Proton radioactivity lifetimes using Skyrme interactions

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Introduction

The phenomena of proton radioactivity is recent and has been possible with the advent of the radioactive ion beams facilities. The neutron deficient nuclei lying above the proton drip line has positive Q values for protons and are spontaneous proton emitters. This limits the possibilities of the creation of ever more exotic nuclei in the proton rich side of the β stability valley. Limited number of works have been done in calculating the half lives of proton emitting nuclei using different models. But calculation of lifetimes of the proton emitting nuclei using Skyrme interaction [1] has not yet been reported. More than 110 Skyrme sets are available, constructed for different purposes, all having the common feature of giving finite nuclei ground state properties and saturation conditions in nuclear matter. Skyrme sets constructed in the late 90's, particularly the construction of SLy sets and others Skyrme sets developed thereafter, have additional care in constraining the parameters for applications to nuclear matter under extreme conditions. Stone et al. [2] have analyzed the Skyrme sets on the basis of available constraints and have sorted out finally 27 Skyrmes sets which can be admitted for calculation of isospin rich dense nuclear matter. The objective of the work is to examine the predictions of the Skyrme sets on the half lives of the proton emitters.

Theoretical formalism

The proton-nucleus (p-N) nuclear potential $U_N^p(r)$ for Skyrme interaction is obtained as

$$\begin{aligned}
U_N^p(r) &= [1-(\frac{M*}{M})_p](E_{CM}-U_{Coul}) \\
&+(\frac{M*}{M})_p\Big[\frac{t_0}{2}[(1-x_0)\rho_p+(2+x_0)\rho_n] \\
&+\frac{t_3}{12}\Big(\gamma[(1-x_3)\frac{\rho_p^2+\rho_n^2}{2}+(2+x_3)\rho_p\rho_n] \\
&+\rho[(1-x_3)\rho_p+(2+x_3)\rho_n)]\Big)\rho^{\gamma-1} \\
&+\frac{1}{8}[t_1(2+x_1)+t_2(2+x_2)]\tau_n \\
&+\frac{1}{8}[t_1(1-x_1)+3t_2(1+x_2)]\tau_p \\
&-\frac{3}{16}[t_1(1-x_1)-t_2(1+x_2)](\nabla^2\rho_p) \\
&-\frac{1}{16}[3t_1(2+x_1)-t_2(2+x_2)](\nabla^2\rho_n)\Big], \quad (1)
\end{aligned}$$

where total density $\rho(r)$=$\rho_p(r)$+$\rho_n(r)$, E_{cm} is centre-of-mass energy, $[\frac{M*}{M}(\rho)]_p$ is the proton effective mass which for Skyrme interaction is

$$\Big[1+\frac{M}{4\hbar^2}\Big([t_1(1-x_1)+3t_2(1+x_2)]\rho_p(r) +[t_1(2+x_1)+t_2(2+x_2)]\rho_n(r)\Big)\Big]^{-1}. \quad (2)$$

The p-N Coulomb potential U_{Coul} is given by Z_de^2/r for $r \geq R_c$, $(Z_de^2/2R_c)[3-(r/R_c)^2]$ for $r \leq R_c$ where $Z_d(A_d)$ is atomic(mass) number of daughter nucleus and R_c is touching radial separation between proton-daughter nucleus.

The proton emission half life is given by $T_{1/2}$=$[(h\ln 2)/(2S_pE_v)][1+\exp(K)]$ where S_p is the spectroscopic factor, E_v is the zero point vibration energy and the action integral in the improved WKB approximation is given by K=$(2/\hbar)\int_{R_a}^{R_b}[2\mu(V(r)-E_v-Q)]^{1/2}dr$ with R_a and R_b being its 2^{nd} and 3^{rd} turning points determined by solving the equations $E(R_a)$=Q+E_v=$E(R_b)$ that provide 3 turning points. Total p-N potential $V(r)$ comprises of nuclear, Coulomb and centrifugal parts.

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TABLE I: The results of the present calculations using the Skyrme p-N potentials are compared with the experimental values along with the results of DDM3Y [3]. The experimental Q values, half lives and l values are from Ref.[4]. Experimental errors in Q values [4] and corresponding errors in calculated half lives are inside parentheses. Asterisk symbol in the parent nucleus denotes isomeric state.

Parent ^AZ	l $\hbar$	Q^{ex} MeV	Measured $log_{10}T(s)$	SLy0 $log_{10}T(s)$	SLy4 $log_{10}T(s)$	SkI3 $log_{10}T(s)$	LNS $log_{10}T(s)$	DDM3Y $log_{10}T(s)$
^{105}Sb	2	0.491(15)	$2.049^{+0.058}_{-0.067}$	1.99(46)	2.00(45)	2.03(45)	2.07(46)	1.90(45)
^{109}I	2	0.829(3)	$-3.987^{+0.020}_{-0.022}$	-4.22(4)	-4.22(5)	-4.18(5)	-4.14(4)	-4.31(5)
^{112}Cs	2	0.824(7)	$-3.301^{+0.079}_{-0.097}$	-3.11(11)	-3.11(10)	-3.07(11)	-3.03(11)	-3.21(11)
^{113}Cs	2	0.978(3)	$-4.777^{+0.018}_{-0.019}$	-5.52(4)	-5.51(4)	-5.47(4)	-5.43(4)	-5.61(4)
^{145}Tm	5	1.753(10)	$-5.409^{+0.109}_{-0.146}$	-5.23(6)	-5.23(7)	-5.17(6)	-5.10(7)	-5.28(7)
^{147}Tm	5	1.071(3)	$0.591^{+0.125}_{-0.175}$	0.87(4)	0.88(4)	0.94(4)	1.02(4)	0.83(4)
$^{147}Tm^*$	2	1.139(5)	$-3.444^{+0.046}_{-0.051}$	-3.37(6)	-3.37(6)	-3.32(6)	-3.28(6)	-3.46(6)
^{150}Lu	5	1.283(4)	$-1.180^{+0.055}_{-0.064}$	-0.69(5)	-0.68(4)	-0.62(4)	-0.55(4)	-0.74(4)
$^{150}Lu^*$	2	1.317(15)	$-4.523^{+0.620}_{-0.301}$	-4.36(15)	-4.35(15)	-4.32(15)	-4.28(14)	-4.46(15)
^{151}Lu	5	1.255(3)	$-0.896^{+0.011}_{-0.012}$	-0.77(3)	-0.77(3)	-0.70(3)	-0.63(4)	-0.82(4)
$^{151}Lu^*$	2	1.332(10)	$-4.796^{+0.026}_{-0.027}$	-4.86(10)	-4.86(10)	-4.81(10)	-4.78(10)	-4.96(10)
^{155}Ta	5	1.791(10)	$-4.921^{+0.125}_{-0.125}$	-4.75(7)	-4.75(7)	-4.69(7)	-4.61(7)	-4.80(7)
^{156}Ta	2	1.028(5)	$-0.620^{+0.082}_{-0.101}$	-0.37(7)	-0.37(8)	-0.33(7)	-0.28(7)	-0.47(8)
$^{156}Ta^*$	5	1.130(8)	$0.949^{+0.100}_{-0.129}$	1.54(11)	1.56(10)	1.62(10)	1.69(11)	1.50(10)
^{157}Ta	0	0.947(7)	$-0.523^{+0.135}_{-0.198}$	-0.40(11)	-0.40(11)	-0.37(12)	-0.33(11)	-0.51(12)
^{160}Re	2	1.284(6)	$-3.046^{+0.075}_{-0.056}$	-2.98(7)	-2.98(7)	-2.93(7)	-2.89(7)	-3.08(7)
^{161}Re	0	1.214(6)	$-3.432^{+0.045}_{-0.049}$	-3.43(7)	-3.43(7)	-3.38(7)	-3.35(7)	-3.53(7)
$^{161}Re^*$	5	1.338(7)	$-0.488^{+0.056}_{-0.065}$	-0.70(7)	-0.69(8)	-0.63(8)	-0.55(7)	-0.75(8)
^{164}Ir	5	1.844(9)	$-3.959^{+0.190}_{-0.139}$	-4.02(6)	-4.02(6)	-3.96(6)	-3.89(6)	-4.08(6)
$^{165}Ir^*$	5	1.733(7)	$-3.469^{+0.082}_{-0.100}$	-3.61(5)	-3.61(5)	-3.55(5)	-3.48(5)	-3.67(5)
^{166}Ir	2	1.168(8)	$-0.824^{+0.166}_{-0.273}$	-1.09(10)	-1.09(10)	-1.05(10)	-1.00(10)	-1.19(10)
$^{166}Ir^*$	5	1.340(8)	$-0.076^{+0.125}_{-0.176}$	0.11(9)	0.12(9)	0.18(9)	0.26(9)	0.06(9)
^{167}Ir	0	1.086(6)	$-0.959^{+0.024}_{-0.025}$	-1.24(9)	-1.24(9)	-1.20(9)	-1.16(9)	-1.35(8)
$^{167}Ir^*$	5	1.261(7)	$0.875^{+0.098}_{-0.127}$	0.58(8)	0.60(8)	0.66(8)	0.73(8)	0.54(8)
^{171}Au	0	1.469(17)	$-4.770^{+0.185}_{-0.151}$	-4.99(16)	-4.99(16)	-4.94(16)	-4.91(16)	-5.10(16)
$^{171}Au^*$	5	1.718(6)	$-2.654^{+0.054}_{-0.060}$	-3.14(5)	-3.13(5)	-3.07(5)	-3.00(4)	-3.19(5)
^{177}Tl	0	1.180(20)	$-1.174^{+0.191}_{-0.349}$	-1.35(27)	-1.35(26)	-1.31(26)	-1.28(26)	-1.44(26)
$^{177}Tl^*$	5	1.986(10)	$-3.347^{+0.095}_{-0.122}$	-4.62(6)	-4.61(7)	-4.54(6)	-4.48(7)	-4.64(6)
^{185}Bi	0	1.624(16)	$-4.229^{+0.068}_{-0.081}$	-5.42(13)	-5.42(13)	-5.37(13)	-5.34(14)	-5.53(14)

Results and Discussion

The half-life calculations for different Skyrme interaction sets are done by evaluating nuclear potentials using Wood-Saxon distributions for $\rho_{p(n)}$ whose diffuseness parameter a is fixed to 0.54 fm, the half density radius c is fixed using $c{=}r_\rho(1-\pi^2a^2/3r_\rho^2)$, $r_\rho{=}1.13A_d^{1/3}$ and central density is fixed by equating volume integral to proton (neutron) numbers. Calculations are performed for $S_p{=}1$ and results are provided in Table-I. We find that different Skyrme interaction sets provide good estimates of proton radioactivity half lives.

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