Two-proton radioactivity within RMF+BCS approach

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Theoretical and experimental studies of proton-rich side of the valley of β-stability constitute one of the most active areas of research in nuclear physics. At the proton drip-line, further addition of protons is not possible as the nucleus becomes unbound. Beyond the drip-line, one or more valence protons may still remain confined due to Coulomb and centrifugal barriers enabling the nucleus to acquire rather long mean life time. Subsequently, it may decay by the process wherein one or more protons tunnel through the barrier leading to observation of one or more protons radioactivity. This situation is quite different from the neutron rich side of the line of β-stability where Coulomb barrier is absent and consequently the drip-line gets extended to highly neutron rich nuclei.

Decay modes of nuclei through one or two proton radioactivity were theoretically proposed in the early 1960's for the first time by Goldansky [1]. The one-proton radioactivity predicted for odd-proton nuclei was indeed observed already in the early 1980's in experiments carried out at GSI, Darmstadt [2], and presently many nuclei (more than 20) which decay in their ground state by one-proton emission are well known [3]. However, the two-proton emission mode was experimentally verified only more than four decades after its prediction in the decay of ^{45}Fe, and subsequently in latter experiments in the decay of ^{54}Zn and ^{48}Ni [1, 3–7]. Many more experiments are being carried out to discover the new candidates.

In view of the hectic experimental studies of two-proton radioactivity in the light-medium mass region, we have employed relativistic mean-field plus state dependent BCS approach [8] including the deformation degree of freedom (referred to below as deformed RMF+BCS) [9] for the investigation of even-Z proton rich nuclei in the $20 \leq Z \leq 40$ region to search for the possible occurrence of two-proton emitters. These calculations have been performed by using the popular TMA force parameters [8].

Two-proton radioactivity occurs when the sequential emission of two independent protons is energetically forbidden. Due to the gain of stability from the pairing energy, the mass of the even-Z two-proton emitter is smaller than the mass of the odd-Z one-proton daughter giving rise to the negative Q value which prohibits one-proton emission. Therefore, the nuclei with $S_p>0$ and $S_{2p}<0$ may be the possible candidates for simultaneous two-proton emission. With this criterion in mind, we have listed in Table I the results of our deformed RMF+BCS calculations for the one proton and two proton separation energies for the even-Z nuclei lying at and beyond two-proton drip-line in the region $20 \leq Z \leq 40$. The available experimental data [10] have been also listed in the table.

We note from Table I that the nuclei ^{45}Fe, ^{48}Ni and ^{54}Zn which have been experimentally identified as two proton emitters [4–7] are located beyond the proton drip line with negative two-proton separation energies of -0.9 MeV, -1.49 MeV and -1.97 MeV respectively from our calculations. Similarly, it is seen from the table that our results for the nuclei ^{38}Ti, ^{42}Cr, ^{45}Fe, ^{48}Ni, ^{55}Zn, ^{60}Ge, ^{64}Se, ^{68}Kr, ^{72}Sr and ^{76}Zr also satisfy the criterion $S_p>0$ and $S_{2p}<0$. These nuclei, therefore, are expected to be the potential candidates for the two-proton radioactivity. The available experimental data [10] of the separation energies for most of the nuclei identified above (with the

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TABLE I: Results for one proton separation energy (S_p) and two proton separation energy (S_{2p}) calculated from deformed RMF+BCS approach with TMA force parameters for the even-Z nuclei lying at and beyond two-proton drip-line in the region $20 \leq Z \leq 40$ alongwith available experimental data [10].

Nucleus	RMF+BCS(TMA)		EXPT.	
	S_p (MeV)	S_{2p} (MeV)	S_p (MeV)	S_{2p} (MeV)
^{32}Ca	-0.81	-3.19	-	-
^{33}Ca	-0.18	-1.24	-	-
^{34}Ca	1.38	1.47	0.90	-0.75
^{37}Ti	-1.11	-4.11	-	-
^{38}Ti	0.25	-1.86	1.03	-0.96
^{39}Ti	0.56	0.13	1.12	0.19
^{41}Cr	-0.11	-1.53	-	-
^{42}Cr	0.41	-0.05	1.06	-0.26
^{43}Cr	1.56	1.40	1.26	1.00
^{44}Fe	-0.82	-2.69	-	-
^{45}Fe	0.43	-0.90	0.13	-1.12
^{46}Fe	1.35	0.64	1.42	0.29
^{47}Ni	-0.85	-2.95	-	-
^{48}Ni	0.08	-1.49	-	-
^{49}Ni	0.71	0.19	-	-
^{53}Zn	-1.40	-3.26	-	-
^{54}Zn	-0.33	-1.97	0.40	-1.51
^{55}Zn	0.24	-0.12	0.52	0.12
^{58}Ge	-0.87	-2.50	-0.24	-2.77
^{59}Ge	-0.39	-1.57	0.30	-1.11
^{60}Ge	0.27	-0.52	0.94	0.05
^{64}Se	0.08	-0.08	-	-
^{65}Se	0.60	1.32	0.69	0.59
^{67}Kr	-0.49	-1.39	-	-
^{68}Kr	0.13	-0.06	-	-
^{69}Kr	0.76	1.27	0.70	0.39
^{71}Sr	-0.03	-1.34	-	-
^{72}Sr	0.36	-0.38	-	-
^{73}Sr	0.53	0.61	0.87	0.18
^{75}Zr	-0.19	-1.66	-	-
^{76}Zr	0.06	-1.00	-	-
^{77}Zr	0.27	0.64	-	-

exception of ^{55}Zn and ^{60}Ge) are also in accord with the criterion $S_p>0$ and $S_{2p}<0$. However, it may be remarked that the separation energy values near the drip line are close to zero and therefore the sign of the separation energy value is very sensitive and at times model dependent.

Furthermore, from our calculations we have obtained the results for the quadrupole deformation for the predicted two-proton emitters mentioned above, and their corresponding daughter nuclei. Out of these, the nuclei ^{45}Fe and ^{48}Ni as well as their corresponding daughter nuclei are found to have spherical or near spherical shape. In contrast, the nuclei ^{38}Ti, ^{55}Zn, ^{60}Ge and ^{64}Se, and their corresponding daughter nuclei have been found to exhibit prolate deformation, whereas the nuclei ^{42}Cr, ^{68}Kr, ^{72}Sr and ^{76}Zr and their corresponding daughter nuclei are predicted to have oblate shapes.

These results are expected to provide additional impetus for more experimental studies to verify the potential candidates mentioned above for the two-proton radioactivity.

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