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Half-lives of proton emitters I, Cs, La, Eu and Ha nuclei using E-RMF densities

T Sahoo[a*], R N Panda[b], Piyush R Das[a] & S K Patra[c,d]

[a]Department of Physics, Veer Surendra Sai University of Technology, Burla 768 018, India
[b]Department of Physics, Siksha O Anusandhan Deemed to be University,
Bhubaneswar 751 030, India
[c]Institute of Physics, Sachivalaya Marg, Bhubaneswar 751 005, India
[d]Homi Bhaba National Institute, Training School Complex, Anushakti Nagar, Mumbai 400 085, India

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We have studied the nuclear properties and life-time of few proton emitters in their ground state using spherical densities obtained from effective field theory motivated relativistic mean field formalism (E-RMF) for two recent parameter sets G3 and IOPB-I. We have found that these emitters have binding energy per nucleon near the iron peak but due to the inadequate number of neutrons, the Coulomb force cannot be compensated completely hence, the nucleus breaks down. Experimental Q-value is used for the calculate of proton emission half-life using WKB approximation. It is noticed that for suitable *l*-values our results meet the experimental half-lives. This study enhances our understanding on the nuclear force and shell structure in the drip line region.

Keywords: Effective relativistic mean field theory, Nuclear drip line, Exotic nucleus, Wentzel karmers brillouin (WKB) approximation

1 Introduction

The stable configuration of nuclei in their ground state helps us to sketch the nuclear valley. Spontaneous emission of nucleons occurs from the energetically unstable nuclei when we move away from the valley of stability. For every nucleus to exist, a minimum number of neutrons for a particular proton and also a maximum number of neutron for the same proton number are needed. The restriction in minimum and maximum neutron number for the particular bound configuration delineates the proton and neutron drip lines. Sometimes few bound state nuclei exist beyond the proton drip-line, known as proton emitters. The proton separation energy for these nuclei is negative. Consequently, they have positive Q values for proton emission. The occurrence of proton emission from ground state restricts the possibility of creation of more exotic nuclei. The emission of proton helps us to reveal the nature of interaction of nucleons near the drip line and it acts as a tool for collecting the spectroscopic information of the emitted proton because the decay process is sensitive to Q-value as well as orbital angular momentum (l) of the unpaired decaying proton. The spectroscopic information is the key to analyze the shell structure of proton rich nuclei.

In 1970, experimentally the first proton emitter was discovered as an isomeric state of ^{53}Co*[1]. Thereafter, in the region around I to Bi more than 30 proton emitters has been found out[2].

2 Theoretical Formalism

To understand the microscopic properties of proton rich nuclei we used the extended relativistic mean field formalism (E-RMF)[3]. With the inclusion of self and cross couplings of various mesons such as isoscalar - scalar σ, isoscalar–vector ω, isovector-scalar δ, isovector-vector ρ –mesons into the lagrangian of the system, the E-RMF formalism is found very much successful in describing the highly asymmetrical system[4].

A self-consistent iteration method is adopted to solve the E-RMF equations[5] with the G3 and IOPB-I[6] parameter sets to obtain the nuclear many body aspects. The matter densities derived from this formalism act as an essential quantity for obtaining the effective interaction potential. In the present work, the proton emission process is considered as quantum mechanical tunneling phenomena through an effective interaction potential. It is composed of the nuclear, Coulomb and centrifugal potentials given by:

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*Corresponding author (E-mail: trupti9vssut@gmail.com)

$$V(R) = V_N(R) + V_C(R) + \hbar^2 l(l+1)/2\mu R \cdots \dots (1)$$

Where, the nuclear potential ($V_N(R)$) is obtained by double folding proton and daughter nucleus spherical densities with the M3Y effective nucleon-nucleon interaction. The proton density being extracted from the experimental scattering data[7] and the daughter density is derived from the spherical E-RMF formalism. $V_C(R)$ is the Coulomb potential. The third term in Eq. 1 defines the centrifugal potential, where μ is the reduced mass of proton-daughter system and l being the orbital angular momentum. The half-life of proton emission is obtained using the relation:

$$T_{1/2} = ln2/\nu_0 P, \qquad \dots (2)$$

Where, P is the penetration probability obtained from the WKB approximation:

$$P = exp\left[-2\int \frac{\sqrt{2m}}{\hbar}\left(V(R) - Q_p\right)^{1/2} dR\right] \qquad \dots (3)$$

The limits of the integration are determined from the turning points where V(R) = Q. Experimental Q-value[7] for the proton emission is used for the calculation. And ν_0 is the assault frequency with which the proton hits the barrier.

3 Results and Discussion

In this brief work, we have calculated the proton emission half-lives of some proton emitters in its ground state and compared them with the experimental data available in the literature[8]. Presuming the proton emitters in spherical shape we performed the calculations in the E-RMF formalism for the interaction G3 and IOPB-I to obtain the following ground state properties. And for the half-life calculation WKB approximation is approached.

3.1 Binding energy per nucleon (B/A)

The measurement of B/A tell us how strongly the nucleons are bonded to each other. Column 2 and 3 of Table 1 shows the B/A of proton emitters for G3 and IOPB-I interactions, respectively. For the validation of our results we have compared them with the experimental data collected[8]. We found the B/A of the considered nuclei lies nears the iron peak (highest peak). This suggests the nuclei to be stable but in practice due to the lack of number of neutrons present in the considered nucleus, they are insufficient to beat the Coulomb force between the protons. After the formation of core of the nucleus the extra number of protons accumulates on the surface. Hence, due to the lowering of binding energy on the nucleons present in the outer orbital and increasing repulsive Coulomb force between the outer accumulated protons they become energetically unstable for emission.

3.2 Neutron skin thickness (Δr_n)

The asymmetrical distribution of neutrons and protons inside the nucleus causes the formation of neutron or proton skin. It is generally defined as $\Delta r_n = r_n - r_p$ where r_n and r_p is the radial distribution of neutrons and protons, respectively. Column 5 and 6 of Table 1 shows the Δr_n values of proton emitters for G3 and IOPB-I parameter sets, respectively. The negative value of Δr_n indicates that $r_n < r_p$. Although number of neutrons is greater than number of protons but due to the high repulsive Coulomb force the number of neutrons found inadequate to compensate it. The strong attractive nuclear force between the protons and neutrons let them to form a tightly bound np-core and the remaining protons are repelled outward hence, forming a very thin layer of protons which can be noticed from the numerical values given in Table 1.

3.3 Proton decay

The half-lives of proton emitters for the parameter set G3 and IOPB-I in the spherical E-RMF are compared with the experimental half-lives in Table 2. We found all the calculated results are in good

Table 1 – The binding energy per nucleon (B/A) in MeV and neutron skin thickness (Δr_n) in fm are shown for proton emitters using G3 and IOPB-I parameter sets. The experimental data of B/A is also shown[8].

Nucleus	B/A			Δr_n	
	G3	IOPB-I	Expt.	G3	IOPB-I
$^{109}_{53}I$	8.161	8.177	8.220	-0.047	-0.046
$^{112}_{55}Cs$	8.032	8.059	8.100	-0.063	-0.061
$^{117}_{57}La$	7.994	8.024	8.088	-0.053	-0.044
$^{131}_{63}Eu$	7.881	7.887	7.995	-0.048	-0.045
$^{140}_{67}Ho$	7.823	7.824	7.906	-0.048	-0.042

Table 2 – The half-lives of proton emitters in their ground state for the parameter sets G3 and IOPB-I. Experimental results[10] are shown for comparison. 'l' represents the orbital angular momentum of the emitting proton.

Parent nucleus	Q in MeV	l	$T_{1/2}$ (ms)		
			G3	IOPB-I	Expt.
$^{109}_{53}I$	0.819	2	$9.7 * 10^{-2}$	$5.4 * 10^{-2}$	0.102
$^{112}_{55}Cs$	0.812	2	0.670	4.188	4.993
$^{117}_{57}La$	0.844	3	17.457	7.730	23.534
$^{131}_{63}Eu$	0.975	3	32.101	21.637	17.810
$^{140}_{67}Ho$	1.129	3	6.639	5.476	6.006

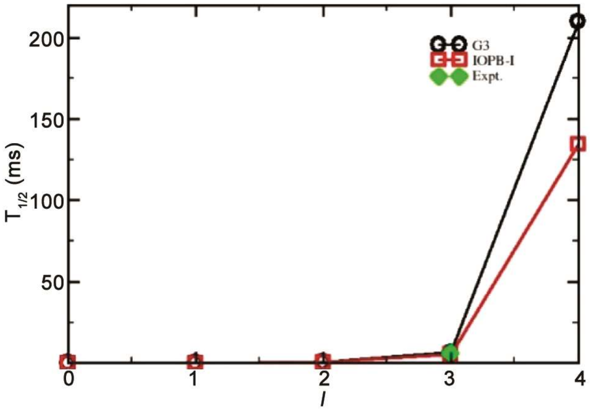

Fig. 1 – Sensitivity of $T_{1/2}$ on l.

agreement with experimental results[10] regardless of the parameter sets for the reported l-values in column 3. The half-life is found sensitive to Q-value and l- value. The reported l- values are suitably chosen to meet the experimental results.

The dependence of $T_{1/2}$ on l is shown in Fig. 1 for the element $^{140}_{67}Ho$ as a representative case. The graph shows $T_{1/2}$ is directly proportional to l which indicates the emission of proton is more liable to take place from l = 0 orbitals. However, due to many other nuclear phenomena such as binding energy, chemical potential, proton separation energy, etc. emission occurs from the orbital which is favorable for all the phenomena. Hence, we get an idealistic knowledge about the shell structure of drip line nuclei.

4 Conclusions

Briefly outlining the above study on proton emitters using spherical E-RMF for G3 and IOPB-I interactions, we end up with the following facts. The considered proton emitters lie around the maximum peak region of the general B/A curve but due to the lack of neutron number, the shape symmetry between the nucleons break down hence, the proton gets emitted from the ground state. Although the neutron number is more than proton number, but the radial distribution of proton (r_p) is found greater than radial distribution for neutron (r_n). Due to the smaller value of Δr_n, the proton skin is very thin for which we call it as accumulated proton lying on the surface of the nucleus rather than proton skin. Using WKB barrier penetration method, the proton decay half-life is successfully calculated. For suitable values of l, the calculated results show good agreement with the experimental results. Moreover, the $T_{1/2}$ is found sensitive to Q - value and orbital angular momentum l. The emission of nucleons from the ground state shows reluctant towards the creation of more exotic nuclei in the drip line region.

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