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Empirical formulae with angular momentum dependence for exotic one and two proton emissions

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Recently, we reported a model independent and l-dependent four parameter formula which accounts very well for the half-lives of experimentally known one-proton emitters and also compares well with other model predictions. Later, the structure of the formula has been retained and fitted with two-proton half-lives predicted by the effective liquid drop model. With the new parameter set, the same form of the formula compared well with available experimental data on half-lives of two proton emitters as well as the predictions of ELDM. The formula has been applied to predict possible proton emitters in super heavy region. In this work, the application of these formulae is studied to predict the half-lives of one and two-proton emitters in the medium and heavy mass region ranging from $84 \leq Z \leq 100$ and $37 \leq Z \leq 100$, respectively.

Keywords: One-proton radioactivity, Two-proton radioactivity, Half-life period

1 Introduction

Proton rich nuclides lying near the proton drip line with positive Q-values undergo decay by the emission of either one-proton or by two-protons. Many different experimental and theoretical methods had been employed to understand the one-proton and two-proton decay processes[1-4]. Since, the decay happens from ground state as well as isomeric states and the transitions to ground state as well as isomeric states, these studies become important to know about the fine structure of the proton rich nuclei along the dripline.

One-proton radioactivity was first discovered in the beginnings of 1970s by Jackson *et al.*[5] from proton unstable isomer ^{53}Co at an excitation energy of 3.2 MeV. Later this was confirmed by Cerny *et al.*[3]. Following that several other experiments were carried out in different laboratories across the globe, reporting various spherical and deformed proton emitters. At Dubna, experiment[6,7] was carried for ^{121}Pr and it was repeated using the argonne tandem linac accelerator (ATLAS) accelerator facility at Argonne by Robinson *et al.*[8]. In the same laboratory Davids *et al.*[9-11] reported the one-proton radioactivity of ^{185m}Bi, ^{165,166,167}Ir, ^{171}Au, ^{130}Eu, ^{159}Re, ^{170}Au, ^{176}Tl. At Gesellschaft für Schwerionenforschung (GSI), Hofmann *et al.*[12] reported the first observation of the ground state proton radioactivity for the decay of ^{151}Lu. At CERN isolde separator, efforts to find the proton radioactivity in ^{113}Cs was done by D'Auria *et al.*[13] and it was later resumed and extended to ^{106}Sb, ^{110}I and ^{188}Bi at the mass separator on line to the UNILAC by Schardt *et al.*[14] At Daresbury laboratory, the extensive proton radioactivity program was conducted in 1990's which lead to the discovery of new proton emitters[15-19] like ^{112}Cs, ^{146}Tm, ^{150}Lu, ^{156m}Ta, ^{160}Re. After closing of the accelerator at Daresbury laboratory, Oak ridge national laboratory (where Bingham *et al.*[20] carried out experiments for ^{141}Ho, ^{144}Tm, ^{145}Tm, ^{146}Tm using Holifield radioactive ion beam facility) and Argonne national laboratory became the main laboratories. Other main laboratories of proton emission investigations were carried out are Legnaro national laboratory[21-23] and the University of Jyvaskyla (^{155}Ta, ^{159}Re, ^{170}Au and ^{176}Tl).

Many experimental studies were carried out to identify the two-proton emitters in different laboratories. KeKelis *et al.*[24] reported the probability of di-proton decay width of ^{16}Ne and ^{12}O in 1978. Later in 1995, Kryger *et al.*[25] using ^{13}O projectile via single neutron stripping confirmed the two-proton decay of ^{12}O. Two-proton decay of ^{45}Fe was reported in the experiments done by Pfutzner *et al.*[26] at GSI and by Giovinazzo *et al.*[27] at Grand accelerator National A Ions Lourds (GANIL). Later, several groups studied the two-proton decay[28-32] of ^{45}Fe using the new facilities at different laboratories and reported the direct evidence. Dossat *et al.*[28] reported the case of ^{48}Ni using the superconducting intense source for secondary ions

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(SISSI) and the achromatic spectrometer Ligned'Ions Super Epluches - (Super Striped Ion Line) LISE3 facility of GANIL along with the 2-p decay of ^{45}Fe. Pomorski *et al.* observed the two-proton decay[33-34] of ^{48}Ni and measured the half-life using a Time Projection Chamber (TPC) and Optical TPC (OTPC).Another experiment by Blank *et al*.[35] using SISSI/LISE3 facility of GANIL reported the 2-p decayof ^{54}Zn. In addition to that, Ascher *et al*.[36] directly observed the 2-p decay of ^{54}Zn using TPC. Mukha *et al*[37]observed the 2-p decay of ^{19}Mg by tracking the decay products and further, recently, using the in-flight decay products[38], they identified ^{30}Ar as a 2-p emitter. The experiment of Goigoux *et al*.[39] at RIKEN Nishina center resulted in the 2-p emission of ^{67}Kr.

Apart from established models, attempts have been made to establish phenomenological relations between half-lives and Q-values, the idea which stems from the Geiger & Nuttall (GN) relation proposed initially for alpha decay half-lives of heavy nuclei. Following the idea put forth by Geiger & Nuttall, (GN) many model dependent and independent formulae were proposed for the studies of α-decay, cluster decay as well as proton decay[40-43]. Recently, we reported an empirical equation to calculate the half-life values of ground and isomeric state one proton emitters in the region of charge numbers of the proton emitters from $53 \le Z \le 83$ in literature[44]. This relation was proposed based grossly on the following facts:

(i) similar to GN relations, the 1-p half-lives & Q-values are dependent on each other and
(ii) half-lives can be calculated by grouping the angular momentum l associated with the transitions.

2 Results and Discussion

By considering these facts, the half-life is calculated for all experimentally known ground state and isomeric state proton emitters with l-values of 0, 2, 5 and three simple linear relations are obtained with two parameters for each of these l values. The slopes and intercepts of these formulae were fitted against angular momentum l values resulting in a four parameter formula which also can be used for other l values as:

$$\log T_{1/2} = \left((a \times l) + b\right)\xi + \left((c \times l) + d\right) \quad \ldots (1)$$

with $a = 0.0322, b = 0.8204, c = -0.1527, d = -26.480$

This simple model independent and l-dependent four parameter formula is found to account very well for the half-lives of experimentally known one-proton emitters and also compares good with other model predictions[44].Apart, from the reported predictions compared with other theoretical models, in this work, we report, the half-lives of possible one proton emitters in the medium and heavy mass region ranging from $84 \le Z \le 100$ in Table 1 which are not experimentally measured or theoretically predicted before. For the calculations, we considered only the cases with Q_{1p} values greater than 1 MeV, which are calculated using the mass table of Moller *et al*.[45] Further, we report our results for five different l values from 0 to 4.

Table 1 – Logarithmic half-lives are calculated for one-proton in the heavy mass region $84 \le Z \le 100$

A	Z	Q_{1p} (MeV)	log $T_{1/2}$				
			l=0	*l*=1	*l*=2	*l*=3	*l*=4
184	85	2.102	-6.886	-6.269	-5.653	-5.036	-4.420
185	85	1.902	-5.881	-5.225	-4.570	-3.914	-3.258
186	85	1.482	-3.144	-2.381	-1.618	-0.854	-0.091
187	85	1.422	-2.657	-1.875	-1.092	-0.310	0.473
188	85	1.082	0.831	1.750	2.669	3.589	4.508
189	87	2.272	-7.275	-6.674	-6.073	-5.471	-4.870
190	87	1.852	-5.208	-4.526	-3.844	-3.162	-2.479
191	87	1.762	-4.672	-3.968	-3.265	-2.562	-1.859
192	87	1.152	0.491	1.397	2.303	3.209	4.115
193	87	1.142	0.609	1.519	2.430	3.340	4.251
195	89	2.162	-6.427	-5.792	-5.158	-4.524	-3.889
196	89	1.592	-3.111	-2.346	-1.582	-0.817	-0.053
197	89	1.592	-3.111	-2.346	-1.582	-0.817	-0.053
198	89	1.322	-0.835	0.018	0.872	1.726	2.580
199	89	1.332	-0.932	-0.082	0.768	1.618	2.468
200	89	1.442	-1.926	-1.115	-0.304	0.508	1.319
201	89	1.372	-1.307	-0.472	0.364	1.199	2.034
200	91	2.112	-5.823	-5.165	-4.507	-3.849	-3.190
201	91	2.092	-5.724	-5.062	-4.400	-3.738	-3.076
202	91	1.752	-3.800	-3.062	-2.325	-1.587	-0.850
203	91	1.492	-1.903	-1.091	-0.279	0.533	1.345
204	91	1.222	0.677	1.590	2.504	3.417	4.330
205	91	1.392	-1.035	-0.189	0.657	1.503	2.349
206	93	1.912	-4.384	-3.670	-2.955	-2.240	-1.526
207	93	1.882	-4.209	-3.487	-2.766	-2.044	-1.323
208	93	1.752	-3.397	-2.644	-1.891	-1.137	-0.384
209	93	1.692	-2.991	-2.222	-1.453	-0.684	0.085
210	93	1.302	0.296	1.195	2.093	2.991	3.889
211	93	1.562	-2.034	-1.227	-0.420	0.387	1.194
212	93	1.152	1.986	2.951	3.915	4.880	5.845
213	93	1.182	1.623	2.573	3.523	4.474	5.424
212	95	2.052	-4.781	-4.082	-3.383	-2.684	-1.985
213	95	1.952	-4.232	-3.512	-2.791	-2.071	-1.350
214	95	1.912	-4.001	-3.271	-2.541	-1.812	-1.082
215	95	1.932	-4.117	-3.392	-2.667	-1.942	-1.217

(*Contd.*)

Table 1 – Logarithmic half-lives are calculated for one-proton in the heavy mass region $84 \leq Z \leq 100$ (*Contd.*)

A	Z	Q_{1p} (MeV)	log $T_{1/2}$				
			l=0	*l*=1	*l*=2	*l*=3	*l*=4
216	95	1.602	-1.922	-1.111	-0.299	0.512	1.323
217	95	1.532	-1.367	-0.534	0.299	1.132	1.965
218	95	1.192	1.990	2.955	3.920	4.884	5.849
219	95	1.232	1.524	2.471	3.417	4.363	5.310
218	97	2.242	-5.368	-4.692	-4.016	-3.340	-2.665
219	97	2.232	-5.321	-4.643	-3.965	-3.288	-2.610
220	97	1.842	-3.188	-2.427	-1.666	-0.904	-0.143
221	97	1.872	-3.376	-2.622	-1.868	-1.114	-0.359
222	97	1.612	-1.582	-0.758	0.067	0.891	1.716
223	97	1.462	-0.336	0.537	1.411	2.284	3.158
224	97	1.172	2.720	3.713	4.706	5.700	6.693
224	99	2.182	-4.724	-4.023	-3.322	-2.620	-1.919
225	99	2.182	-4.724	-4.023	-3.322	-2.620	-1.919
226	99	1.772	-2.338	-1.543	-0.748	0.047	0.842
227	99	1.542	-0.600	0.263	1.126	1.989	2.852
228	99	1.252	2.241	3.216	4.190	5.165	6.140

After the success of the l-dependent four parameter formula for calculating the half-life values of one-proton emitters, in a later and a very recent work[46], we reported the extension of the empirical formula, retaining its form by fitting to the ELDM predicted half-lives of 33 two-proton emitters[47] with proton emitters charge numbers ranging from $4 \leq Z \leq 36$ for l=0, 2 and 4 by retaining the same form of the formula but with a new set of the four parameters as:

$$\mathrm{a} = 0.1578, \mathrm{b} = 1.9474,$$

$$\mathrm{c} = -1.879, \mathrm{d} = -24.847$$

Using this relation, we found a fair comparison with available experimental data of 2p half-lives as well as with the ELDM predictions. Encouraged by the results, in this work we surveyed the possible two proton emitters, with charge numbers from $37 \leq \mathrm{Z} \leq 100$ for l values, 0 to 4 for the first time. However, it is to be mentioned that, in this region, there are no experimental values and other model results available for comparison. The Q_{2p} values are calculated using the mass table of Moller *et al.*[45] and we considered only the Q_{2p} values greater than 1MeV. The results indicate a preference of 2p emission only in the range of $37 \leq \mathrm{Z} \leq 60$. Hence, we present our results only in this range in Table 2. Calculation shows the strong probability of one proton emitters in the heavy mass region for all the considered l values. Table 1 shows the logarithmic half-lives of 1p emitters for different

Table 2 – Logarithmic half-lives of two-proton emitters in the region $37 \leq Z \leq 100$.

A	Z	Q_{2p} (MeV)	log $T_{1/2}$				
			l=0	*l*=1	*l*=2	*l*=3	*l*=4
66	37	5.723	-10.854	-11.600	-12.345	-13.090	-13.835
67	37	4.343	-8.784	-9.362	-9.939	-10.517	-11.094
68	37	3.233	-6.230	-6.601	-6.971	-7.341	-7.712
69	37	1.983	-1.076	-1.029	-0.982	-0.934	-0.887
68	38	5.403	-10.118	-10.803	-11.489	-12.174	-12.860
69	38	4.293	-8.323	-8.863	-9.403	-9.943	-10.483
70	38	3.093	-5.380	-5.681	-5.983	-6.284	-6.586
71	38	2.123	-1.349	-1.324	-1.299	-1.274	-1.249
70	39	4.953	-9.122	-9.727	-10.332	-10.937	-11.542
71	39	3.853	-7.018	-7.453	-7.887	-8.321	-8.756
72	39	3.023	-4.719	-4.967	-5.215	-5.463	-5.711
73	39	1.923	0.389	0.555	0.721	0.887	1.053
72	40	5.483	-9.579	-10.221	-10.863	-11.505	-12.147
73	40	4.253	-7.512	-7.986	-8.460	-8.934	-9.409
74	40	3.193	-4.840	-5.098	-5.356	-5.613	-5.871
75	40	1.963	0.670	0.858	1.047	1.235	1.424
74	41	5.593	-9.413	-10.041	-10.669	-11.298	-11.926
75	41	4.903	-8.362	-8.906	-9.449	-9.992	-10.535
76	41	3.803	-6.130	-6.492	-6.854	-7.217	-7.579
77	41	2.733	-2.768	-2.857	-2.947	-3.037	-3.127
78	41	1.663	3.458	3.872	4.287	4.702	5.116
77	42	4.853	-7.939	-8.448	-8.957	-9.465	-9.974
78	42	4.443	-7.176	-7.623	-8.070	-8.517	-8.964
79	42	4.013	-6.253	-6.626	-6.998	-7.370	-7.742
80	42	1.873	2.370	2.696	3.022	3.349	3.675
79	43	5.023	-7.896	-8.401	-8.907	-9.412	-9.917
80	43	4.433	-6.803	-7.220	-7.637	-8.054	-8.470
81	43	3.713	-5.131	-5.412	-5.694	-5.975	-6.257
82	43	2.883	-2.472	-2.538	-2.604	-2.670	-2.736
83	43	1.323	8.183	8.980	9.777	10.575	11.372
81	44	4.353	-6.283	-6.658	-7.033	-7.408	-7.783
82	44	4.553	-6.696	-7.104	-7.512	-7.920	-8.329
83	44	4.943	-7.427	-7.894	-8.361	-8.829	-9.296
84	44	2.573	-0.702	-0.624	-0.547	-0.469	-0.391
85	44	1.493	6.850	7.540	8.229	8.919	9.608
83	45	4.453	-6.144	-6.508	-6.871	-7.235	-7.598
84	45	4.293	-5.799	-6.135	-6.470	-6.806	-7.141
85	45	3.363	-3.326	-3.461	-3.596	-3.731	-3.866

(*Contd.*)

Table 2 – Logarithmic half-lives of two-proton emitters in the region $37 \leq Z \leq 100$. (*Contd.*)

A	Z	Q_{2p} (MeV)	log $T_{1/2}$				
			l=0	l=1	l=2	l=3	l=4
86	45	2.443	0.403	0.570	0.738	0.905	1.072
86	46	2.903	-1.253	-1.221	-1.188	-1.155	-1.122
87	46	1.993	3.628	4.056	4.485	4.913	5.341
88	47	2.863	-0.658	-0.577	-0.496	-0.415	-0.334
90	48	2.903	-0.399	-0.297	-0.195	-0.093	0.009
91	48	1.933	5.113	5.662	6.211	6.759	7.308
92	49	2.703	0.929	1.138	1.348	1.558	1.767
94	50	2.433	2.783	3.143	3.502	3.862	4.222
97	51	5.103	-5.452	-5.759	-6.066	-6.374	-6.681
98	51	4.213	-3.501	-3.650	-3.800	-3.949	-4.098
99	51	3.353	-0.920	-0.860	-0.800	-0.740	-0.680
99	52	7.923	-9.028	-9.625	-10.222	-10.819	-11.416
100	52	6.913	-7.912	-8.418	-8.925	-9.432	-9.938
101	52	6.233	-7.012	-7.445	-7.879	-8.313	-8.747
102	52	5.263	-5.437	-5.744	-6.050	-6.356	-6.662
103	52	3.993	-2.564	-2.637	-2.710	-2.784	-2.857
101	53	7.643	-8.483	-9.036	-9.589	-10.142	-10.696
102	53	6.923	-7.654	-8.139	-8.625	-9.111	-9.597
103	53	6.423	-6.997	-7.429	-7.862	-8.295	-8.727
104	53	4.853	-4.311	-4.526	-4.741	-4.956	-5.171
105	53	3.473	-0.572	-0.484	-0.396	-0.308	-0.220
103	54	8.053	-8.656	-9.223	-9.790	-10.357	-10.924
104	54	7.583	-8.162	-8.689	-9.215	-9.742	-10.269
105	54	6.323	-6.575	-6.973	-7.371	-7.770	-8.168
106	54	5.253	-4.800	-5.054	-5.309	-5.563	-5.818
107	54	3.443	-0.085	0.043	0.170	0.298	0.425
106	55	7.243	-7.512	-7.987	-8.461	-8.935	-9.410
107	55	6.193	-6.100	-6.460	-6.820	-7.180	-7.540
108	55	4.543	-2.959	-3.064	-3.170	-3.275	-3.381
109	55	3.253	1.019	1.236	1.453	1.670	1.887
108	56	6.933	-6.862	-7.284	-7.705	-8.127	-8.549
109	56	5.853	-5.273	-5.566	-5.859	-6.152	-6.445
110	56	4.583	-2.726	-2.813	-2.900	-2.986	-3.073
111	56	2.913	2.899	3.268	3.638	4.007	4.376
110	57	6.653	-6.216	-6.585	-6.955	-7.324	-7.693
111	57	5.503	-4.362	-4.581	-4.800	-5.019	-5.238
112	57	4.723	-2.735	-2.822	-2.909	-2.996	-3.083

(*Contd.*)

Table 2 – Logarithmic half-lives of two-proton emitters in the region $37 \leq Z \leq 100$. (*Contd.*)

A	Z	Q_{2p} (MeV)	log $T_{1/2}$				
			l=0	l=1	l=2	l=3	l=4
113	57	3.273	1.716	1.989	2.263	2.536	2.809
113	58	5.763	-4.538	-4.772	-5.005	-5.238	-5.472
114	58	4.563	-2.024	-2.053	-2.083	-2.112	-2.142
115	58	2.783	4.378	4.867	5.356	5.845	6.334
115	59	5.353	-3.474	-3.622	-3.769	-3.916	-4.063
116	59	3.953	0.024	0.160	0.297	0.433	0.569
117	59	2.453	6.725	7.405	8.084	8.763	9.443
118	60	3.943	0.404	0.571	0.739	0.906	1.073
119	60	2.563	6.473	7.132	7.791	8.450	9.109

l values from 0 to 4. But in the case of 2p emitters strong probability can be seen in the range of $37 \leq Z \leq 60$ for all the considered l values. Beyond this range, the probability diminishes for $60 \leq Z \leq 100$. Table 2 shows the prediction of 2p emitters for l = 0 to 4.

3 Conclusions

The model independent four parameter empirical formula with Q and angular momentum dependence proposed by us recently for the one and two-proton emission has been extended for possible predictions in the medium and heavy mass region. The obtained results show a stronger preference of the 1p emitters in the heavy mass region, whereas, the preference of observing 2p emission is found low in the heavy as well as super heavy region. However, a stronger preference is predicted for the 2p emission in the light and medium mass region. This l-dependent four parameter formula can be used as a reference tool to plan new experiments.

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