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Systematics of proton decay of actinides

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The phenomenon of proton emission from nuclear ground states limits the possibilities of the creation of more exotic proton rich nuclei that are usually produced by fusion-evaporation nuclear reactions. In the energy domain of radioactivity, proton can be considered as a point charge having highest probability of being present in the parent nucleus. Conclaves *et al.*[1] studied the two-proton radioactivity of nuclei of mass number A<70 using the effective liquid drop model. Delion *et al.*[2] reviewed the theories of proton emission to analyse the properties of nuclear matter. Maglione *et al.*[3] analysed the proton emission from the some deformed nuclei. We have studied proton decay in almost all actinide nuclei. We have calculated the energy released during the proton decay (Q_P), penetration factor (P), and half-lives of proton decay. Proton decay half-lives are also longer than that of other decay modes such as alpha decay and spontaneous fission. To check the Geiger-Nuttal law for proton decay in actinide nuclei, we have plotted the logarithmic proton decay half-lives versus 1/sqrt(Q). The competition of proton decay with different decay modes such as alpha decay and spontaneous fission are also studied. We have also highlighted possible proton emitters with the corresponding energies and half-lives in the actinide region.

Keywords: Proton decay, Half-lives, Probability, Geiger-Nuttal law

1 Introduction

The nuclei beyond the proton drip line with the $Qp > 0$ are the one with proton unstable and also exhibit exotic decay modes. The understanding of the proton decay is important to study the nuclear structure. The exotic nuclei exists away from the stability. The binding energy of protons above the drip line gradually decreases and hence one-proton and two proton decay is predicted. Brown[4] studied two proton decay in Z=22-28 in the ground state. Goldanskii[5] for the first time studied the one proton and two proton decay for odd and even atomic number. Janecke[6] studied the emission of protons from the light nuclei $^{12,13}O$, ^{21}Mg and $^{24,\ 32}Si$. The spherical proton and deformed proton emitters were investigated in lanthanides and transaction metals. Previous workers[7-18] experimentally observed one and two proton decay in proton rich nuclei. They are several theoretical models[19-21], studied one proton and two proton activity in light nuclei. Using different proximity potentials previous workers[22-24] studied proton activity in the light nuclei. The emission of heavy particles such as one proton, one neutron, two protons, 2 neutrons and alpha particle emission takes place when the nuclei are proton rich, neutron rich and very heavy nuclei. Successively many theoretical models[25-32] were presented to study the half-lives of spherical and deformed nuclei. Dobaczewski and Nazarewicz[33] studied two-proton stability in doubly magic nuclei ^{100}Sn using self-consistent Skyrme-Hartree-Fock-Bogoliubov theory. Olsen *et al.*[34-35] investigated two-proton decay in even-even nuclei and also studied competition between proton decay and alpha decay. Poenaru *et al.*[36] measured half-lives and branching ratios for ^{12}C, ^{16}O and ^{28}Si and proton and neutron rich nuclei with Z=56-64.

The observations of the proton decay is quite recent, they are several approaches to study this proton decay process, such as distorted-wave Born approximation[37], the study of effective interaction by the density dependent M3Y (DDM3Y)[38,39]. The construction of proton nucleus potential by Jeukenne, Lejeune and Mahaux (JLM) applied to finite nuclei in the Local Density Approximation[40], the unified fission model[2], the coupled-channels approach[41] and also generalized liquid drop models[42-44]. Earlier workers[45-53] studied half-lives of spontaneous fission, ternary fission, cluster decay and alpha decay in the

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superhaevy region using different proximity potentials. Faestermann[54] experimentally observed proton decay half-lives and proton energies in ^{113}Cs and ^{109}I. Sellin[55] experimentally measured proton decay half-lives in ^{150}Lu, ^{151}Lu and ^{147}Tm. Page *et al.*[56] reported proton emitter ^{112}Cs with the half-life of 500±100μs. Livingston[57] experimentally observed proton emission from the ^{146}Tm. The two proton radioactivity[58-63] was experimentally observed ^{45}Fe, ^{19}Mg, ^{48}Ni and ^{54}Zn. In the year 1970, Jackson[64] confirmed the proton radioactivity form the proton emitter ^{53}Co.

The proton radioactivity is applied for nuclear astrophysics. In the nuclear astrophysics, the process of two-proton radiation capture process is considered, which is important for extremely high densities and temperatures. The example of such an astrophysical environment is the sources of gamma bursts related with the explosive burning of deposited hydrogen on the surface of neutron stars. Previous workers[65-67] explained the astrophysical applications of the two-proton radioactivity.

From the available literature, the study on one proton emission in the actinide region is required. The study on the proton decay not only provides information about the drip line, but also provides spectroscopic information on the unpaired proton not substantial in its orbit. Hence, in the present work we want to emphasize on the possible proton emitters in the actinide region and also prediction of half-lives in the same region. The main objective is to systematically study the one proton decay half-lives of spherical and deformed nuclei in the actinide region.

2 Theoretical Framework

2.1 Proton emission half-lives

The reaction of nuclear one proton decay can be written as:

$$^{A}_{Z}(X)_N \rightarrow ^{A-1}_{Z-1}(Y)_N + ^{1}_{1}(H) + Q_P \qquad \text{... (1)}$$

where Q_P is the amount of energy released during proton decay. To study the proton decay, we have used preformed cluster model[68,69]. The decay constant and half-lives is defined as

$$\lambda = \nu \; P P_0 \qquad \text{... (2)}$$

$$T_{1/2} = \frac{\ln 2}{\lambda} \qquad \text{... (3)}$$

where ν, P and P_0 are the assault frequency[79] with which proton hits the barrier, probability of penetration barrier and preformation probability respectively. In the present work we have selected P_0=1 for the emitted proton. The penetration probability is solved numerically using WKB approximation[71].

$$P = \exp\left[-\frac{2}{\hbar} \int_{Rin}^{Rout} \sqrt{2\mu(V - Q_P)}\, dr \right] \qquad \text{... (4)}$$

where μ is reduced mass of proton decay, Q_P is the energy released during proton decay. R_{in} and R_{out} are the inner and outer turning points. The inner turning point is given by:

$$R_{in} = r_0 (A_1^{1/3} + A_2^{1/3}) \qquad \text{... (5)}$$

where A_1=1 and A_2=A-1 for proton emission. R_{out} is determined by the condition V=Q. The r_0 is the effective nuclear constant. The total interacting potential is defined by:

$$V = V_C + V_P + V_l \qquad \text{... (6)}$$

where V_c Coulomb interaction potential[72], Vp is the proximity potential and V_l is the angular potential. Proximity potential[73-74] given by:

$$V_P = 4\pi\gamma b \left[\frac{C_1 C_2}{C_1 + C_2} \right] \phi \qquad \text{... (7)}$$

where $b \approx 1$ fm is the width of the nuclear surface, ϕ is the universal function[34], C_1 and C_2 are the Susmann central radii and γ is the nuclear surface tension coefficient it is given by:

$$\gamma = \gamma_0 \left[1 - K_S \left(\frac{N - Z}{A} \right)^2 \right] \text{MeV/fm}^2 \qquad \text{... (8)}$$

neutron mass (N), atomic mass (A) and proton number (Z) of the parent nuclei. Where $\gamma_0 =$ 1.460734 MeV/fm^2 and Ks=4.0[75]. C1 and C2 are the Susmann central radii, R_i is the sharp radii[74] of the daughter nuclei.

3 Results and Discussion

The proton decay rates are sensitive to amount of energy released (Q_P) and the orbital angular momentum of the emitted proton. The proton emission is energetically possible when Q_P is positive and it is given by:

$$Q_P = \Delta M(A,Z) - \sum_{i}^{n} \Delta M(A_i, Z_i) \quad \ldots (9)$$

where $\Delta M(A, Z)$ and $\Delta M(A_i, Z_i)$ are mass excess of the parent and emitted daughter and proton nuclei, respectively. We have selected experimental and theoretical values in case of non-availability of experimental values available in the literature[76-80]. We have studied total interacting potential which is a sum of coulomb, proximity and angular potential as explained in the theory. During the proton emission, the ground state to ground state transactions has zero angular momentum $\ell = 0$. Thus we neglect the effects of angular potential in case of proton emission and we have also considered deformed nuclei in the present work. We have evaluated penetration probability using WKB approximation and studied logarithmic half-lives of proton decay in the actinide region. The amount of energy released during proton decay as function of mass number of parent nuclei in the actinide region as shown in Fig. 1. From the figure it is observed that the amount of energy released during proton decay gradually decreases with the increase in mass number of parent nuclei.

The studied logarithmic half-lives of proton decay in the actinide region is plotted as function of the mass number of parent nuclei is presented in Fig. 2. The figure indicates that the logarithmic half-lives increases with increase in mass number of parent nuclei. The half-lives values are of the order of 10^{-6} to 10^{-4} S for the actinides ^{195}Ac, ^{200}Pa, ^{206}Np, ^{212}Am, ^{218}Bk, ^{224}Es, ^{229}Md and ^{235}Lr and the corresponding values of Q(MeV), penetration factor and half-lives are tabulated in Table 1. Hence proton decay is favourably observed in the actinides such as ^{195}Ac, ^{200}Pa, ^{206}Np, ^{212}Am, ^{218}Bk, ^{224}Es, ^{229}Md and ^{235}Lr. Then we have also plotted logarithmic half-lives of proton decay with the product of $Z_d Q^{-1/2}$ in the actinide region and is as shown in Fig. 3. From the

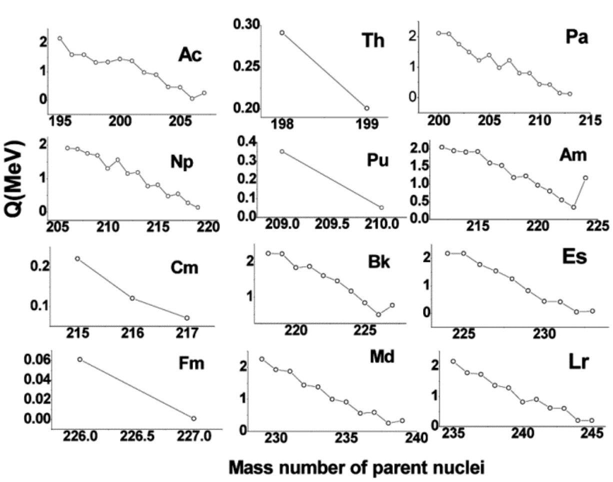

Fig. 1 — The variation of amount of energy released during proton decay with the mass number of parent nuclei in the actinide region.

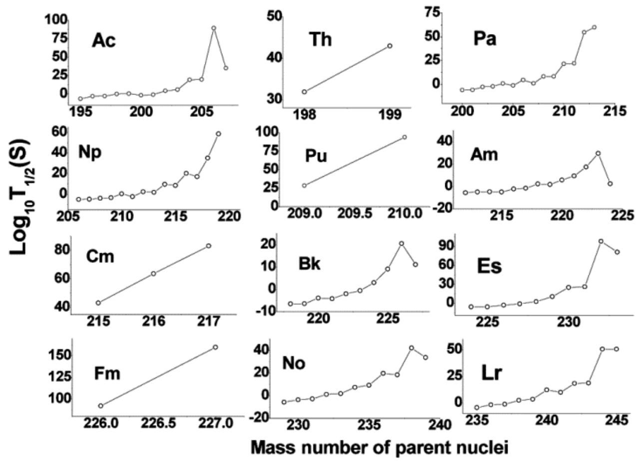

Fig. 2 — The variation of logarithmic half-lives of proton decay with the mass number of parent nuclei in the actinide region.

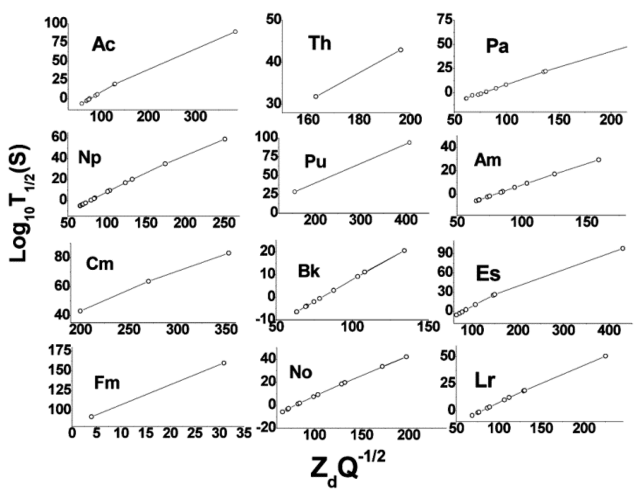

Fig. 3 — Variation of logarithmic half-lives of proton decay with the product of $Z_d Q^{-1/2}$ in the actinide region.

Table 1 — Proton decay half-lives, penetration factor and amount of energy released during proton decay in actinides.

Nuclei	Q(MeV)	Penetration factor	$LogT_{1/2}$
^{195}Ac	2.161	2.142×10^{-15}	1.892×10^{-7}
^{200}Pa	2.111	3.807×10^{-16}	1.073×10^{-6}
^{206}Np	1.911	5.525×10^{-18}	7.471×10^{-5}
^{212}Am	2.051	1.838×10^{-17}	2.267×10^{-5}
^{218}Bk	2.241	1.015×10^{-16}	4.142×10^{-6}
^{224}Es	2.181	1.426×10^{-17}	2.976×10^{-5}
^{229}Md	2.251	1.482×10^{-17}	2.883×10^{-5}
^{235}Lr	2.161	1.317×10^{-18}	3.273×10^{-4}

Table 2 — A comparison of logarithmic half-lives of proton decay with Royer, Univ, NRDX, Denisov and Bao.

		LogT$_{1/2}$(S)						Decay mode
Z_P	A_P	Proton	Royer(α)	UNIV(α)	NRDX(α)	Denisov(α)	Bao(SF)	
89	195	-6.7230	1.9019	1.3890	1.0527	1.4794	19.2850	Proton decay
89	196	-2.5360	4.1825	3.6576	3.2810	3.7588	20.3250	Proton decay
89	197	-2.5300	4.1610	3.6370	3.2830	3.7390	21.3300	Proton decay
89	198	0.3608	5.3396	4.8169	4.4464	4.9171	22.3023	Proton decay
89	199	0.2533	5.2725	4.7510	4.4043	4.8513	23.2399	Proton decay
89	200	-1.0245	4.7543	4.2340	3.9256	4.3348	24.1421	Proton decay
89	201	-0.2156	5.0479	4.5289	4.2323	4.6293	25.0094	Proton decay
89	202	5.8323	6.9328	6.4209	6.0791	6.5134	25.8415	Proton decay
89	203	4.9426	6.6779	6.1659	5.8550	6.2600	26.6385	Proton decay
89	204	16.461	8.8704	8.3763	7.9999	8.4513	27.4004	α decay
89	205	12.42	8.2391	7.7403	7.4114	7.8219	28.1272	α decay
89	206	28.92	10.038	9.5593	9.1753	9.6197	28.8189	α decay
89	207	39.985	10.65	10.180	9.7900	10.2318	29.4757	α decay
90	198	34.275	11.31	10.813	10.10	10.8917	16.1819	α decay
90	199	54.525	11.845	11.357	10.641	11.4272	17.1443	α decay
91	200	-5.9691	2.9029	2.3410	1.9651	2.5071	12.2615	Proton decay
91	201	-5.8597	2.9600	2.3991	2.0424	2.5654	13.1791	Proton decay
91	202	-3.3992	4.3279	3.7624	3.3775	3.9330	14.0680	Proton decay
91	203	-0.9587	5.4434	4.8786	4.4705	5.0485	14.9279	Proton decay
91	204	2.3428	6.6790	6.1190	5.6790	6.2840	15.7583	Proton decay
91	205	0.1534	5.8572	5.2957	4.9125	5.4643	16.5588	Proton decay
91	206	6.3757	7.8264	7.2758	6.8254	7.4327	17.3293	Proton decay
91	207	2.3511	6.6162	6.0597	5.6857	6.2249	18.0696	Proton decay
91	208	10.530	8.7260	8.1856	7.7340	8.3337	18.7794	α decay
91	209	10.533	8.7054	8.1659	7.7364	8.3143	19.4586	α decay
91	212	27.078	10.794	10.281	9.8076	10.4027	21.3128	α decay
91	213	-8.0673	11.60	11.10	10.61	11.2130	21.8698	α decay
92	203	31.073	11.764	11.23	10.42	11.3731	9.4360	α decay
93	206	-4.1266	4.5136	3.9048	3.4685	4.1449	6.7169	Proton decay
93	207	-3.8922	4.6184	4.0107	3.5904	4.2508	7.4948	Proton decay
93	208	-2.8658	5.1529	4.5460	4.1214	4.7860	8.2485	Proton decay
93	209	-2.3300	5.3939	4.7883	4.3730	5.0279	8.9775	Proton decay
93	210	1.8826	7.1678	6.5688	6.0847	6.8012	9.6813	Proton decay
93	211	-1.0955	5.9324	5.3299	4.9296	5.5683	10.3596	Proton decay
93	212	4.0769	7.8628	7.2705	6.7906	7.4977	11.0122	Proton decay
93	213	3.6098	7.6927	7.1005	6.6504	7.3291	11.6388	Proton decay
93	214	12.224	9.8169	9.2454	8.6965	9.4522	12.2391	α decay
93	215	11.11	9.5771	9.0040	8.4897	9.2138	12.8132	α decay
93	216	24.926	11.5	10.95	10.34	11.1356	13.3607	α decay
93	217	20.957	11.065	10.516	9.9510	10.7020	13.8818	α decay
94	209	35.156	12.929	12.374	11.439	12.5655	4.1089	α decay
95	212	-4.6445	4.7376	4.0882	3.6407	4.3973	1.6163	Proton decay
95	213	-3.9192	5.1358	4.4870	4.0386	4.7962	2.2689	Proton decay
95	214	-3.6105	5.2852	4.6376	4.2014	4.9467	2.9012	Proton decay
95	215	-3.7671	5.1793	4.5329	4.1226	4.8422	3.5128	Proton decay
95	216	-0.9294	6.6160	5.9729	5.5024	6.2785	4.1033	Proton decay
95	217	-0.2120	6.9190	6.2783	5.8103	6.5824	4.6721	Proton decay
95	218	4.1200	8.5489	7.9199	7.3731	8.2118	5.2192	Proton decay
95	219	3.5138	8.3273	7.6976	7.1848	7.9916	5.7441	Proton decay
95	220	8.0934	9.6523	9.0362	8.4594	9.3163	6.2466	Proton decay
95	221	12.231	10.5613	9.9572	9.3406	10.2256	6.7266	SF
95	222	21.504	11.9864	11.4037	10.7102	11.6503	7.1840	SF
95	223	36.899	13.2599	12.6999	11.9365	12.9237	7.6186	SF

(*Contd.*)

Table 2 — A comparison of logarithmic half-lives of proton decay with Royer, Univ, NRDX, Denisov and Bao. (*Contd.*)

		LogT$_{1/2}$(S)						Decay mode
Z_P	A_P	Proton	Royer(α)	UNIV(α)	NRDX(α)	Denisov(α)	Bao(SF)	
95	224	4.3046	8.4788	7.8558	7.4335	8.1488	8.0304	Proton decay
96	215	55.684	14.7612	14.1951	13.0602	14.4243	-0.7570	SF
97	218	-5.3828	4.7539	4.0643	3.6171	4.4420	-3.0072	Proton decay
97	219	-5.3288	4.7740	4.0855	3.6571	4.4633	-2.4670	Proton decay
97	220	-2.5529	6.4100	5.7228	5.2133	6.0987	-1.9435	Proton decay
97	221	-2.8104	6.2571	5.5707	5.0908	5.9472	-1.4371	Proton decay
97	222	-0.4836	7.4155	6.7345	6.1991	7.1056	-0.9482	SF
97	223	1.1511	8.1082	7.4325	6.8702	7.7987	-0.4774	SF
97	224	5.1142	9.5409	8.8787	8.2362	9.2310	-0.0248	SF
97	225	11.964	11.3070	10.6676	9.9153	10.9964	0.4093	SF
97	226	25.362	13.2970	12.6906	11.8050	12.9856	0.8245	SF
97	227	13.962	11.6660	11.0339	10.2944	11.3574	1.2206	SF
98	221	46.841	15.3640	14.7670	13.5179	15.0549	-5.1307	SF
99	224	-4.5262	5.7952	5.0641	4.5505	5.5104	-7.1242	SF
99	225	-4.5235	5.7749	5.0449	4.5523	5.4914	-6.6849	SF
99	226	-1.4450	7.5555	6.8314	6.2318	7.2712	-6.2589	SF
99	227	0.8213	8.6204	7.9043	7.2448	8.3362	-5.8467	SF
99	228	4.5384	10.0548	9.3534	8.6021	9.7703	-5.4488	SF
99	229	13.329	12.3930	11.7244	10.8019	12.1071	-5.0656	SF
99	230	30.619	14.6914	14.0653	12.9649	14.4042	-4.6974	SF
99	231	32.236	14.8004	14.1776	13.0875	14.5144	-4.3445	SF
101	229	-4.5400	6.3166	5.5442	4.9712	6.0582	-11.0676	SF
101	230	-2.1781	7.7399	6.9732	6.3081	7.4812	-10.7089	SF
101	231	-1.7682	7.9478	7.1833	6.5207	7.6900	-10.3599	SF
101	232	2.5638	9.9984	9.2518	8.4382	9.7396	-10.0213	SF
101	233	3.3468	10.2843	9.5419	8.7231	10.0264	-9.6935	SF
101	234	9.6969	12.3090	11.5948	10.6168	12.0501	-9.3769	SF
101	235	11.772	12.8028	12.0975	11.0941	12.5445	-9.0719	SF
101	236	24.179	14.9003	14.2344	13.0556	14.6409	-8.7790	SF
101	237	22.642	14.6912	14.0222	12.8826	14.4333	-8.4983	SF
101	238	54.221	16.9150	16.2950	14.9613	16.6559	-8.2302	SF
101	239	42.18	16.3479	18.4435	21.3829	16.0906	-7.9750	SF
102	232	14.287	13.8567	13.1417	11.8994	13.6041	-12.6100	SF
102	233	42.826	17.0247	16.3769	14.8403	16.7700	-12.2943	SF
103	235	-3.4850	7.5036	6.6935	6.0196	7.2718	-14.0132	SF
103	236	-0.4616	9.2220	8.4237	7.6179	8.9895	-13.7382	SF
103	237	0.0075	9.4420	8.6467	7.8401	9.2105	-13.4702	SF
103	238	4.2212	11.2859	10.5120	9.5541	11.0536	-13.2097	SF
103	239	5.3901	11.6911	10.9237	9.9465	11.4596	-12.9572	SF
103	240	15.307	14.3468	13.6242	12.4066	14.1136	-12.7131	SF
103	241	12.82	13.7897	13.0578	11.9148	13.5583	-12.4779	SF
103	242	22.712	15.5493	14.8527	13.5519	15.3172	-12.2519	SF
103	243	23.179	15.5979	14.8991	13.6128	15.3628	-12.0354	SF

figure we have observed that there is a linear variation half-lives with the product of $Z_d Q^{-1/2}$. We have also compared logarithmic half-lives of proton decay with that of alpha decay (Royer[81], Univ[82], NRDX[83], Denisov[84])and spontaneous fission (Bao[85]) and are tabulated in Table 2. From the table it is clear that the predicted isotopes such as $^{195\text{-}203}$Ac, $^{200\text{-}207}$Pa, $^{212\text{-}220,224}$Am, and $^{218\text{-}221}$Bk are having less half-lives compared to alpha decay and spontaneous fission decay mode. We have also identified and specified the dominant decay mode in the actinide region Z=89-103 in the corresponding table. Due to non-availability of experimental values in the actinide region, the predictive power is tested by comparing the available experimental values with the present work and it is tabulated in Table 3. From the table it is observed that studied values obtained from the present work agrees well with the available experimental values.

Table 3 — The comparison of calculated half-lives with the experimental values [54-56,87-102].

Isotopes	Z_d	A_d	l	logT (present work)	$logT_{1/2}$ (experimental)	Ref.
^{105}Sb	49	101	2	2.430	1.7	87
^{109}I	51	105	2	-3.779	-4	88,54-55
^{112}Cs	53	108	2	-2.856	-3.3	56
^{113}Cs	53	109	2	-5.100	-4.77	88, 56
^{117}La	55	113	2	-1.812	-1.623	98-102
^{121}Pr	57	117	2	-2.188	-2	98-102
^{130}Eu	61	126	2	-2.637	-3.046	98-102
^{131}Eu	61	127	2	-1.639	-1.67	98-102
^{135}Tb	63	131	3	-3.178	-3.027	98-102
^{140}Ho	65	136	3	-1.920	-2.222	98-102
^{141}Ho	65	137	3	-2.941	-2.387	98-102
^{144}Tm	67	140	5	-4.767	-5.569	98-102
^{145}Tm	67	141	5	-4.996	-5.456	98-102
^{146}Tm	67	142	5	-0.086	-0.63	89
^{147}Tm	67	143	5	0.723	0.43	55,87-88
^{150}Lu	69	146	5	-1.153	-1.4	55,92
^{151}Lu	69	147	5	-0.876	0.89	55,92
^{155}Ta	71	151	5	-2.563	-2.538	98-102
^{156}Ta	71	152	2	-0.584	-0.609	98-102
^{157}Ta	71	153	0	-0.030	-0.523	98-102
^{159}Re	73	155	5	-4.636	-4.678	98-102
^{160}Re	73	156	2	-3.026	-3.06	94
^{161}Re	73	157	3	-3.171	-3.43	95
^{164}Ir	75	160	5	-4.459	-3.947	98-102
^{165}Ir	75	161	5	-3.529	-3.46	96
^{166}Ir	75	162	2	-0.642	-0.82	96
^{167}Ir	75	163	0	-1.163	-0.96	96
^{170}Au	77	166	2	-4.027	-3.493	98-102
^{171}Au	77	167	0	-4.458	-4.611	98-102
^{171}Au	77	167	4	-2.745	-2.65	96
^{176}Tl	79	172	0	-2.148	-2.284	98-102
^{177}Tl	79	173	0	-0.947	-1.174	98-102
^{185}Bi	81	181	0	-4.402	-4.35	97

4 Conclusions

We have studied one proton decay in the actinide region through the study of energy released, penetration probability and logarithmic half-lives in the actinide region. The studied half-lives of present work is compared with the different decay modes such as alpha decay and spontaneous fission. We have identified the possible proton emitters with the corresponding energies and half-lives in the actinide region. The possible proton emitters in the actinide region are $^{195-203}Ac$, $^{200-207}Pa$, $^{212-220,224}Am$, and $^{218-221}Bk$. We have identified the proton emitters in the unexplored isotopes of actinide region which is not specified in the nuclear chart[86].

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