parity state is likely to be isomeric. Thus one may have two groups of α-particles connecting the different parity levels among themselves which are nearly equal in energy and hence comparable lifetime values. An isomeric state may also decay to the ground state by γ-emission. In most of the nuclei studied the ground state spin predicted by the two forces agree with each other lending confidence to the ability of RMF to predict the spin-parity of the correct ground state in this mass region.

The present results differ in one important detail from that of Geng *et al* [9]. In their work the calculated quadrupole deformation values decrease smoothly from 0.22 in ^{267}Db to 0.17 in $^{283}113$. However, at $^{287}115$, this suddenly jumps up to 0.50. Any abrupt change in deformation value should translate in an increase in α-lifetime. However, as discussed later, experimental lifetime estimates do not show any large increase in lifetime for decay from $^{287}115$. The calculated quadrupole deformation parameter for both the forces in our calculation, on the other hand, vary smoothly from 0.28 to 0.17 approximately with increase in mass number. This decrease may possibly be ascribed to the shell closure at neutron magic number $N = 172$ in agreement with other relativistic calculations [16, 17] which predict the neutron and proton shell closures at 172 and 120, respectively. It is also known that $Z = 114$ shows a small gap which is manifested here in the larger excitation energy values of the quasiparticle states in $^{287}115$, particularly for the calculation using the NL3 force.

A particular level may decay either via α-decay or γ-emission. Ground state,

and frequently, isomeric states will undergo α-decay. In table 4 the theoretical Q-values for α-decay are given for different levels. The calculated Q-values have been taken assuming that α-decay takes place between states having the same parity and nearly equal spin. The hindrance factors for these transitions are expected to be close to one. In $^{287}115$, the α-decay may even start from the isomeric positive parity state. Q-value for any other transition may be easily calculated from tables 2 and 3. The experimental Q-values appear to agree very well with theory, particularly with the transitions involving negative parity states calculated using the force NL3.

In table 5, we compare the experimentally obtained lifetime with the phenomenological estimate derived from the theoretical Q_α-value obtained using the NL3 force for the transitions involving negative parity states given in the first row of table 4. All these transitions are between states having the same spin-parity and should have low hindrance factor. The Viola-Seaborg formula[18]

$$\log_{10}(T_\alpha) = (aZ + b)Q_\alpha^{-1/2} + cZ + d \tag{1}$$

where T_α are given in seconds and Q_α in MeV, has been used. The values of the parameters a, b, c and d are taken from Ref. [19] where they were obtained by fitting the experimental data of middle and heavy nuclei. The values are a=1.66175, b= -8.5166, c= -0.20228 and d= -33.9069. Except for the transition from $^{283}113$, all the other T_α values agree with experimentally observed values indicating that the hindrance factor is close to one, i.e. the transitions are between states having nearly equal spin and the same parity. As mentioned earlier, the lifetime estimate of α-decay from $^{287}115$ does not indicate any large difference in deformation values between the parent and the daughter states as predicted by Geng *et al* [9].

3 Summary

The structure of superheavy odd proton nuclei belonging to the α-decay chain starting from $^{287}115$ has been investigated. RMF approach in the blocked BCS approximation gives very similar structure for two forces NL1 and NL3. The quadrupole deformation increases smoothly from $^{287}115$ to ^{267}Db. The Q-values for probable decays have been calculated and compared with experiment. The experimental values agree very well with the theoretical ones for the negative parity levels calculated using the force NL3. Lifetime estimates obtained from phenomenological prescription indicate that the decays take place between states having nearly identical quantum numbers.

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Table 1: Results of calculation in Md nuclei with using the forces NL1 and NL3. The binding energy values are given in MeV. The quantities within the parentheses are the calculated values of the energy levels in MeV. The experimental binding energy values are from Audi *et al* [15]

Nucleus	Expt.	Theo.			
	g.s.	NL1		NL3	
	J^π	B.E.	$J^\pi(\mathrm{E}_{ex})$	B.E.	$J^\pi(\mathrm{E}_{ex})$
	B.E.	β		β_2	
^{253}Md	$\frac{1}{2}^-$	1885.82	$\frac{7}{2}^-$(g.s.),$\frac{1}{2}^-$(0.02)	1886.17	$\frac{3}{2}^-$(g.s.),$\frac{7}{2}^-$(0.18),
	1881.81*	0.31	$\frac{7}{2}^+$(0.10),$\frac{3}{2}^-$(0.50)	0.29	$\frac{7}{2}^+$(0.24),$\frac{1}{2}^-$(0.43)
^{255}Md	$\frac{7}{2}^-$	1897.11	$\frac{7}{2}^-$(g.s.),$\frac{1}{2}^-$(0.01),	1898.88	$\frac{3}{2}^-$(g.s.),$\frac{7}{2}^+$(0.27),
	1894.33	0.31	$\frac{7}{2}^+$(0.14),$\frac{3}{2}^-$(0.53)	0.28	$\frac{1}{2}^-$(0.53),$\frac{7}{2}^-$(0.57)
^{257}Md	$\frac{7}{2}^-$	1907.68	$\frac{7}{2}^-$(g.s.),$\frac{1}{2}^-$(0.03),	1910.42	$\frac{3}{2}^-$(g.s.),$\frac{7}{2}^+$(0.21),
	1906.32	0.31	$\frac{7}{2}^+$(0.13)	0.27	$\frac{1}{2}^-$(0.48),$\frac{7}{2}^-$(0.53)

*Estimated value

Table 2: Calculated binding energy of the ground state of of nuclei belonging to the decay-chain of ^{287}115.

Nucleus	B.E.(MeV)	
	NL1	NL3
^{287}115	2057.72	2055.84
^{283}113	2039.02	2038.87
^{279}111	2019.36	2020.65
^{275}Mt	2000.69	2002.03
^{271}Bh	1982.04	1983.22
^{267}Db	1962.15	1964.47

Table 3: Calculated excitation energy and quadrupole deformation of low-lying one quasiparticle states of nuclei belonging to the decay-chain of $^{287}115$. The states are denoted by Nilsson quantum nembers.

		NL1			NL3	
Nucleus	State	E(MeV)	β_2	State	B(MeV)	β_2
$^{287}115$	$\frac{1}{2}^-[510]$	0.00	0.165	$\frac{1}{2}^-[510]$	0.00	0.170
	$\frac{7}{2}^-[503]$	0.79	0.149	$\frac{3}{2}^-[512]$	1.02	0.172
	$\frac{3}{2}^-[512]$	0.95	0.167	$\frac{11}{2}^+[615]$	1.86	0.178
	$\frac{11}{2}^+[615]$	1.22	0.172	$\frac{9}{2}^-[505]$	1.92	0.188
$^{283}113$	$\frac{3}{2}^-[512]$	0.00	0.182	$\frac{3}{2}^-[512]$	0.00	0.178
	$\frac{11}{2}^+[615]$	0.21	0.187	$\frac{1}{2}^-[550]$	0.72	0.167
	$\frac{9}{2}^-[505]$	0.58	0.200	$\frac{11}{2}^+[615]$	0.76	0.182
	$\frac{1}{2}^-[510]$	0.65	0.187	$\frac{9}{2}^-[505]$	1.26	0.191
$^{279}111$	$\frac{3}{2}^-[512]$	0.00	0.191	$\frac{11}{2}^+[615]$	0.00	0.219
	$\frac{9}{2}^-[505]$	0.03	0.222	$\frac{5}{2}^-[512]$	0.38	0.189
	$\frac{11}{2}^+[615]$	0.08	0.219	$\frac{3}{2}^-[512]$	0.47	0.190
	$\frac{1}{2}^-[510]$	0.40	0.234	$\frac{1}{2}^-[550]$	0.78	0.186
^{275}Mt	$\frac{3}{2}^-[512]$	0.00	0.255	$\frac{5}{2}^-[512]$	0.00	0.210
	$\frac{9}{2}^-[505]$	0.41	0.243	$\frac{11}{2}^+[615]$	0.38	0.223
	$\frac{11}{2}^+[615]$	0.52	0.250	$\frac{9}{2}^-[505]$	0.53	0.223
	$\frac{1}{2}^-[510]$	0.84	0.256	$\frac{1}{2}^-[521]$	0.58	0.198
	$\frac{5}{2}^-[512]$	1.03	0.249	$\frac{9}{2}^+[624]$	1.11	0.208
^{271}Bh	$\frac{5}{2}^-[512]$	0.00	0.271	$\frac{5}{2}^-[512]$	0.00	0.263
	$\frac{9}{2}^+[624]$	0.53	0.270	$\frac{9}{2}^-[505]$	0.33	0.247
	$\frac{3}{2}^-[512]$	1.08	0.269	$\frac{9}{2}^+[624]$	1.08	0.259
	$\frac{9}{2}^-[505]$	1.13	0.259	$\frac{11}{2}^+[615]$	1.11	0.256
^{267}Db	$\frac{9}{2}^+[624]$	0.00	0.282	$\frac{9}{2}^+[624]$	0.00	0.274
	$\frac{5}{2}^-[512]$	0.58	0.280	$\frac{1}{2}^-[521]$	0.30	0.268
	$\frac{1}{2}^-[521]$	0.83	0.276	$\frac{5}{2}^-[512]$	0.99	0.269
	$\frac{7}{2}^+[633]$	1.27	0.278	$\frac{9}{2}^-[505]$	1.39	0.258

Table 4: Calculated and experimental Q-values for α-decay. The subscript g to the levels indicate that the concerned level is the predicted ground state.

Parent Nuclus	Transition(Q-value in MeV)		Q-value in MeV
	Theo.		Expt.[1]
	NL1	NL3	
$^{287}115$	$\frac{1}{2}^-_g \rightarrow \frac{1}{2}^-(8.95)$	$\frac{1}{2}^-_g \rightarrow \frac{1}{2}^-(10.61)$	10.74±0.09
	$\frac{1}{2}^-_g \rightarrow \frac{3}{2}^-_g(9.60)$	$\frac{1}{2}^-_g \rightarrow \frac{3}{2}^-_g(11.33)$	
	$\frac{11}{2}^+ \rightarrow \frac{11}{2}^+(10.61)$	$\frac{11}{2}^+ \rightarrow \frac{11}{2}^+(12.43)$	
$^{283}113$	$\frac{3}{2}^-_g \rightarrow \frac{3}{2}^-_g(8.64)$	$\frac{3}{2}^-_g \rightarrow \frac{3}{2}^-(9.61)$	10.26±0.09
		$\frac{3}{2}^-_g \rightarrow \frac{5}{2}^-(9.70)$	
	$\frac{11}{2}^+ \rightarrow \frac{11}{2}^+(8.77)$	$\frac{11}{2}^+ \rightarrow \frac{11}{2}^+_g(10.84)$	
$^{279}111$	$\frac{3}{2}^-_g \rightarrow \frac{3}{2}^-_g(9.63)$	$\frac{5}{2}^- \rightarrow \frac{5}{2}^-_g(10.06)$	10.52±0.16
	$\frac{11}{2}^+ \rightarrow \frac{11}{2}^+(9.19)$	$\frac{11}{2}^+_g \rightarrow \frac{11}{2}^+(9.30)$	
^{275}Mt	$\frac{3}{2}^-_g \rightarrow \frac{3}{2}^-(8.57)$	$\frac{5}{2}^-_g \rightarrow \frac{5}{2}^-_g(9.49)$	10.48±0.09
	$\frac{3}{2}^-_g \rightarrow \frac{5}{2}^-_g(9.65)$	$\frac{11}{2}^+ \rightarrow \frac{9}{2}^+(8.79)$	
	$\frac{11}{2}^+ \rightarrow \frac{9}{2}^+(9.64)$	$\frac{11}{2}^+ \rightarrow \frac{11}{2}^+(8.76)$	
^{271}Bh	$\frac{5}{2}^-_g \rightarrow \frac{5}{2}^-(7.83)$	$\frac{5}{2}^-_g \rightarrow \frac{5}{2}^-(8.56)$	
	$\frac{9}{2}^+ \rightarrow \frac{9}{2}^+_g(8.94)$	$\frac{9}{2}^+ \rightarrow \frac{9}{2}^+_g(10.63)$	

Table 5: Calculated and experimental lifetime for α-decay. The theoretical values have been iestimated using the Q_α values from the NL3 calculation given in the first row of table 4 for each nucleus. See text for details.

Parent	$T_{\alpha th}$	$T_{\alpha ex}$[1]
$^{287}115$	76.7 ms	32^{+155}_{-14} ms
$^{283}113$	11.5 s	100^{+490}_{-45} ms
$^{279}111$	128.9 ms	170^{+810}_{-80} ms
^{275}Mt	1.2 s	$9.7^{+46}_{-4.4}$ s
^{271}Bh	204.9 s	