Alpha decay of naturally occurring neodymium isotopes

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Neodymium isotopes

Five of seven naturally occurring neodymium isotopes are potentially alpha unstable

isotope	abundance (%)	decay mode, Q (keV)	$T_{1/2}$ (exp), y	$T_{1/2}$ (theor), y
^{143}Nd	12.173	α, 530.5	> 2×10^{17} [1]	$1.0\times10^{79} - 3.5\times10^{92}$
^{144}Nd	23.798	α, 1901.3	g.s. to g.s.: = $2.29(16)\times10^{15}$ [2]	$2.3\times10^{15} - 5.0\times10^{15}$
			to 1^{st} excited ^{140}Ce 2^+ (1596.2 keV) level: —	$7.8\times10^{121} - 9.5\times10^{121}$
^{145}Nd	8.293	α, 1574.1	> 1×10^{17} [1, 3]	$2.2\times10^{22} - 4.9\times10^{23}$
^{146}Nd	17.189	α, 1182.1	g.s. to g.s.: —	$2.0\times10^{34} - 4.0\times10^{34}$
			to 1^{st} excited ^{142}Ce 2^+ (641.3 keV) level: > 1.6×10^{18} [4]	$5.8\times10^{77} - 8.5\times10^{77}$
^{148}Nd	5.756	α, 599	—	$6.1\times10^{70} - 1.1\times10^{71}$
		2α, 1011.5	—	$3.0\times10^{172} - 1.1\times10^{183}$ [5, 6]

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Experiment

Total mass of all samples m(Nd_2O_3) = 2381 g

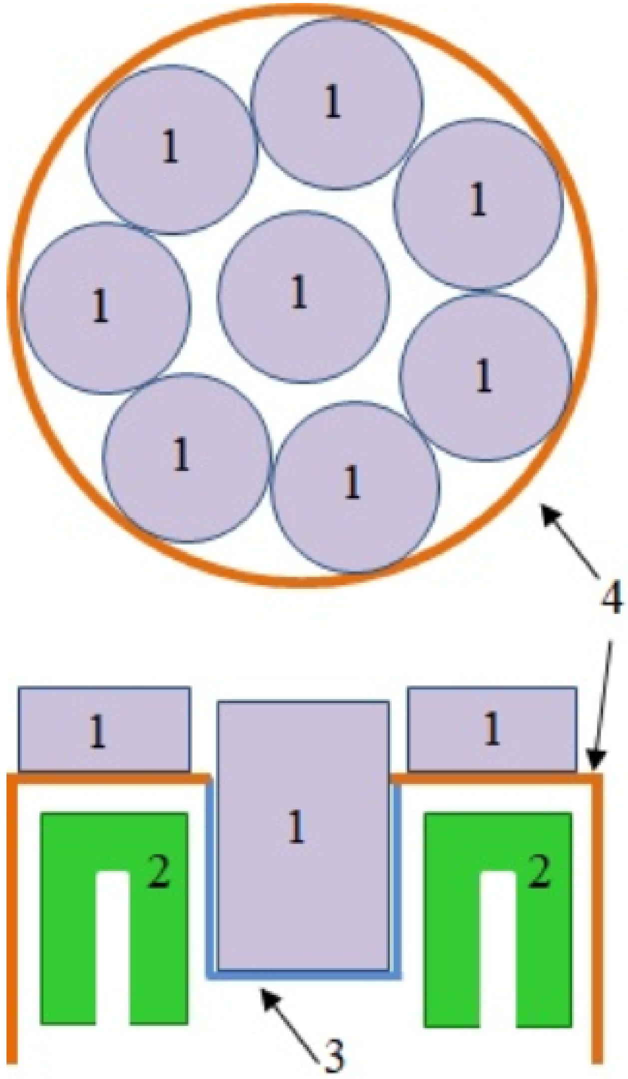
Ultra-low background HPGe-detector system GeMulti located at the depth of ~ 3600 m of water equivalent underground at the STELLA facility of the Gran Sasso underground laboratory of the INFN (Italy).

Passive shield:
low-radioactive copper 10 cm thick
20 cm layer of lead

The Plexiglas box with the detector was flashed by high-purity nitrogen gas to eliminate environmental radon.

The live time of the measurements is 51237 h.

The experiment was mainly devoted to studies of $2\nu2\beta$ decay of ^{150}Nd to excited levels of ^{150}Sm.



1. Nd_2O_3 source samples
2. two of four coaxial HPGe detectors (225 cm^3 each)
3. aluminium cup of the detector system endcap
4. copper walls of the endcap

α and 2α decays accompanied by γ quanta

γ quanta appear in α decay in the following cases:

1) if an excited level of a daughter nucleus is populated, with subsequent emission of deexcitation γ;
2) if daughter nucleus is unstable and decays further with emission of γ;

α decay:

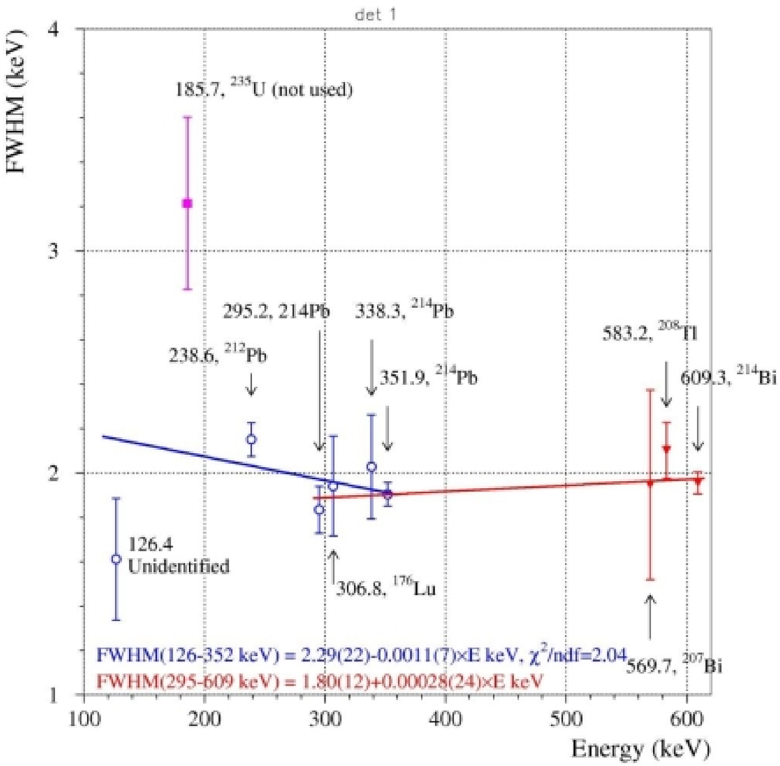
- $^{143}Nd \rightarrow {}^{139}Ce \rightarrow {}^{139}La$
- $^{144}Nd \rightarrow {}^{140}Ce$
- $^{145}Nd \rightarrow {}^{141}Ce \rightarrow {}^{141}Pr$
- $^{146}Nd \rightarrow {}^{142}Ce$
- $^{148}Nd \rightarrow {}^{144}Ce \rightarrow {}^{144}Pr \rightarrow {}^{144}Nd$

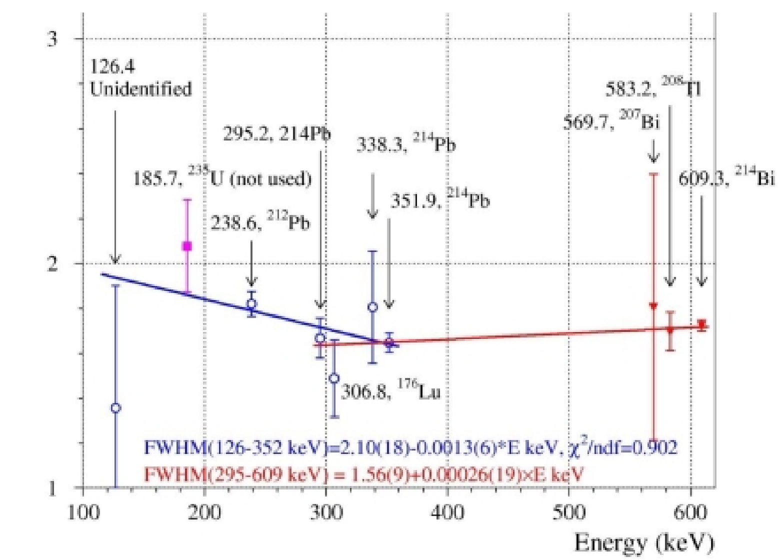
2α decay:

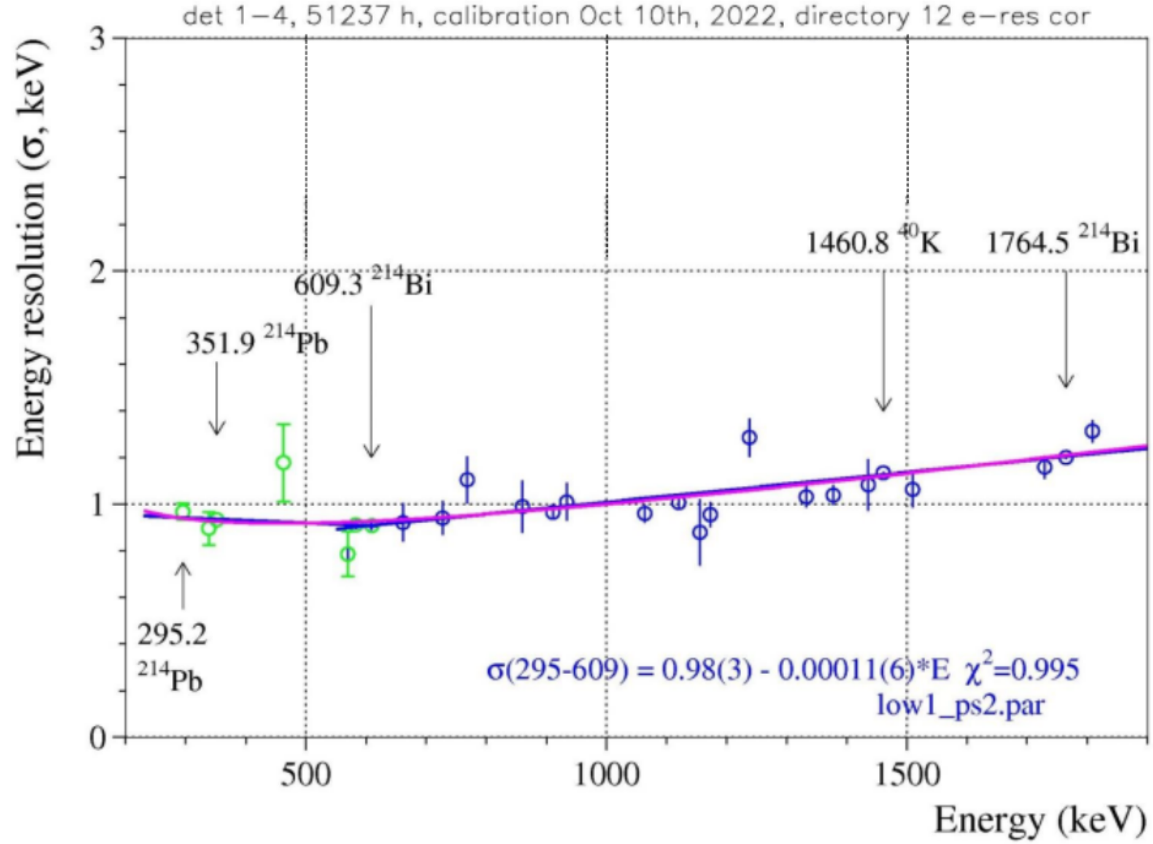
- $^{148}Nd \rightarrow {}^{140}Ba \rightarrow {}^{140}La \rightarrow {}^{140}Ce$

In the cases ^{143}Nd, ^{145}Nd and ^{148}Nd, daughter Ce isotopes are unstable and decay with emission of γ's.
^{144}Nd and ^{146}Nd decays can be observed (in our approach) only in the case of decays to excited Ce level.

Energy resolution

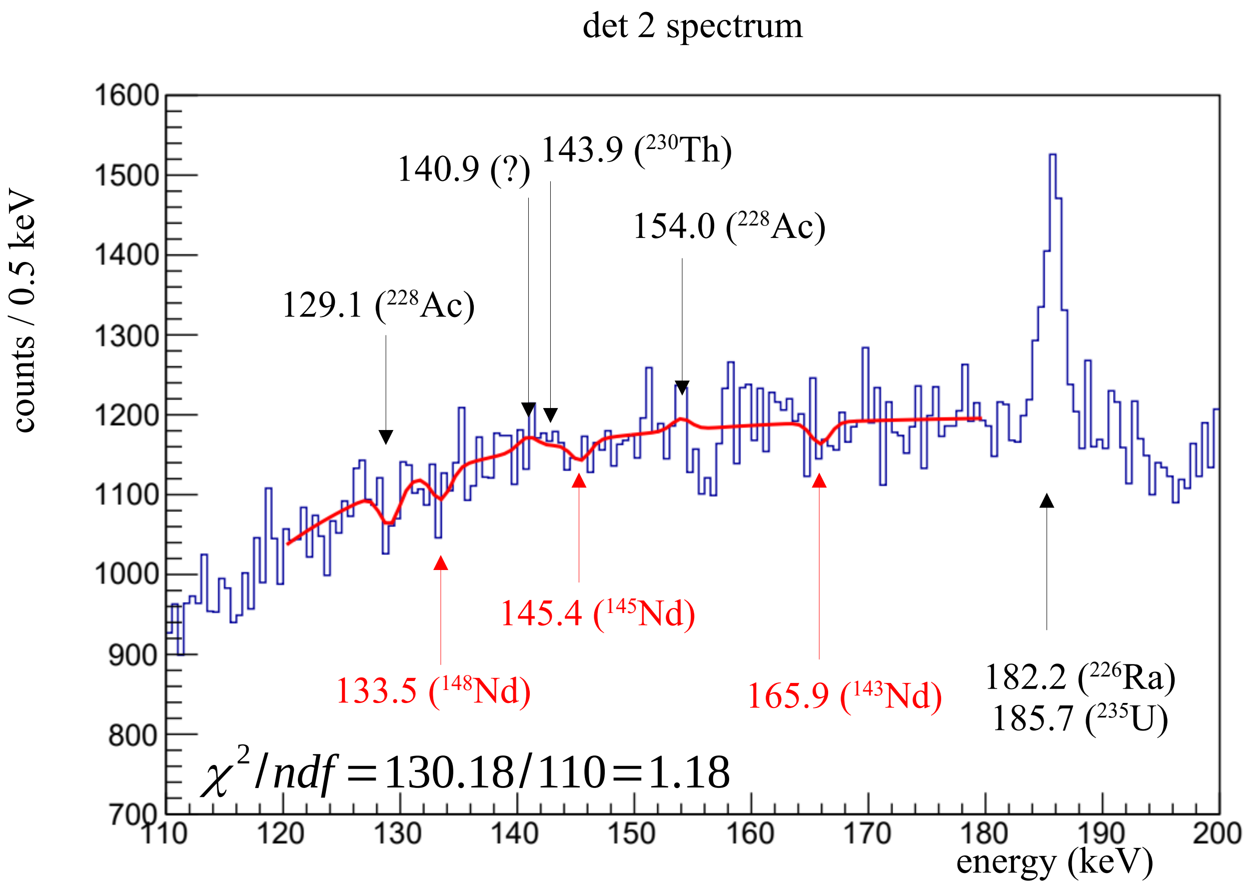






1. detector 1 FWHM dependence
2. detector 2 FWHM dependence
3. energy resolution in the sum spectrum of all detectors

Search for α decays of ^{143}Nd, ^{145}Nd, ^{148}Nd



μ (keV)	σ (keV)	S
129.1	0.82	-94 ± 45
133.5	0.82	-74 ± 46
140.9	0.82	32 ± 46
143.9	0.81	-2 ± 47
145.4	0.81	-49 ± 47
154.0	0.81	29 ± 44
165.9	0.80	-54 ± 43

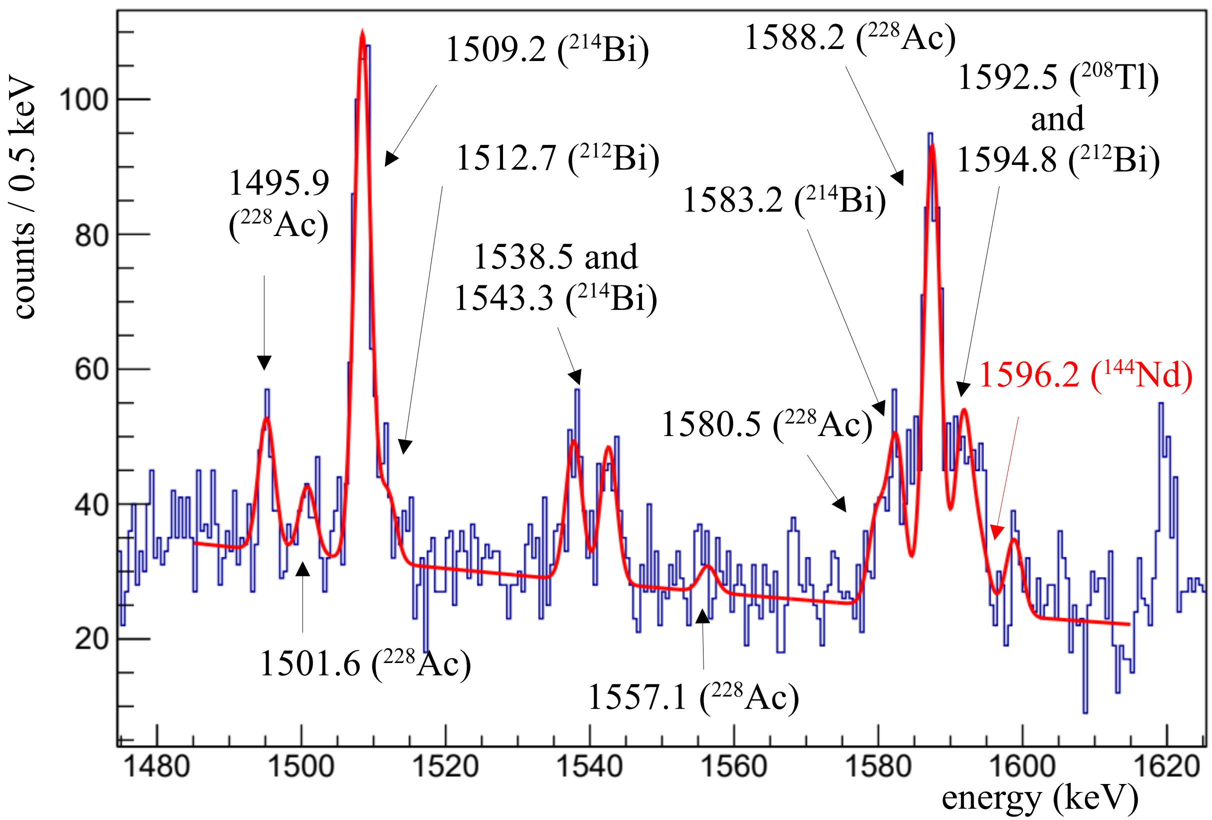
$$\lim T_{1/2} = \frac{\ln 2 \cdot N \cdot t \cdot eff \cdot \eta}{\lim S}$$

Data measured over 51237 h by detector 2 with low energy threshold

- N – number of nuclei
- t – time of measurements
- eff – efficiency (calculated with EGSnrc)
- η – yield of γ quanta

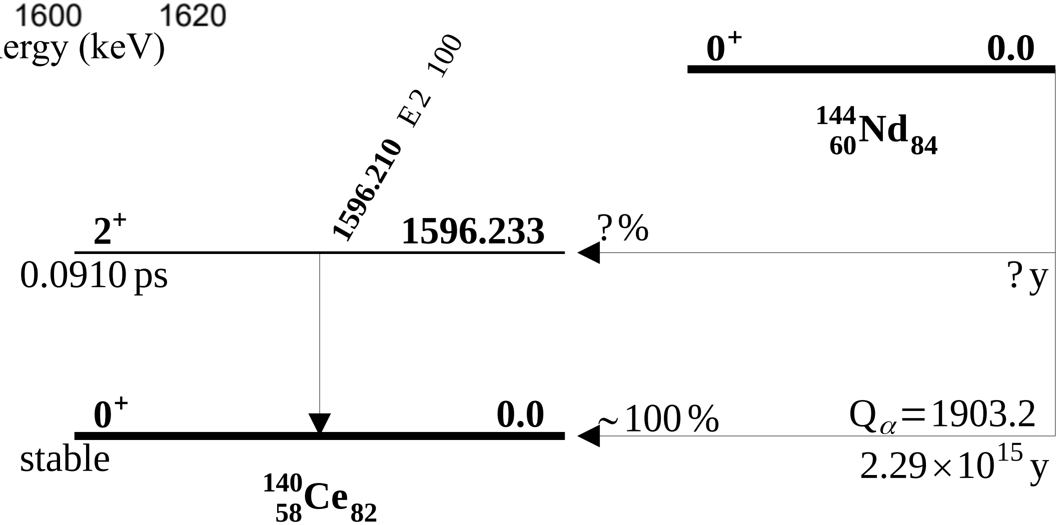
lim S – number of events that can be excluded with some confidence level

nuclide, decay channel	energy (keV)	lim S	$T_{1/2}$ (y)
^{143}Nd, α	165.9	29	> 1.4×10^{20}
^{145}Nd, α	145.4	37	> 6.2×10^{19}
^{148}Nd, α	133.5	24	> 2.2×10^{19}

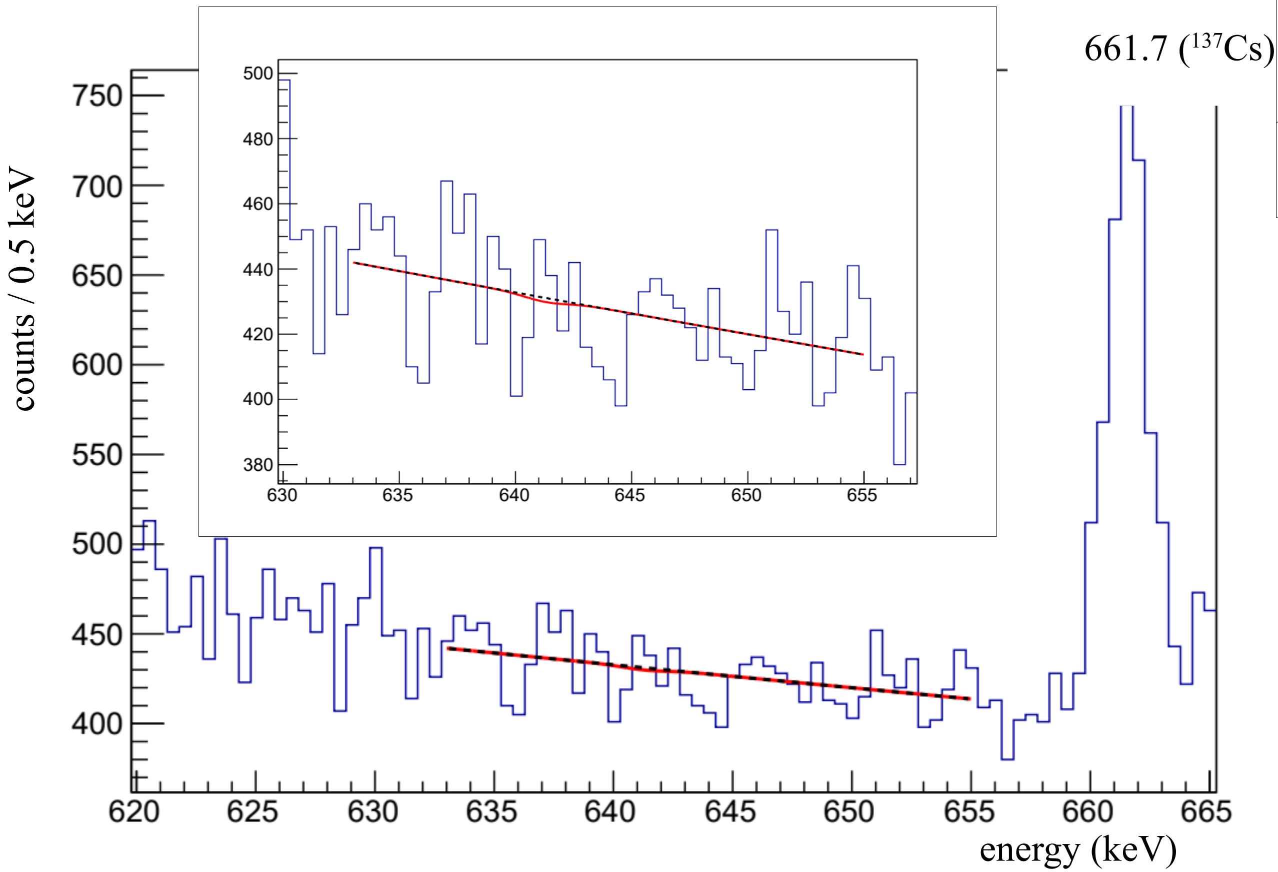


Nuclide	μ (keV)	σ (keV)	S
^{144}Nd	1596.2	1.16	3 ± 8
^{212}Bi	1512.7	1.14	29 ± 9
^{208}Tl	1592.5	1.16	83 ± 10
^{228}Ac	1588.2	1.16	200 ± 12
^{214}Bi	1509.2	1.14	222 ± 12
	1538.5	1.14	59 ± 10
	1543.3	1.15	58 ± 10

$$\lim S = 17 \rightarrow \lim T_{1/2}\,(^{144}\text{Nd}) = 8.9 \times 10^{21}\ \text{y}$$

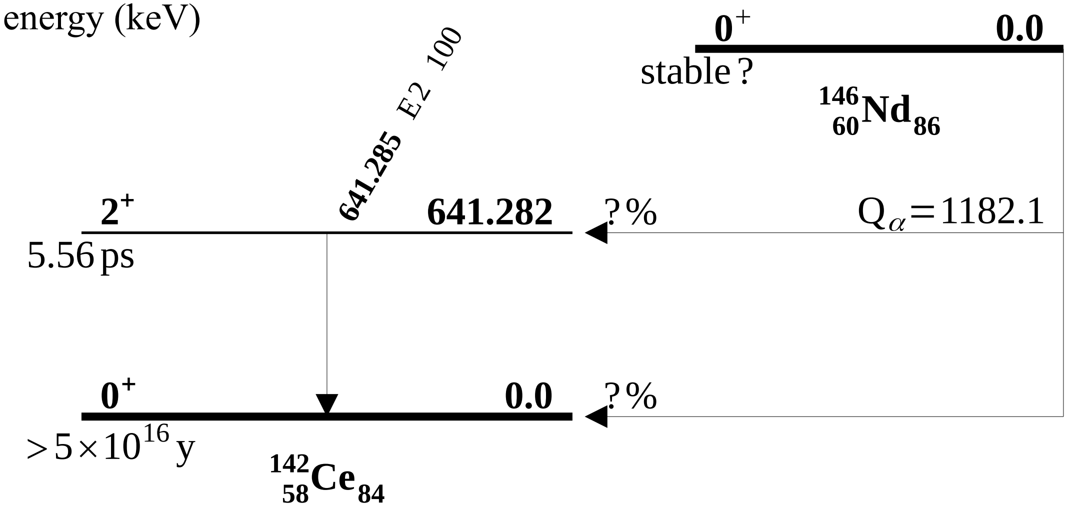


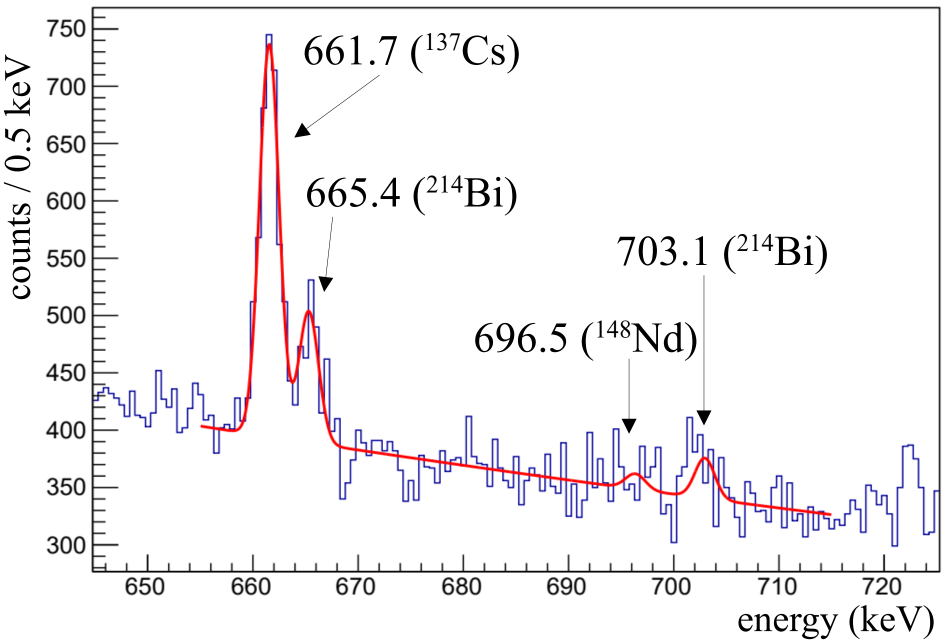
Search for α decays of ^{146}Nd

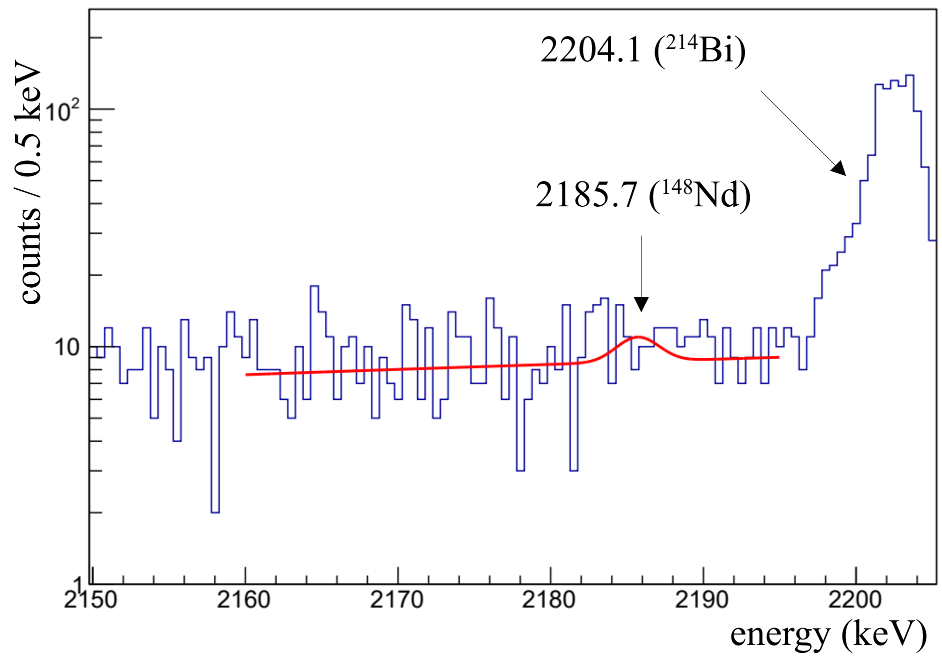


Nuclide	μ (keV)	σ (keV)	S
^{146}Nd (α)	641.3	0.93	-8 ± 33

lim S = 45 → lim $T_{1/2}$ (^{146}Nd) = 3.3×10^{21} y







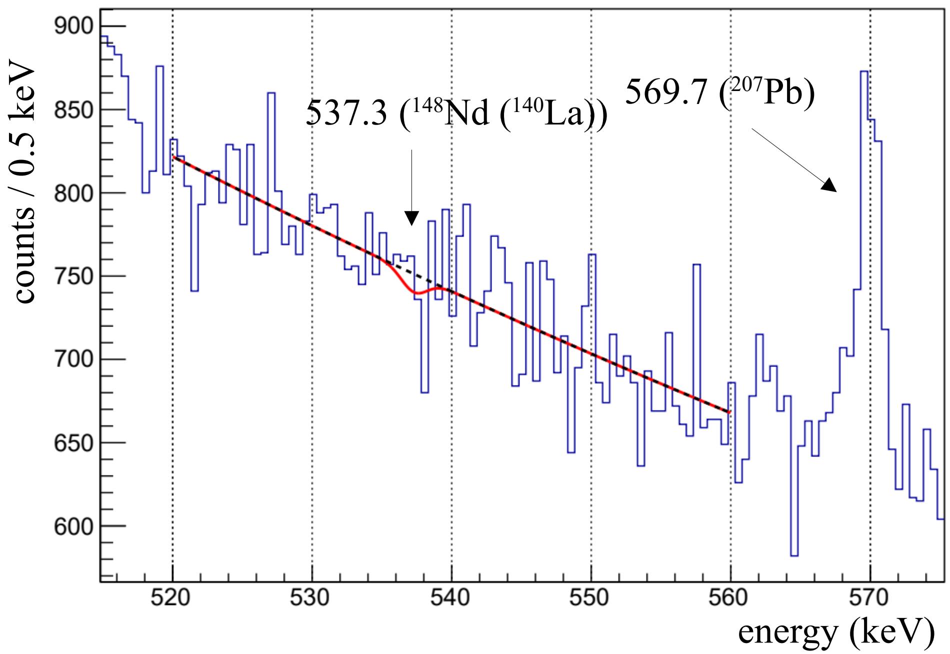
Nuclide	μ (keV)	σ (keV)	S
^{148}Nd (α)	696.5	0.93	32 ± 25

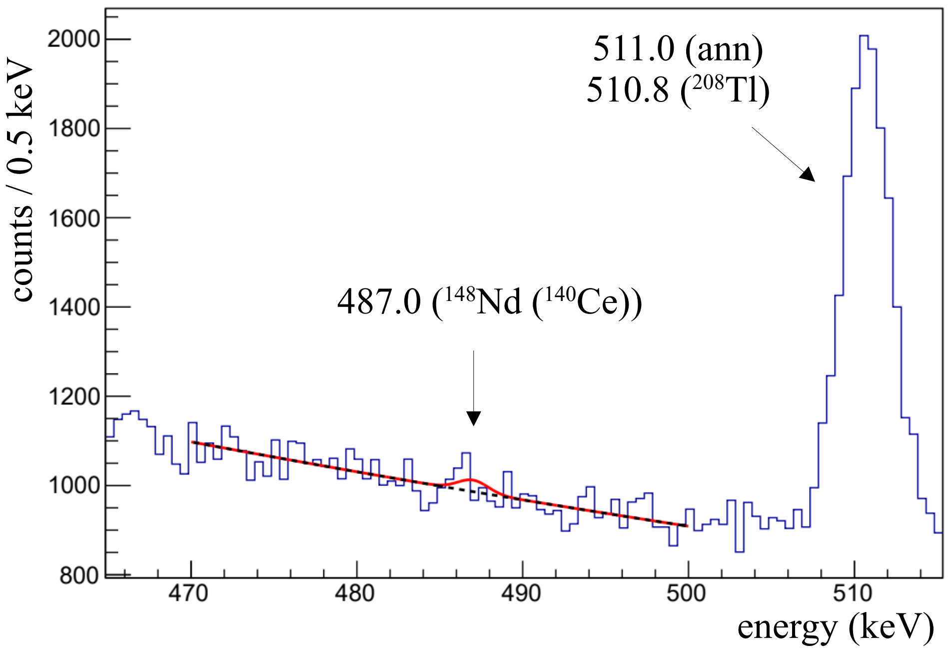
Nuclide	μ (keV)	σ (keV)	S
^{148}Nd (α)	2185.7	1.34	8 ± 5

lim S = 73 → lim $T_{1/2}$ (^{148}Nd, α) = 9.1×10^{18} y

lim S = 17 → lim $T_{1/2}$ (^{148}Nd, α) = 1.2×10^{19} y

Search for 2α decays of ^{148}Nd





Nuclide	μ (keV)	σ (keV)	S
^{148}Nd (2α)	537.3	0.92	-25 ± 36

Nuclide	μ (keV)	σ (keV)	S
^{148}Nd (2α)	487.0	0.92	60 ± 43

lim S = 37 → lim $T_{1/2}$ (^{148}Nd, 2α) = 3.4×10^{20} y

lim S = 130 → lim $T_{1/2}$ (^{148}Nd, 2α) = 1.9×10^{20} y

Summary

Decay	Q_α ($Q_{2\alpha}$) (keV)	Transition (energy of level (keV))	Energy of γ-quanta (keV)	best previous limit $T_{1/2}$, y	this work $T_{1/2}$, y (preliminary)	theor. estimations $T_{1/2}$, y
α decay						
^{143}Nd $\rightarrow$ ^{139}Ce	530.5	$7/2^+ \rightarrow 3/2^+$ (g.s.)	165.9	$> 2\times10^{17}$	$> 2.8\times10^{19}$	1.0×10^{79} — 3.5×10^{92}
^{144}Nd $\rightarrow$ ^{140}Ce	1901.3	$0^+ \rightarrow 2^+$ (1596.2)	1596.2	—	$> 8.9\times10^{21}$	7.8×10^{121} — 9.5×10^{121}
^{145}Nd $\rightarrow$ ^{141}Ce	1574.1	$7/2^- \rightarrow 7/2^-$ (g.s.)	145.4	$> 1\times10^{17}$	$> 6.1\times10^{19}$	2.2×10^{22} — 4.9×10^{23}
^{146}Nd $\rightarrow$ ^{142}Ce	1182.1	$0^+ \rightarrow 2^+$ (641.3)	641.3	$> 1.6\times10^{18}$	$> 3.3\times10^{21}$	5.8×10^{77} — 8.5×10^{77}
^{148}Nd $\rightarrow$ ^{144}Ce	599	$0^+ \rightarrow 0^+$ (g.s.)	2185.7	—	$> 1.2\times10^{19}$	6.1×10^{70} — 1.1×10^{71}
2α decay						
^{148}Nd $\rightarrow$ ^{140}Ba	1011.5	$0^+ \rightarrow 0^+$ (g.s.)	537.3	—	$> 3.4\times10^{20}$	3.0×10^{172} — 1.1×10^{183}

Conclusions

1) The search for alpha decays of naturally occurring neodymium isotopes was realized with low-background HPGe gamma spectrometry.

2) The obtained $T_{1/2}$ limits for ^{143}Nd, ^{145}Nd and ^{146}Nd α decay were improved by 2-3 orders of magnitude compared to current best limits.

3) For the first time $T_{1/2}$ limits were set for ^{144}Nd α decay on the first excited ^{140}Ce level 1596.2 keV and α and 2α decays of ^{148}Nd.

4) Theoretical predictions of ^{145}Nd α decay is just 3-4 orders higher than experimental limit. So there are several ways to rich this predictions, for example, increase the sample mass with enriched ^{145}Nd, increase the detection efficiency and decrease background.

Back-up slides

2α decay possibility

Possibility of nuclear decay with simultaneous emission of two alpha particles, 2α decay: (A,Z) → (A–8,Z–4) + 2α was theoretically considered at the first time in 1980's [1,2,3,4]; in these works the expected half-lives were estimated for several nuclides. There were no further theoretical and experimental activities in this field during next ~40 years. Recently, it was re-considered in [5], with theoretical calculations of the expected $T_{1/2}$'s for naturally occurring nuclides and the first experimental limit for half-life set for ^{209}Bi as $T_{1/2} > 2.9\times10^{20}$ yr. In approaches, where the emitted two α particles are considered as a cluster [2,3,4,5,6,7,8], the calculated $T_{1/2}$'s are very big, e.g. in [5] for "stable" or long-lived nuclides – on the level of 10^{33} yr or higher. However, in refs. [9,10,11] the so-called symmetric 2α decay was considered, when two α particles are emitted in opposite directions and with equal energies $Q_{2\alpha}/2$. Microscopic calculations [9] of $T_{1/2}$ for such a process gave values much lower than those in approach of [5] (where semiempirical formulae of ref. [12] for cluster decay were used): 7.3×10^{10} yr instead of 2.1×10^{31} yr for ^{212}Po, and 5.5×10^{6} yr instead of 2.3×10^{20} yr for ^{224}Ra. And even lower value of only 2.6 yr was obtained for ^{224}Ra in a phenomenological treatment of symmetric 2α decay in ref. [10]. Thus, from the theoretical side, situation in 2α decay is very intriguing. Experimental investigations of this process could greatly help to clarify the picture.

2α decay possibility (refs)

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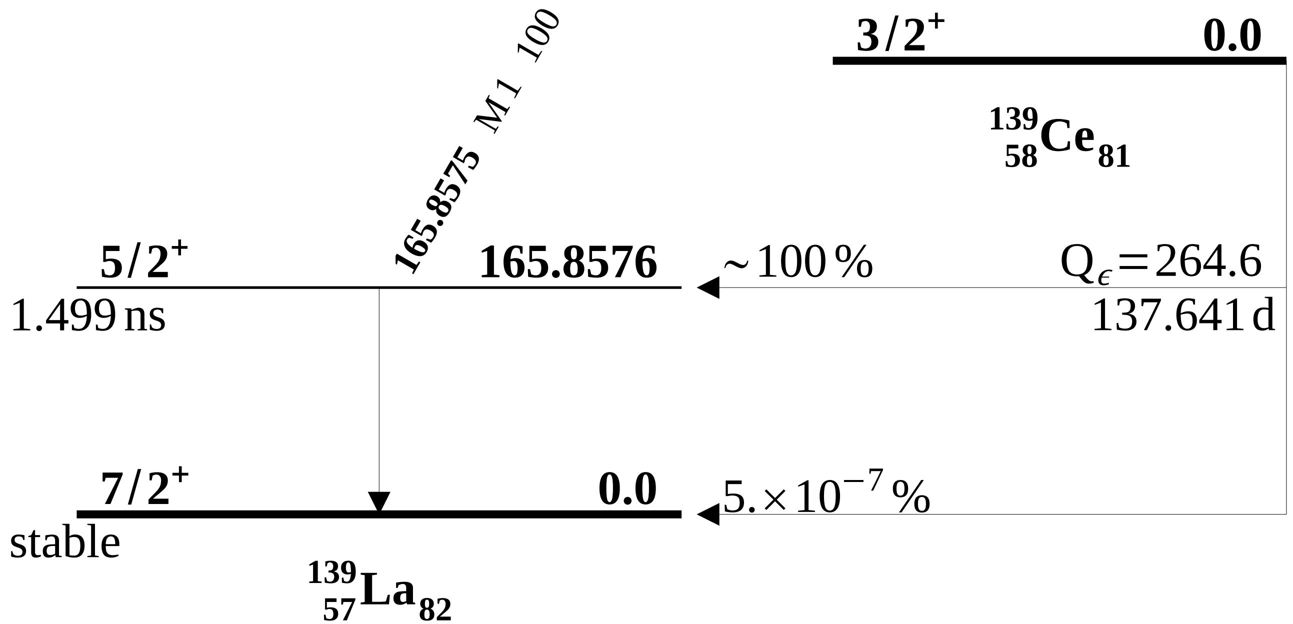
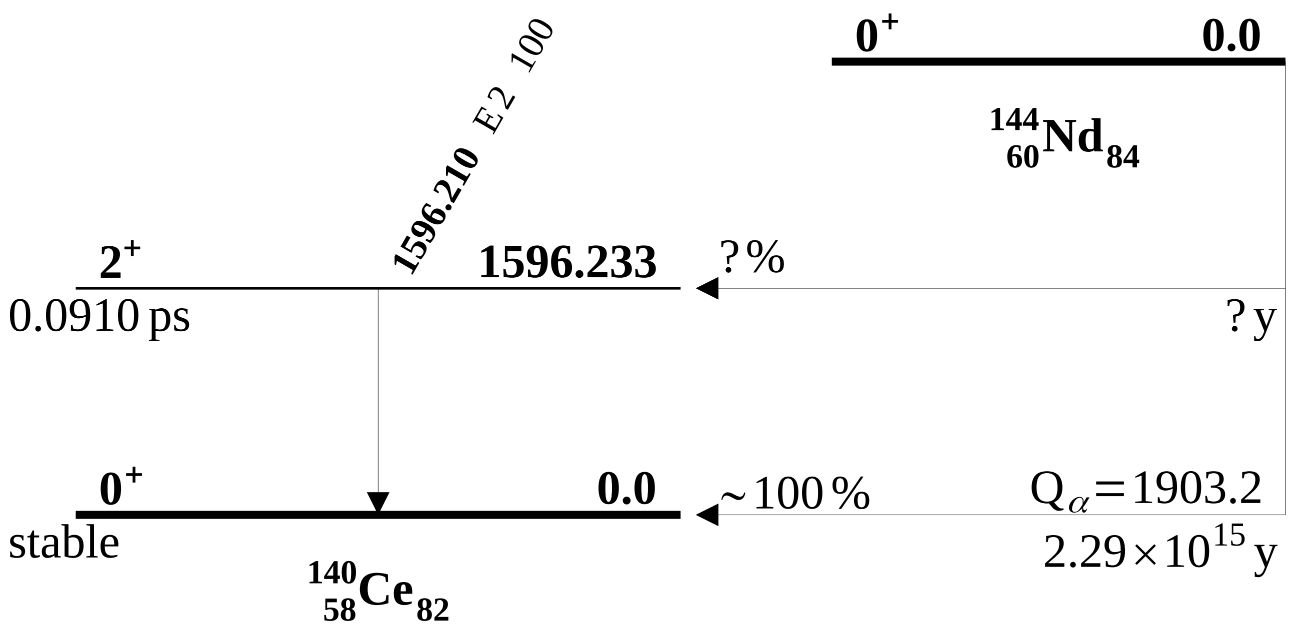
Decay scheme of ^{143}Nd and ^{144}Nd

$^{143}\mathrm{Nd} \rightarrow {}^{143}\mathrm{Ce}$

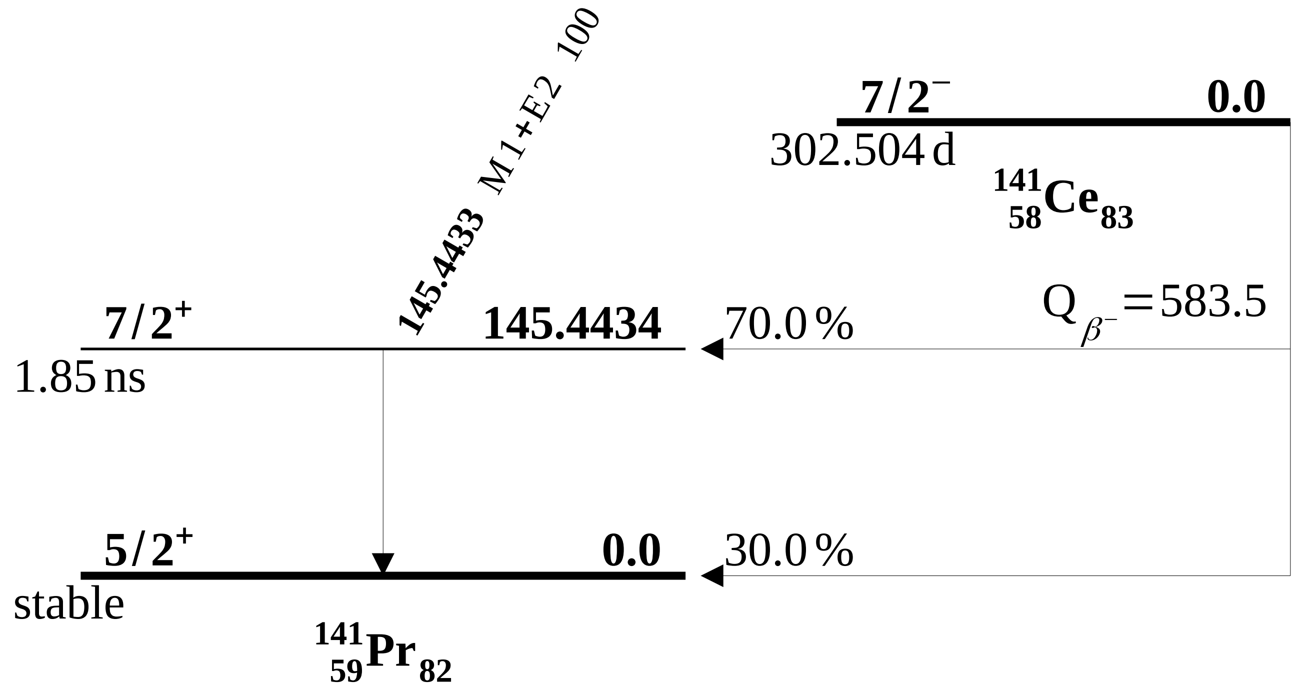


$^{144}\mathrm{Nd} \rightarrow {}^{140}\mathrm{Ce}$

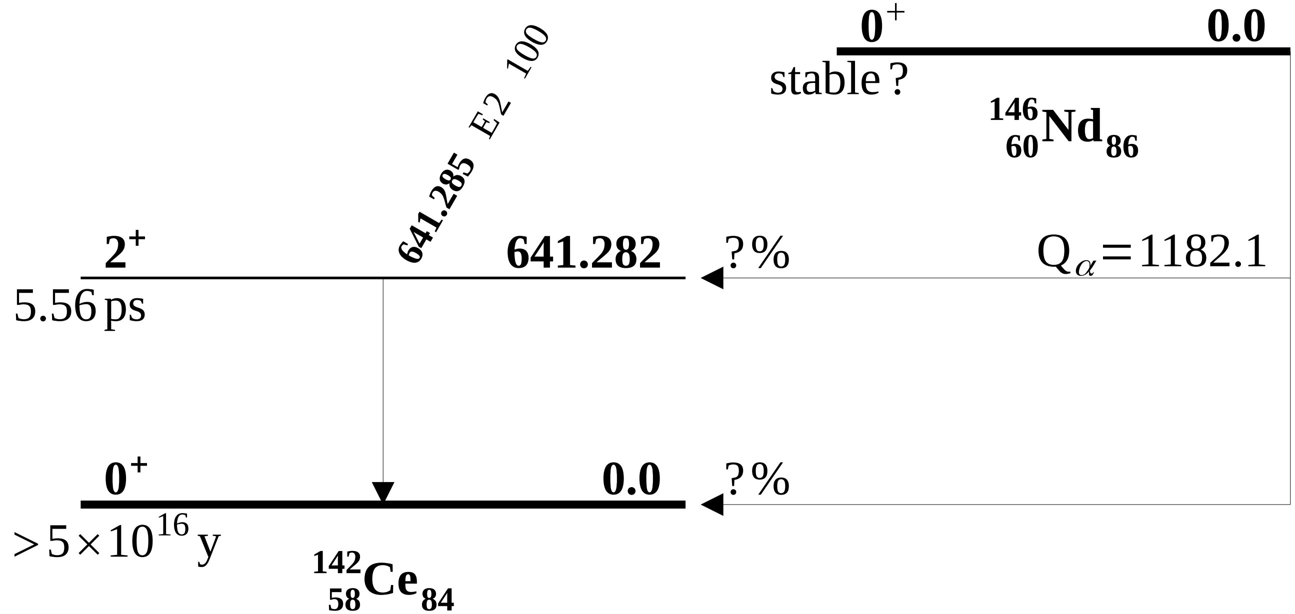


Decay scheme of ^{145}Nd and ^{146}Nd

$^{145}Nd \rightarrow {}^{141}Ce$

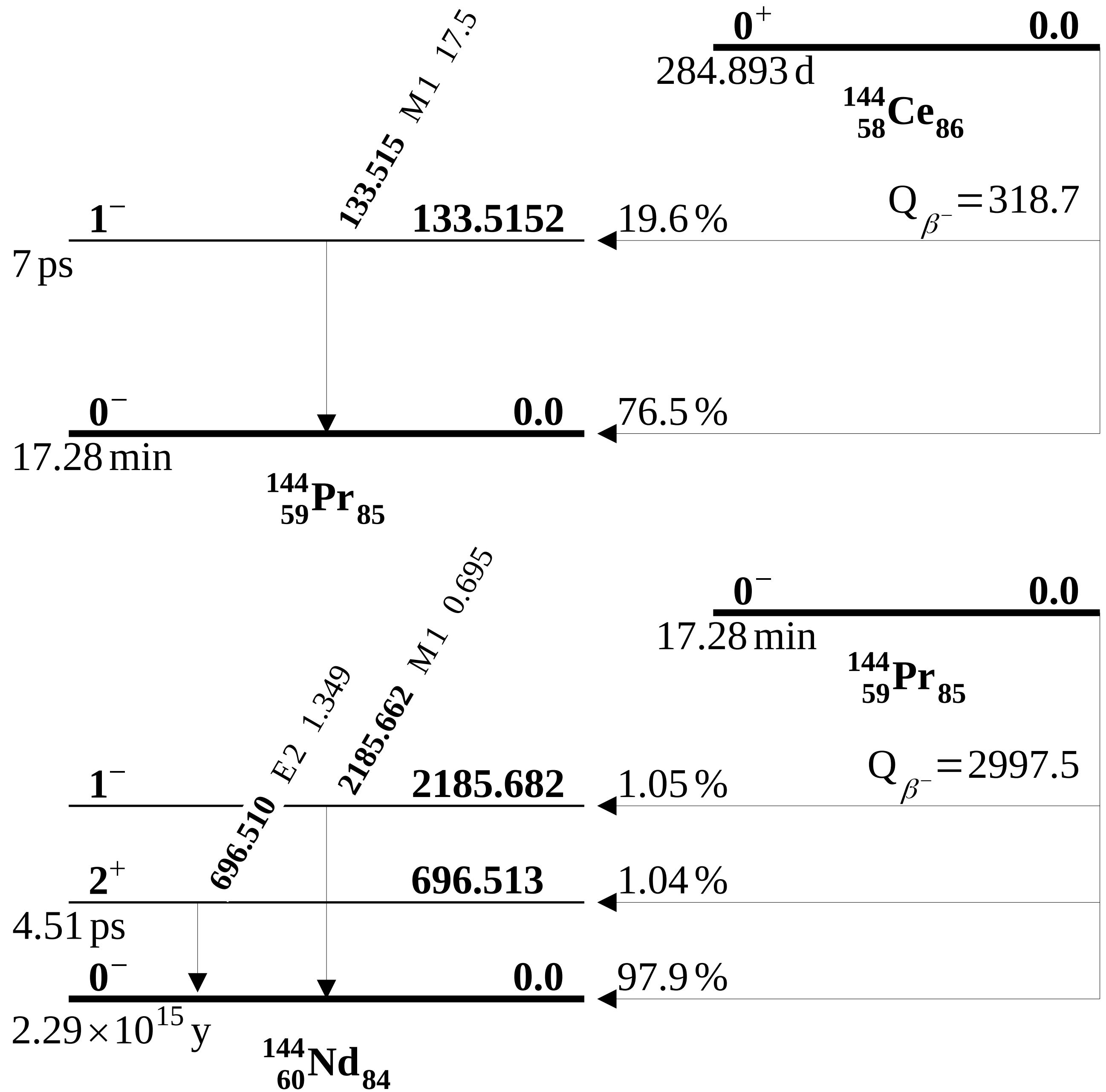


$^{146}Nd \rightarrow {}^{142}Ce$



Decay scheme of ^{148}Nd

$^{148}Nd \rightarrow {}^{144}Ce$



Decay scheme of ^{148}Nd 2α decay

$^{148}Nd \rightarrow {}^{140}Ce \rightarrow {}^{140}Ba$