Nuclear Data Sheets for A = 224^{*}

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Abstract: The experimental nuclear spectroscopic data for ten experimentally known nuclides of mass number 224 (Bi, Po, At, Rn, Fr, Ra, Ac, Th, Pa, U) have been evaluated and presented together with the Adopted properties for levels and γ rays. For ^{224}Bi , ^{224}Po , ^{224}At , ^{224}Rn , ^{224}Fr , ^{224}Pa and ^{224}U nuclei, only the ground-state information is known. Half-lives of ground states of ^{224}Bi and ^{224}Po have not yet been measured. The decay of ^{224}Rn to ^{224}Fr has been studied, but no decay scheme has been proposed. The decay of ^{224}Ac to ^{224}Ra is reported only in an abstract style conference proceedings. For a definite $J\pi$ assignment for ground state of ^{224}Ac , a detailed study of this decay may be helpful. In the decay of ^{228}Pa to ^{224}Ac , authors of 1994Ah03 state that the lowest state observed in their work may not be the ground state. Thus an extensive study of ^{228}Pa α decay, and studies involving nuclear reactions are warranted since the level scheme of ^{224}Ac presented in this evaluation is considered as incomplete due to the lack of confirmed information about multipolarities, mixing ratios and other spectroscopic details. Three new nuclides ^{224}Bi , ^{224}Po , and ^{224}At are added in this revision, together with new in-beam γ -ray and Coulomb excitation data for ^{224}Ra . Although, not much new experimental data have appeared since the previous evaluation (1997Ar05), extensive modifications have been made in almost all the datasets. This work supersedes the information presented in the previous NDS evaluations of A=224: 1997Ar05, 1986Ma45 and 1976E105.

Cutoff Date: Literature available up to October 15, 2015, has been consulted. The bibliographic source is mainly the NSR database (2011Pr03) at Brookhaven National Laboratory webpage: www.nndc.bnl.gov/nsr/

General Policies and Organization of Material: see <http://www.nndc.bnl.gov/nds/NDSPolicies.pdf>.

Acknowledgments: The current evaluation benefited from all the previous NDS evaluations stated above in addition to some of the A=228 and 220 NDS evaluations pertaining to α -decay chains. We thank Jagdish Tuli (NNDC,BNL) for a detailed review of this work, Murray Martin (ORNL) for his comments on the spin-parity assignment of ^{224}Ac g.s., and Joann Totans (NNDC,BNL) for sending us copies of several secondary references.

General Comments: The statistical analysis of γ -ray data and deduced level schemes is carried out through computer codes available at data center in Brookhaven (www.nndc.bnl.gov). Theoretical conversion coefficients are from BrIcc computer code (2008Ki07) with "Frozen Orbitals" approximation, and with an implicit uncertainty of 1.4%, when not stated. All Q values are from 2012Wa38. In cases where averages have been taken, the assigned uncertainty in the recommended result is set so that it is not lower than the lowest uncertainty in a dataset that is being averaged.

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NUCLEAR DATA SHEETS

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Skeleton Scheme for A=224

$S(p) \dots 8770^{\text{CA}}$

$S(n) \dots 3440^{\text{SY}}$

$S(p) \dots 9520^{\text{SY}}$

$S(n) \dots 3788^{26}$

$S(p) \dots 8272^{17}$

$S(n) \dots 7463^{14}$

$S(p) \dots 6845.6^{21}$
 $S(n) \dots 6478.8^{23}$

$S(n) \dots 5663^8$

$S(p) \dots 5122^{12}$

$S(p) \dots 4289^5$

Skeleton Scheme for A=224 (continued)

Ground-State and Isomeric-Level Properties				
Nuclide	Level	J π	T _{1/2}	Decay Modes
^{224}Bi	0.0		>300 ns	% β^{-} =?; % $\beta^{-}\text{n}$ =?
^{224}Po	0.0	0+	>300 ns	% β^{-} =?
^{224}At	0.0		1.3 min +23-4	% β^{-} =?
^{224}Rn	0.0	0+	107 min 3	% β^{-} =100
^{224}Fr	0.0	1(-)	3.33 min 10	% β^{-} =100
^{224}Ra	0.0	0+	3.6319 d 23	% α =100
^{224}Ac	0.0	(0-)	2.78 h 16	% ϵ =90.9 +14-20; % α =9.1 +20-14
^{224}Th	0.0	0+	1.04 s 2	% α =100
^{224}Pa	0.0	(5-)	0.846 s 20	% α =100
^{224}U	0.0	0+	0.84 ms +40-22	% α =100
^{228}Th	0.0	0+	1.9125 y 9	% α =100
^{228}Pa	0.0	3+	22 h 1	% α =2.0 2; ...
^{228}U	0.0	0+	9.1 min 2	% α =97.5 25; ...
^{228}Np	0.0		61.4 s 14	% α =40 7; ...
^{228}Pu	0.0	0+	1.1 s +20-5	% α =100

Adopted Levels

Q(β⁻)=6860 SY; S(n)=3440 SY; S(p)=8770 CA; Q(α)=1650 CA 2012Wa38,1997Mo25.

Estimated uncertainties in 2012Wa38: 450 for Q(β⁻), 570 for S(n).

Q(β⁻), and S(n) from 2012Wa38, S(p) and Q(α) from 1997Mo25.

Q(β⁻n)=1620 450, S(2n)=8050 500 (syst,2012Wa38), S(2p)=19460 (1997Mo25,calculated).

2010Al24: ²²⁴Bi nuclide identified in ⁹Be(²³⁸U,X) reaction with a beam energy of 1 GeV/nucleon produced by the SIS synchrotron at GSI facility. Target=2500 mg/cm². The fragment residues were analyzed with the high resolving power magnetic spectrometer Fragment Separator (FRS). The identification of nuclei was made on the basis of magnetic rigidity, velocity, time-of-flight, energy loss and atomic number of the fragments using two plastic scintillators and two multisampling ionization chambers. The FRS magnet was tuned to center on ²¹⁰Au, ²¹⁶Pb, ²¹⁹Pb, ²²⁷At and ²²⁹At nuclei along the central trajectory of FRS.

Unambiguous identification of nuclides required the separation of different charge states of the nuclei passing through the FRS. At 1 GeV/nucleon incident energy of ²³⁸U, fraction of fully stripped ²²⁶Po nuclei was about 89%. Through the measurement of difference in magnetic rigidity in the two sections of the FRS and the difference in energy loss in the two ionization chambers, the charge state of the transmitted nuclei was determined, especially, that of the singly charged (hydrogen-like) nuclei which preserved their charge in the current experimental setup. Measured production cross sections with statistical uncertainty<10% and systematic uncertainty=20%.

Criterion established in 2010Al24 for acceptance of identification of a new nuclide: 1. number of events should be compatible with the corresponding mass and atomic number located in the expected range of positions at both image planes of the FRS spectrometer; 2. number of events should be compatible with >95% probability that at least one of the counts does not correspond to a charge-state contaminant. Comparisons of measured σ with model predictions using the computer codes COFRA and EPAX.

²²⁴Bi Levels

E(level)	T _{1/2}	Comments
0.0	>300 ns	%β⁻=? ; %β⁻n=? In A/Z plot (figure 1 in 2010Al24), four or five events are assigned to ²²⁴Bi. Production cross section measured in 2010Al24, values are given in figure 2, plot of σ versus mass number for Bi isotopes. Statistical uncertainty<10%, systematic uncertainty=20% Production σ=89.2 pb (priv. comm. from H. Alvarez-Pol as e-mail reply of Oct 29, 2010 to B. Singh, which also stated that further analysis was in progress). See also D0607 dataset in the EXFOR database. E(level): the observed fragments are assumed to be in the ground state of ²²⁴Bi nuclei. The β⁻ and delayed neutron decay are the only decay modes expected. Calculated %β⁻n=10 (1997Mo25). T_{1/2}: lower limit from time-of-flight as given in 2006Ca30 for a similar setup. Actual half-life is expected to be much longer as suggested by the calculated value of 4.1 s for β decay and >10²⁰ s for α decay (1997Mo25), and systematic value of 300 ms for β decay (2012Au07). Jπ: 2- or 3- from coupling of 1/2+ for proton and 5/2- neutron orbitals predicted in 1997Mo25 calculations; 1- from systematics (2012Au07).

Adopted Levels

$Q(\beta^-)=2200$ SY; $S(n)=5240$ SY; $S(p)=9520$ SY; $Q(\alpha)=3820$ SY 2012Wa38.

Estimated uncertainties in 2012Wa38: 200 for $Q(\beta^-)$, 280 for $S(n)$ 450 for $S(p)$ and $Q(\alpha)$.

$S(2n)=8720$ 200 (syst,2012Wa38), $S(2p)=18010$ (1997Mo25,calculated).

2010Al24: ^{224}Po nuclide identified in $^9\text{Be}(^{238}\text{U},X)$ reaction with a beam energy of 1 GeV/nucleon produced by the SIS synchrotron at GSI facility. Target=2500 mg/cm². The fragment residues were analyzed with the high resolving power magnetic spectrometer Fragment Separator (FRS). The identification of nuclei was made on the basis of magnetic rigidity, velocity, time-of-flight, energy loss and atomic number of the fragments using two plastic scintillators and two multisampling ionization chambers. The FRS magnet was tuned to center on ^{210}Au , ^{216}Pb , ^{219}Pb , ^{227}At and ^{229}At nuclei along the central trajectory of FRS.

Unambiguous identification of nuclides required the separation of different charge states of the nuclei passing through the FRS. At 1 GeV/nucleon incident energy of ^{238}U , fraction of fully stripped ^{226}Po nuclei was about 89%. Through the measurement of difference in magnetic rigidity in the two sections of the FRS and the difference in energy loss in the two ionization chambers, the charge state of the transmitted nuclei was determined, especially, that of the singly charged (hydrogen-like) nuclei which preserved their charge in the current experimental setup. Measured production cross sections with statistical uncertainty<10% and systematic uncertainty=20%.

Criterion established in 2010Al24 for acceptance of identification of a new nuclide: 1. number of events should be compatible with the corresponding mass and atomic number located in the expected range of positions at both image planes of the FRS spectrometer; 2. number of events should be compatible with >95% probability that at least one of the counts does not correspond to a charge-state contaminant. Comparisons of measured σ with model predictions using the computer codes COFRA and EPAX.

 ^{224}Po Levels

E(level)	$J\pi$	$T_{1/2}$	Comments
0.0	0+	>300 ns	%β^-=? From A/Z plot (figure 1 in 2010Al24), ≈ 100 events are assigned to ^{224}Po. Production cross section measured in 2010Al24, values are given in figure 2, plot of σ versus mass number for Po isotopes. Statistical uncertainty<10%, and systematic uncertainty=20% Production $\sigma=5.97$ nb (priv. comm. from H. Alvarez-Pol as e-mail reply of Oct 29, 2010 to B. Singh, which also stated that further analysis was in progress). See also D0607 dataset in the EXFOR database. The β^- decay is the only decay mode expected. $T_{1/2}$: lower limit from time-of-flight as given in 2006Ca30 for a similar setup. Actual half-life is expected to be much larger as suggested by the calculated value of 12 s for β decay and $\approx 10^{20}$ s for α decay (1997Mo25), and systematic value of 1 min for β decay (2012Au07).

Adopted Levels

$Q(\beta^-)=5266$ 24; $S(n)=3788$ 26; $S(p)=6660$ SY; $Q(\alpha)=4470$ SY 2012Wa38.

Estimated uncertainties: 200 for $S(p)$, 300 for $Q(\alpha)$ (2012Wa38).

$S(2n)=9385$ 27, $S(2p)=15540$ 300 (syst) (2012Wa38).

2010Ch19: ^{224}At nuclide was discovered in the $^9\text{Be}(^{238}\text{U},X)$ reaction; beam energy 670 MeV/nucleon with target= $4\text{g}/\text{cm}^2$ using Fragment Recoil Separator facility at GSI. The fragments were then injected into the cooler electron storage ring ESR. Measured mass and half-life by time-resolved Schottky Mass Spectrometry technique.

2010Al24 measured σ . Figure 2 of this reference plots σ versus A . Statistical uncertainty $<10\%$, and systematic uncertainty= 20% Comparisons of measured σ with model predictions using the computer codes COFRA and EPAX; COFRA provides an overall good description of the measured σ .

Measured mass excess= 27711 keV 22 (2012Ch19; also 2010Ch19).

2012Zh46: theoretical calculation of binding energies, rotational correction energies, β_2 deformation parameter.

Comparison of binding energy with experimental value from 2012Ch19.

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 ^{224}At Levels

E(level)	$T_{1/2}$	Comments
0.0	1.3 min +23-4	$\% \beta^-=?$ $T_{1/2}$: for ionized (hydrogen-like) ^{224}At (2010Ch19), value quoted in 2010Ch19 is 76 s +138-23. Half-life is measured from number of stored $^{224}\text{At}^{84+}$ ions. $J\pi$: 2+ or 3+ from coupling of 1/2+ for proton and 5/2+ for neutron orbitals predicted in 1997Mo25 calculations.

Adopted Levels

$Q(\beta^-)=650\ 16$; $S(n)=6016\ 13$; $S(p)=8272\ 17$; $Q(\alpha)=4757\ 20$ 2012Wa38.

$S(2n)=10072\ 10$, $S(2p)=14620\ 40$ (2012Wa38).

1961Be28 (also 1961Po06): ^{224}Rn produced and identified in $^{232}\text{Th}(p,X)$, $E=230$ MeV, followed by chemical separation; but half-life of 4.9 h reported in this work is in disagreement with later measurements.

1964Bu02: ^{224}Rn produced and identified in $^{232}\text{Th}(p,X)$, $E=660$ MeV; measured half-life.

2012Ch19: precise mass measurement by Schottky Mass Spectrometry.

2009Ne03: measured mass using ISOLTRAP mass spectrometer.

2013Ro30: theoretical calculations of energies of 1^- states, $B(E1)$, $B(E3)$.

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 ^{224}Rn Levels

E(level)	$J\pi$	$T_{1/2}$	Comments
0.0	0+	107 min 3	$\%\beta^-=100$. $T_{1/2}$: from 1973AfZY. Other: 114 min 6 (1964Bu02). Weighted average of the two results is 108 min 3. 2012Gu11 (also 2011GuZY) investigated temperature dependence on half-life, but no difference was detected; measured values are not listed in this paper.

Adopted Levels

Q(β^-)=2968 13; S(n)=4660 13; S(p)=5884 15; Q(α)=4994 19 2012Wa38.
S(2n)=10697 25, S(2p)=13736 21 (2012Wa38).
1981Ku02, 1969Ha03: ²²⁴Fr produced and identified in Th(p,X),E=600 MeV at ISOLDE-CERN facility. Measured β and γ radiation, half-life.
1964Bu02: searched for ²²⁴Fr activity but no evidence was found, authors estimated half-life to be <2 min.
2014Kr09: mass determination with Penning-trap mass spectrometer ISOLTRAP facility at ISOLDE, CERN. Measured mass excess=21748 12, as compared to 21795 13 in AME-2012 (2012Wa38).
2012Ch19: precise mass measurement by Schottky Mass Spectrometry.
A 4.27 MeV α group has been assigned to the decay of ²²⁸Ac with branching=5.5 $\times$ 10⁻⁸ 22 per ²²⁸Ac decay in a chemically separated source (1969Lu12). This group would feed a level at 330 keV 42 in ²²⁴Fr. However, such a group would have an unreasonably low α hindrance factor, HF=4 $\times$ 10⁻⁴. Therefore, the assignment of this α group to the decay of ²²⁸Ac is considered as questionable by evaluators.
Ten γ rays have been observed (1979Va20) in the decay of ²²⁴Rn, and are listed in the table, but no decay scheme has been proposed as yet. Evaluators note that a 202.21 γ and 63.55 γ cascade with 265.76 γ as a crossover transition is suggested by 202.21 5 + 63.55 10=265.76 11 consistent with observed γ of 265.806 keV 17. Also, almost equal intensities of 260.581 γ and 265.806 γ suggest a cascade of these two gamma rays.
\$See unplaced γ rays in ²²⁴Rn β^- decay (1979Va20).

²²⁴Fr Levels

Cross Reference (XREF) Flags

A ²²⁴Rn β^- Decay (107 min)

E(level)	J π	XREF	T _{1/2}	Comments
0.0	1(-)	A	3.33 min 10	β^- =100. μ =+0.40 1 (1985Co24,2014StZZ). Q=+0.517 4 (1985Co24,2014StZZ,2013StZZ). Evaluated RMS charge radius=5.706 fm 18 (2013An02). J π : spin from atomic beam laser spectroscopy (1985Co24); π from agreement of experimental and theoretical magnetic dipole and electric quadrupole moments based on configuration= π 3/2 $\otimes$ v1/2 (1986Ek02). T _{1/2} : from γ decay curve (1981Ku02). Others: 2.67 min 20 from β decay curve (1969Ha03), <2 min (1964Bu02, activity not seen). Value from γ decay is preferred here due to better selectivity. No decay curves or other details of T _{1/2} measurements done at ISOLDE-CERN facility are given in 1981Ku02 and 1969Ha03. μ ,Q: atomic-beam laser spectroscopy (1985Co24). Measured isotope shift: $\Delta\langle r^2 \rangle$ =1.28937 4 relative to ²¹² Fr (1987Co19) (correction of earlier value of 0.52269 2 quoted in 1985Co24). Other: 1.487 15 (2005Dz02).

²²⁴Rn β^- Decay (107 min) 1979Va20

Parent ²²⁴Rn: E=0.0; J π =0+; T_{1/2}=107 min 3; Q(g.s.)=650 16; β^- decay=100.
²²⁴Rn-T_{1/2}: From ²²⁴Rn Adopted Levels.
²²⁴Rn-Q(β^-): From 2012Wa38.
1979Va20: ²²⁴Rn source produced in Th(p,X),E=660 MeV protons followed by mass separation. Measured E γ , I γ , conversion electrons using Ge detectors for γ rays and magnetic toroidal β spectrometer for electrons. 1973AfZY is an earlier report from many of the same authors.
Decay scheme is unknown. Evaluators note that a 202.21 γ and 63.55 γ cascade with 265.76 γ as a crossover transition is suggested by 202.21 5 + 63.55 10=265.76 11 consistent with the observed γ of 265.806 keV 17. Also, almost equal intensities of 260.581 γ and 265.806 γ suggest a cascade of these two gamma rays.

²²⁴Fr Levels

E(level)	J π	T _{1/2}	Comments
0.0	1(-)	3.33 min 10	J π ,T _{1/2} : from Adopted Levels.

^{224}Rn β^- Decay (107 min) $^{1979}\text{Va20}$ (continued) $\gamma(^{224}\text{Fr})$

$E_{\gamma}^{\dagger}$	$I_{\gamma}^{\ddagger}$	Mult. [§]	$\delta^{\S}$	α	Comments
^x 63.55 10	1.4 3	M1 (+E2)	<0.10	10.9 4	$\alpha(\text{L1})\text{exp}+\alpha(\text{L2})\text{exp}=5.7$ 21.
^x 108.44 8	1.5 2	M1 (+E2)	<1.8	9.4 20	$\alpha(\text{L1})\text{exp}+\alpha(\text{L2})\text{exp}=1.98$ 48.
^x 113.35 7	2.35 25	M1 (+E2)	<1.6	8.3 18	$\alpha(\text{L1})\text{exp}+\alpha(\text{L2})\text{exp}=1.64$ 30.
^x 156.17 3	1.45 10	M1 (+E2)	<0.4	3.85 19	$\alpha(\text{K})\text{exp}=5.0$ 11.
^x 202.21 5	4.7 5	M1 (+E2)	<1.9	1.4 6	$\alpha(\text{L1})\text{exp}+\alpha(\text{L2})\text{exp}=0.44$ 17.
^x 209.78 10	2.1 3	M1 (+E2)	<1.5	1.3 5	$\alpha(\text{L1})\text{exp}+\alpha(\text{L2})\text{exp}=0.4$.
^x 256.84 4	2.9 3	M1 (+E2)	<0.5	0.92 8	$\alpha(\text{K})\text{exp}=1.40$ 37.
					$\alpha(\text{L1})\text{exp}+\alpha(\text{L2})\text{exp}=0.27$.
^x 260.581 17	21.5 10	M1 (+E2)	<0.20	0.946 20	$\alpha(\text{K})\text{exp}=0.92$ 10.
					$\alpha(\text{L1})\text{exp}+\alpha(\text{L2})\text{exp}=0.20$ 4.
^x 265.806 17	20.1 10	M1 (+E2)	<0.25	0.888 24	$\alpha(\text{K})\text{exp}=0.88$ 11.
					$\alpha(\text{L1})\text{exp}+\alpha(\text{L2})\text{exp}=0.13$ 2.
^x 328.331 21	3.7 3	M1 (+E2)	<1.2	0.39 12	$\alpha(\text{K})\text{exp}=0.43$ 22.

[†] From 1979Va20.[‡] From 1979Va20, values are relative to 100 4 for 131.6 γ in ^{224}Ra from ^{224}Fr decay.[§] M1 assigned to all the γ rays in 1979Va20. Mixing ratios have been deduced by evaluators from I_{γ} and $I(\text{ce})$ data in 1970Va20 for ^{224}Rn - ^{224}Fr equilibrium source and normalized to $\alpha(\text{K})(\text{theory}, \text{E1})=0.0601$ 9 for 216 γ , E1 in ^{224}Ra from ^{224}Fr decay.^x γ ray not placed in level scheme.

Adopted Levels, Gammas

Q(β⁻)=-1408 4; S(n)=6478.8 23; S(p)=6845.6 21; Q(α)=5788.85 15 2012Wa38.

S(2n)=11637 5, S(2p)=12124.6 19 (2012Wa38).

In the past, ²²⁴Ra was called ThX, and was first identified by Rutherford and Soddy, Phil. Mag. 4, 370 (1902), extracted from thorium with an estimated half-life of ≈4 d. Later studies of decay of ²²⁴Ra: 1938Le07, 1962Ll02, 1962Wa28, 1971Jo14, 1977Ku15, 2004Sc04.

2014Bo26: mass determination with Penning-trap mass spectrometer ISOLTRAP facility at ISOLDE, CERN. Measured mass excess=18826 28, as compared to 18827.3 22 in AME-2012 (2012Wa38).

2015Bo05, 2015Na11, 2014De43, 2014No01, 2013Mh01, 2012Na10, 2006Mi05, 2001Ga32: theoretical level energies, B(E2) values, band structures.

²²⁴Ra Levels

Cross Reference (XREF) Flags

A ²²⁴Fr β⁻ Decay (3.33 min)
B ²²⁴Ac ε Decay (2.78 h)
C ²²⁸Th α Decay (1.9125 y)
D Coulomb Excitation

E ²²⁶Ra(p,t)
F ²²⁶Ra(α,α'2nγ)
G ²²⁶Ra(⁵⁸Ni,⁶⁰Niγ)
H ²³²Th(¹³⁶Xe,Xγ)

E(level) [†]	Jπ	XREF	T _{1/2}	Comments
0.0 ^{\$}	0+	ABCDEFGH	3.6319 d 23	%α=100; % ¹⁴ C=4.0×10 ⁻⁹ 10 (1992Ar02). % ¹⁴ C=4.0×10 ⁻⁹ 10 (1992Ar02), 6.5×10 ⁻⁹ 10 (1991Ho15,1991Ho24), 4.3×10 ⁻⁹ 12 (1985Pr01); fine structure looked for, but not observed (1991Ho15). Evaluated rms charge radius=5.705 fm 26 (2013An02). Isotope shift: Δ<r ² >=+1.09 11, relative to ²¹⁴ Ra (1988Ah02); other: 1989Ne03. T _{1/2} : from 2001Sc04 (4π ionization chamber). Other measurements: 3.66 d 4 (1971Jo14), 3.62 d 1 (1962Ll02), 3.64 d (1938Le07). μ=+0.92 22 (1973He13,2014StZZ). Jπ: E2 γ to 0+. μ: from IPAC in ²²⁸ Th α decay (1973He13). B(E2)=3.96 12 from Coul. ex. (2013GA23,2012GAZV). Q ₂ =6.32 10, β ₂ =0.154 (2012GaZV,2013Ga23). T _{1/2} : from αγ(t) in ²²⁸ Th α decay. Jπ: E1 γ to 0+. Jπ: αγ(0) from 0+ parent (²²⁸ Th α decay, 1989Po19). T _{1/2} : from αγ(t) in ²²⁸ Th α decay. Jπ: E1 γ to 2+; no γ to 0+; HF=47 for α branch from 0+; no β ⁻ decay from 1- ²²⁴ Fr; member of Kπ=0- octupole band. Jπ: E1 γ to 4+; no γ to levels with J<3; member of Kπ=0- octupole band. γ-ray branching ratio is in disagreement in various experiments. Jπ: γ to 4+; member of g.s. band. T _{1/2} : from 2012GaZV. Jπ: (E2) γ to (5)-; member of Kπ=0- octupole band. Jπ: γ to (6+); member of g.s. band. T _{1/2} : from 2012GaZV. Jπ: γ to (7-); member of Kπ=0- octupole band. Jπ: L(p,t)=0. Jπ: γ rays to 0+ and 2+; populated in Coulomb excitation. Possible bandhead of Kπ=2+ γ-vibrational band. Jπ: γ rays to 2+ and 4+; possible γ to 0+; HF=6.8 for α branch from 0+. Jπ: 1+E2 γ to 1-; γ to 0+. Jπ: γ to (8+); member of g.s. band. Jπ: M1(+E2) γ to (3)-; γ rays to 1- and 2+. Jπ: γ rays to 1- and 2+; log ft=8.2 from 1(-). Jπ: γ rays to 1- and (3)-; log ft=8.1 from 1(-). Jπ: γ to (9-); member of Kπ=0- octupole band. Jπ: L(p,t)=0. Jπ: γ rays to 2+ and 4+; log ft=7.76 11, log f ^{1u} t=8.5 from 1(-). Jπ: M1 γ to 1-; γ rays to 0+ and 2+. Jπ: M1 γ to (2+); γ to 1-; log ft=6.87 from 1(-). Jπ: γ rays to 1- and 2+; log ft=7.59 from 1(-). Jπ: possible member of g.s. band.
84.372 ^{\$} 3	2+	ABCDEFGH	0.748 ns 19	
215.985 [#] 4	1-	ABCDE GH		
250.782 ^{\$} 5	4+	ABCD FGH	0.181 ns 9	
290.352 [#] 21	3-	ABCD FGH		
433.02 [#] 7	(5)-	A CD FGH		
479.12 ^{\$} 10	6+	CDEFGH	52.7 ps 42	
640.69 [#] 18	(7-)	D FGH		
754.88 ^{\$} 20	8+	D FGH	20.8 ps +49-55	
906.17 [#] 25	(9-)	D FGH		
916.38 6	0+	A C E		
965.65 6	2+	A D		
992.70 6	(2+)	A C		
1053.041 23	1-	A		
1068.5 ^{\$} 3	10+	D FGH		
1090.087 24	(2,3)-	A		
1187.1 4	0+,1,2	A		
1216.89 19	(1-,2)	A		
1220.7 [#] 4	(11-)	FGH		
1223 4	0+	E		
1348.22 9	2+,3+	A		
1378.41 3	1-	A		
1379.04 6	(1+,2+)	A		
1389.93 15	(0+,1,2)	A		
1413.7 ^{\$} 4	(12+)	FGH		

Continued on next page (footnotes at end of table)

Adopted Levels, Gammas (continued)

²²⁴Ra Levels (continued)

E(level) [†]	J π	XREF	Comments
1425.152 20	(0, 1, 2)-	A	J π : M1 γ rays to 1- and (2,3)-.
1435.54 3	1-	A	J π : M1 γ to 1-; γ to 0+.
1437.11 6	2+	A	J π : γ rays to 0+ and 4+.
1553.67 14	1, 2+	A	J π : γ to 0+ g.s.
1573.6# 6	(13-)	GH	J π : possible member of K π =0- octupole band.
1614.42 17	(1-, 2)	A	J π : γ rays to (3)- and 1-; log ft=7.80 from 1(-).
1627 3		E	
1652.49 4	2+	A	J π : γ rays to 0+ and 4+.
1658.49 9	1(-), 2+	A	J π : γ rays to 0+ and (3)-.
1736.44 16	1, 2+	A	J π : γ to 0+ g.s.
1754.84 9	0+, 1, 2 $\frac{1}{2}$	A	J π : γ rays to 1- and 2+.
1761 4		E	E(level): possibly the same as the 1755 level.
1787.5\$ 6	(14+)	H	
1789.61 6	1, 2+	A	J π : γ rays to 0+ and 2+.
1796.71 9	(1-, 2) $\frac{1}{2}$	A	J π : γ rays to 1- and (3)-.
1818.06 19	(1-, 2) $\frac{1}{2}$	A	J π : γ rays to 1- and (3)-.
1838.53 10	0, 1, 2 $\frac{1}{2}$	A	J π : γ to 1- level.
1896.3 3	(1-, 2) $\frac{1}{2}$	A	J π : γ rays to 1- and (3)-.
1949 4		E	
1964.7# 8	(15-)	H	
1969.92 10	(0, 1, 2) $\frac{1}{2}$	A	J π : γ to 1-.
2000.26 17	(1-, 2) $\frac{1}{2}$	A	J π : γ to 1- and (3)-.
2043.0 3	0, 1, 2 $\frac{1}{2}$	A	J π : γ to 1-.
2052.3 4	2+ $\frac{1}{2}$	A	J π : γ rays to 4+ and 1-.
2077.3 4	0+, 1, 2 $\frac{1}{2}$	A	J π : γ rays to 1- and 2+.
2117.4 4	1, 2+	A	J π : γ to 0+ g.s.
2135.3 5	0, 1, 2 $\frac{1}{2}$	A	J π : γ to 1-.
2187.7\$ 8	(16+)	H	
2229.4 4	(1-, 2) $\frac{1}{2}$	A	J π : γ rays to 1- and (3)-.
2246.5 3	1, 2+	A	J π : γ to 0+ g.s.
2368.7 4	1, 2+	A	J π : γ to 0+ g.s.
2384.1# 9	(17-)	H	
2612.1\$ 10	(18+)	H	
2827.0# 11	(19-)	H	
3059.2\$ 11	(20+)	H	
3289.8# 12	(21-)	H	
3526.3\$ 12	(22+)	H	
3769.6# 13	(23-)	H	
4011.4\$ 13	(24+)	H	
4266.4# 14	(25-)	H	
4512.2\$ 14	(26+)	H	
4778.0?# 15	(27-)	H	
5030.4?\$ 15	(28+)	H	

[†] From least-squares fit to E γ data for levels deduced from γ -ray data.

 $\frac{1}{2}$ log ft<7.8, log f^{lu}_t<7.8 from 1- ²²⁴Ra rules out J=3.

\$ (A): K π =0+ g.s. band.

(B): K π =0- band.

$\gamma(^{224}\text{Ra})$

E(level)	E γ [†]	I γ [†]	Mult. ^{\$}	δ ^{\$}	α [#]	Comments
84.372	84.373 3	100	E2 $\frac{1}{2}$		21.2	B(E2)(W.u.)=99 3.
215.985	131.613 4	51.4 6	E1 $\frac{1}{2}$		0.247	
	215.983 5	100.0 4	E1 $\frac{1}{2}$		0.0752	
250.782	166.410 4	100	E2 $\frac{1}{2}$		1.164	B(E2)(W.u.)=140 7.
290.352	74.4 1	1.4 4	[E2]		38.5	
	205.936 27	100.0 10	E1		0.0841	
	290.5		[E3]		1.084	E γ : from Coulomb excitation.

Continued on next page (footnotes at end of table)

Adopted Levels, Gammas (continued)
 $\gamma(^{224}\text{Ra})$ (continued)

E(level)	E $\gamma^{\dagger}$	I $\gamma^{\dagger}$	Mult. [§]	$\delta^{\S}$	$\alpha^{\#}$	Comments
433.02	142.66 10	56 13	[E2]		2.14	I γ : from Coulomb excitation based on extensive data for yield measurements. This value agrees with 54 19 from (⁵⁸ Ni, ⁶⁰ Ni γ), but not with 26 10 from α decay and 139 39 from (¹³⁶ Xe,X γ). Weighted average of all four measurements is 43 13 with reduced $\chi^2=3.4$ as compared to critical $\chi^2=2.6$.
	182.29 10	100 12	[E1]		0.1126	
	348.5		[E3]		0.508	E γ : from Coulomb excitation.
479.12	228.3 1	100	[E2]		0.367	B(E2)(W.u.)=157 13.
640.69	160.5 5	13 4	[E1]		0.1530 25	E γ ,I γ : from (¹³⁶ Xe,X γ).
	207.8 2	100 19	[E2]		0.510	
754.88	113.9 5	<11	[E1]		0.350 7	E γ : uncertainty assigned by evaluators.
	275.8 2	100 5	[E2]		0.197	B(E1)(W.u.)=0.0003 3.
906.17	151.2 5	<15	[E1]		0.177 3	B(E2)(W.u.)=170 50.
	265.5 2	100 8	[E2]		0.223	
916.38	700.5 $\frac{1}{2}$ 5	$\approx 21\frac{1}{2}$				
	832.01 8	100 $\frac{1}{2}$ 17				
965.65	881.32 7	100 6				
	965.56 10	63 7				
992.70	741.9 2	88 19				
	908.10 10	100 8				
	992.9@ 10	≈ 88				
1053.041	762.63 4	23.4 12	(E2)		0.01536	
	837.03 7	100 5	M1+E2	1.6 +18-4	0.0219 66	
	968.62 13	3.4 4				
	1053.01 8	2.2 3				
1068.5	313.6 2	100	[E2]		0.1332	E γ : NRM average of three values. Weighted average gives 313.3 4 with reduced $\chi^2=9.2$.
1090.087	799.705 37	100 6	M1(+E2)		0.033 19	α : for $\delta(E2/M1)=1$.
	874.10 7	39 3				α : overlaps M1 and E2.
	1005.5 5	5.5 7				
1187.1	970.9 5	86 9				
	1103.0 5	100 27				
1216.89	926.5 2	100 24				
	1001.1 5	71 9				
1220.7	314.5 2	100				
1348.22	1097.6 2	100 27				
	1263.80 10	81 11				
1378.41	325.348 19	34.9 17	M1(+E2)	<0.3	0.549 20	
	461.98 8	11.2 6				
	1294.21 6	28.2 31				
	1378.45 10	100 6				
1379.04	386.4 10	27.9 23				
	413.40 5	94 6	M1(+E2)	<0.5	0.272 24	
	1163.04 10	100 7				
1389.93	1173.89 23	100 15				
	1305.6 2	48 7				
1413.7	345.2 2	100				
1425.152	335.056 19	22.9 9	M1(+E2)	<0.5	0.48 5	
	372.08 4	14.4 7	M1(+E2)	<1.1	0.308 86	
	1209.2 2	1.50 15				
	1340.800 25	100 7				
1435.54	382.511 25	45.9 22	M1(+E2)	<0.7	0.32 5	
	442.78 8	24 3				
	519.5 2	7.9 6				
	1219.42 10	20.8 24				
	1350.9 2	38 11				
	1435.60 10	100 10				
1437.11	1186.35 10	34 4				
	1352.60 10	86 12				

Continued on next page (footnotes at end of table)

Adopted Levels, Gammas (continued) $\gamma(^{224}\text{Ra})$ (continued)

E(level)	$E_{\gamma}^{\dagger}$	$I_{\gamma}^{\dagger}$	Mult. [§]	$\alpha^{\#}$	Comments
1437.11	1437.20 10	100 10			
1553.67	1338.0 5	=100			
	1469.4 2	100 12			
	1553.5 2	48 6			
1573.6	356.7 5	100	[E2]	0.0920	E_{γ} : 348.5 2 in (^{58}Ni , ^{60}Ni) is discrepant.
1614.42	1323.9 3	42 7			
	1398.5 2	100 13			
1652.49	659.64 10	11.5 21			
	1401.6 2	7.0 10			
	1568.18 6	55 7			
	1652.47 5	100 12			
1658.49	1368.1 2	68 16			
	1442.3 2	40 5			
	1658.54 10	100 20			
1736.44	1520.6 2	22 3			
	1736.19 25	100 17			
1754.84	702.0 2	51 16			
	1538.4 2	22 3			
	1670.53 10	100 16			
1787.5	373.8 5	100	[E2]	0.0809	
1789.61	1573.73 8	100 12			
	1705.12 10	49 8			
	1789.4 2	76 12			
1796.71	1506.4 2	43 6			
	1580.8 2	39 6			
	1712.30 10	100 17			
1818.06	1527.7 2	89 17			
	1602.1 5	100 17			
1838.53	1622.54 10	100			
1896.3	1607.1 5	100 17			
	1679.5 5	61 17			
	1811.6 5	72 17			
1964.7	391.1 5	100	[E2]	0.0717	
1969.92	1753.93 10	100			
2000.26	947.2 2	100 12			
	1784.3 3	70 12			
2043.0	1827.05 27	100			
2052.3	1801.3 5	100 19			
	1836.5 5	63 19			
2077.3	1862.0 5	47 9			
	1992.4 4	100 17			
2117.4	2033.2 5	65 12			
	2117.3 5	100 14			
2135.3	1919.3 5	100			
2187.7	400.2 5	100	[E2]	0.0674	
2229.4	1938.3 10	73 18			
	2013.4 5	91 18			
	2145.2 5	100 18			
2246.5	2030.5 5	100 16			
	2162.0 5	93 15			
	2246.6 5	14 3			
2368.7	2152.5 5	100 16			
	2368.8 5	53 11			
2384.1	419.4 5	100	[E2]	0.0597	
2612.1	424.4 5	100	[E2]	0.0579	
2827.0	442.9 5	100	[E2]	0.0520	
3059.2	447.1 5	100	[E2]	0.0508	
3289.8	462.8 5	100	[E2]	0.0466	
3526.3	467.1 5	100	[E2]	0.0456	
3769.6	479.8 5	100	[E2]	0.0427	
4011.4	485.1 5	100	[E2]	0.0416	
4266.4	496.8 5	100	[E2]	0.0393	
4512.2	500.8 5	100	[E2]	0.0385	

Continued on next page (footnotes at end of table)

Adopted Levels, Gammas (continued)

$\gamma(^{224}\text{Ra})$ (continued)

<u>E(level)</u>	<u>$E\gamma^{\dagger}$</u>
4778.0?	511.6@ 5
5030.4?	518.2@ 5

† From weighted averages of available data.

‡ From ^{228}Th α decay.

§ From ce data in ^{224}Fr β^- decay, unless otherwise noted.

$^{\#}$ From BrIcc v2.3b (16-Dec-2014) 2008Ki07, "Frozen Orbitals" appr.

@ Placement of transition in the level scheme is uncertain.

Adopted Levels, Gammas (continued)

²²⁴Fr β⁻ Decay (3.33 min) 1981Ku02,1980KuZL,1979Va20

Parent ²²⁴Fr: E=0; Jπ=1(-); T_{1/2}=3.33 min 10; Q(g.s.)=2968 13; %β⁻ decay=100.

²²⁴Fr-J, T_{1/2}: From ²²⁴Fr Adopted Levels.

²²⁴Fr-Q(β⁻): From 2012Wa38.

1981Ku02, 1980KuZL: measured Eγ, Iγ, γγ-coin, ²²⁴Fr half-life; deduced levels, J, π. A total of 120 γ rays were assigned to ²²⁴Fr decay, with only 20 γ rays out of these not assigned in the decay scheme.

1979Va20 (1973AfZY): measured Eγ, Iγ, ce, (ce)γ-coin; deduced 11 excited states incorporating 26 γ rays, J, π.

Another 17 γ rays were unplaced, some of which are now assigned in level scheme by 1981Ku02.

1975We23: measured Eβ, βγ-coin; deduced Q value.

The decay scheme is that of 1981Ku02, 1980KuZL. It is consistent with, but more extensive than that of 1979Va20 (also 1973AfZY).

²²⁴Ra Levels

E(level) [†]	Jπ [‡]	T _{1/2} [‡]	E(level) [†]	Jπ [‡]
0.0 §	0+	3.6319 d 23	1614.41 17	(1-, 2)
84.373 § 3	2+		1652.42 6	2+
215.985 # 4	1-		1658.52 9	1(-), 2+
250.783 § 5	4+		1736.3 2	1, 2+
290.36 # 4	3-		1754.84 9	0+, 1, 2
433.07 # 10	(5)-		1789.61 7	1, 2+
916.34 7	0+		1796.75 9	(1-, 2)
965.51 6	2+		1818.1 2	(1-, 2)
992.65 6	(2+)		1838.49 10	0, 1, 2
1052.95 3	1-		1896.3 3	(1-, 2)
1089.98 6	(2, 3)-		1969.92 10	(0, 1, 2)
1187.1 4	0+, 1, 2		2000.2 2	(1-, 2)
1216.9 2	(1-, 2)		2043.2 5	0, 1, 2
1348.22 9	2+, 3+		2052.3 4	2+
1378.35 5	1-		2077.3 4	0+, 1, 2
1378.93 7	(1+, 2+)		2117.4 4	1, 2+
1389.71 9	(0+, 1, 2)		2135.3 5	0, 1, 2
1425.03 5	(0, 1, 2)-		2229.4 4	(1-, 2)
1435.47 4	1-		2246.5 3	1, 2+
1437.08 6	2+		2368.7 4	1, 2+
1553.7 2	1, 2+			

[†] From least-squares fit to Eγ data.

[‡] From Adopted Levels.

§ (A): Kπ=0+ g.s. band.

(B): Kπ=0- band.

β⁻ radiations

There is unexpected apparent β feeding of 1.2% to 433, (5)- level, whereas none is expected from Jπ=1(-) of the parent. Note that several γ rays are still unplaced, although, none is strong enough to counterbalance 1.2% β feeding.

Eβ ⁻	E(level)	Iβ ^{-†}	Log ft	Comments
(599 13)	2368.7	0.050 9	7.1 1	
(722 13)	2246.5	0.27 5	6.6 1	
(739 13)	2229.4	0.050 9	7.4 1	
(833 13)	2135.3	0.045 9	7.6 1	
(851 13)	2117.4	0.10 2	7.3 1	
(891 13)	2077.3	0.12 2	7.3 1	
(916 13)	2052.3	0.08 2	7.5 1	
(925 13)	2043.2	0.10 2	7.4 1	
(968 13)	2000.2	0.13 2	7.4 1	
(998 13)	1969.92	0.10 2	7.5 1	
(1072 13)	1896.3	0.073 13	7.8 1	
(1130 13)	1838.49	0.20 4	7.4 1	
(1150 13)	1818.1	0.059 10	8.0 1	
(1171 13)	1796.75	0.49 8	7.1 1	
(1178 13)	1789.61	0.98 14	6.80 7	
(1213 13)	1754.84	0.30 6	7.4 1	
(1232 13)	1736.3	0.20 4	7.6 1	

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^{224}Fr β^- Decay (3.33 min) 1981Ku02,1980KuZL,1979Va20 (continued) β^- radiations (continued)

$E\beta^-$	E(level)	$I\beta^-^\dagger$	Log ft	Comments
(1309 13)	1658.52	0.36 7	7.4 1	
(1316 13)	1652.42	1.8 3	6.71 8	
(1354 13)	1614.41	0.12 2	7.9 1	
(1414 13)	1553.7	0.22 3	7.74 7	
(1531 13)	1437.08	1.9 3	6.9 1	
(1533 13)	1435.47	2.8 4	6.76 7	
(1543 13)	1425.03	7.2 9	6.36 6	
(1578 13)	1389.71	0.33 6	7.7 1	
(1589 13)	1378.93	1.9 3	7.0 1	
(1590 13)	1378.35	5.6 7	6.52 6	
(1620 13)	1348.22	0.27 6	7.9 1	
(1751 13)	1216.9	0.16 3	8.2 1	
(1781 13)	1187.1	0.14 3	8.3 1	
(1878 $\frac{1}{2}$ 13)	1089.98	<0.09	>8.6	
(1915 13)	1052.95	10.3 14	6.6 1	$E\beta^-$: 1780 50 (1975We23, $\beta\gamma$ -coin).
(2002 13)	965.51	0.37 10	8.1 1	
(2052 $\frac{1}{2}$ 13)	916.34	<0.04	>9.1	
(2752 13)	215.985	43 6	6.5 1	$E\beta^-$: 2580 80 (1975We23, singles β).
(2884 13)	84.373	14 8	7.1 3	
(2968 $\frac{1}{2}$ 13)	0.0	10 10	>6.8	$I\beta^-$: 7 13 from decay scheme.

 † Absolute intensity per 100 decays. $\frac{1}{2}$ Existence of this branch is questionable. $\gamma(^{224}\text{Ra})$

$I\gamma$ normalization: $I\gamma(216\gamma)=34\%$ 4 (adjustment of 33% 4 measured in 1979Va20 for revised absolute $I\gamma(240\gamma)=4.10\%$ 5 recommended in 1991BaZS evaluation). Value in 1979Va20 was deduced from measured ratio of $I\gamma(216\gamma)$ and $I\gamma(240\gamma)$ in ^{224}Ra α decay, using absolute $\gamma(240\gamma)=3.95\%$ 13.

$E\gamma^\dagger$	E(level)	$I\gamma^\dagger^b$	Mult.&	δ	α	Comments
74.4 $\frac{1}{2}$ 5	290.36	0.16 $\frac{1}{2}$ 3	[E2]		38.5 14	
84.373 $\frac{1}{2}$ 3	84.373	12.8@ 18	E2 ^a		21.2	$\alpha(\text{L1})\text{exp}+\alpha(\text{L2})\text{exp}=10.4$ 28; $\alpha(\text{L3})\text{exp}=7.8$ 18; $\alpha(\text{M})\text{exp}=4.7$ 11; $\alpha(\text{N})\text{exp}=1.6$ 5.
$\times$ 110.34 5		0.84 6				
131.613 $\frac{1}{2}$ 4	215.985	100 $\frac{1}{2}$ 4	E1 ^a		0.247	$\alpha(\text{L1})\text{exp}+\alpha(\text{L2})\text{exp}=0.033$ 11.
142.0 10	433.07	1.04 27	[E2]		2.18 7	$I\gamma$: from $I\gamma/I\gamma(182\gamma)=0.56$ 13 from Adopted Gammas. 1980KuZL report $I\gamma<0.8$ and do not place this transition.
166.410 $\frac{1}{2}$ 4	250.783	2.35 $\frac{1}{2}$ 11	E2 ^a		1.164	$\alpha(\text{L1})\text{exp}+\alpha(\text{L2})\text{exp}=0.82$ 33. Mult.: $\alpha(\text{L1})\text{exp}+\alpha(\text{L2})\text{exp}$ agrees with M1 or E2; E2 in Adopted Gammas.
182.30 10	433.07	1.86 22	[E1]		0.1126	
205.942 $\frac{1}{2}$ 35	290.36	13.9 $\frac{1}{2}$ 7	E1		0.0841	
215.983 $\frac{1}{2}$ 5	215.985	195 $\frac{1}{2}$ 9	E1 ^a		0.0752	Ice(K)=11.5 10, Ice(L1+L2)=2.6 6.
325.348 $\frac{1}{2}$ 19	1378.35	5.86 $\frac{1}{2}$ 28	M1(+E2)	<0.3	0.549 20	$\alpha(\text{K})\text{exp}=0.57$ 14.
335.056 $\frac{1}{2}$ 19	1425.03	6.17 $\frac{1}{2}$ 25	M1(+E2)	<0.5	0.48 5	$\alpha(\text{K})\text{exp}=0.48$ 13.
372.08 $\frac{1}{2}$ 4	1425.03	3.89 $\frac{1}{2}$ 19	M1(+E2)	<1.1	0.31 9	$\alpha(\text{K})\text{exp}=0.31$ 14.
382.511 $\frac{1}{2}$ 25	1435.47	2.89 $\frac{1}{2}$ 14	M1(+E2)	<0.7	0.32 5	$\alpha(\text{K})\text{exp}=0.46$ 25.
386.4 10	1378.93	1.23 10	[M1, E2]		0.21 14	
$\times$ 396.65 10		0.48 6				
413.398 $\frac{1}{2}$ 25	1378.93	4.13 $\frac{1}{2}$ 25	M1(+E2)	<0.5	0.272 24	$\alpha(\text{K})\text{exp}=0.30$. Mult.: assuming 30% uncertainty in $\alpha(\text{K})\text{exp}$.
442.78 8	1435.47	1.50 20	[E1]		0.01513	
461.98 8	1378.35	1.86 10	[E1]		0.01386	
$\times$ 478.30 10		0.48 7				
519.5 2	1435.47	0.50 4	[E1]		0.01092	
659.64 10	1652.42	0.70 13	[M1, E2]		0.05 4	
702.0 2	1754.84	0.50 16				
741.8 $\frac{1}{2}$ 2	992.65	1.40 $\frac{1}{2}$ 30	[E2]		0.01625	

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²²⁴Fr β⁻ Decay (3.33 min) 1981Ku02,1980KuZL,1979Va20 (continued)

γ(²²⁴Ra) (continued)

Eγ [†]	E(level)	Iγ ^{†b}	Mult.&	δ	α	Comments
762.63# 4	1052.95	13.9# 7	(E2)		0.01536	α(K)exp<0.015. Mult.: α(K)exp agrees with M1, E2 or E1, but ΔJπ requires E2. Mult.: E1,E2 from α(K)exp<0.016; but E1 is inconsistent with ΔJπ.
799.705# 37	1089.98	5.98# 38	M1(+E2)	<1.9	0.037 15	α(K)exp=0.051 34.
832.01# 8	916.34	2.34# 20	[E2]		0.01289	
837.03# 7	1052.95	59.5# 30	M1+E2	1.6 +16-6	0.022 8	α(K)exp=0.017 5.
874.10# 7	1089.98	2.34# 18	[M1,E2]		0.026 15	
881.32# 7	965.51	4.51# 27	[M1,E2]		0.026 14	
908.10 10	992.65	1.60 13	[M1,E2]		0.024 13	
926.5 2	1216.9	0.55 13				
^x 943.8 2		1.10 13				
947.2 2	2000.2	0.43 5				
965.56# 10	965.51	2.74# 27	[E2]		0.00963	
968.62# 13	1052.95	2.01# 20				
970.9 5	1187.1	0.38 4				
992.9 ^c 10	992.65	=1.4				Eγ: reported earlier by 1977Ku15 in their study of ²²⁸ Th α decay, Iγ/Iγ(742γ)=1. Not listed in 1980KuZL or 1981Ku02, although a 992.1γ is labeled in spectrum figure 1 in 1981Ku02.
1001.1 5	1216.9	0.39 5				
1005.5 5	1089.98	0.33 4				
1053.01# 8	1052.95	1.30# 20				
1097.6 2	1348.22	0.84 23	[M1,E2]		0.015 8	
1103.0 5	1187.1	0.44 12				
^x 1127.7 2		0.86 10				
^x 1133.8 2		0.86 10				
1163.09# 5	1378.93	4.41# 30				
1173.89# 23	1389.71	1.30# 20				
1186.35# 10	1437.08	1.68# 17				
1209.2# 2	1425.03	0.40# 4	[M1,E2]		0.012 6	
1219.46# 10	1435.47	1.31# 15	[M1,E2]		0.012 6	
^x 1239.1 2		0.30 6				
1263.80 10	1348.22	0.68 9	[M1,E2]		0.011 5	
^x 1274.50 10		1.22 16				
1294.21# 6	1378.35	4.7# 5				
1305.6 2	1389.71	0.62 9				
1323.9 3	1614.41	0.20 3				
1338.0 [§] 5	1553.7	=0.5 [§]				
1340.800# 25	1425.03	27.0# 20				
1351.14# 14	1435.47	2.4#@ 7				
1352.60 10	1437.08	4.2 6				
1368.1 2	1658.52	0.68 16				
1378.45 10	1378.35	16.8 10				
1398.5 2	1614.41	0.48 6				
1401.6 2	1652.42	0.43 6				
1435.60 10	1435.47	6.3 6				
1437.20 10	1437.08	4.9 5				
1442.3 2	1658.52	0.40 5				
1469.4 2	1553.7	0.50 6				
1506.4 2	1796.75	0.66 9				
1520.6 2	1736.3	0.21 3				
1527.7 2	1818.1	0.16 3				
1538.4 2	1754.84	0.22 3				
1553.5 2	1553.7	0.24 3				
1568.18# 6	1652.42	3.36# 40				
1573.73# 8	1789.61	2.49# 30				
1580.8 2	1796.75	0.60 10				
1602.1 5	1818.1	0.18 3				
1607.1 5	1896.3	0.18 3				
1622.54# 10	1838.49	1.13# 15				

Continued on next page (footnotes at end of table)

^{224}Fr β^- Decay (3.33 min) 1981Ku02,1980KuZL,1979Va20 (continued) $\gamma(^{224}\text{Ra})$ (continued)

$E\gamma^\dagger$	E(level)	$I\gamma^{\ddagger b}$	$E\gamma^\dagger$	E(level)	$I\gamma^{\ddagger b}$
1652.47 5	1652.42	6.1 7	1938.3 10	2229.4	0.08 2
1658.54# 10	1658.52	1.00# 20	^x 1944.8 5		0.12 2
1670.53# 10	1754.84	0.98# 16	^x 1950.1 5		0.12 2
1679.5 5	1896.3	0.11 3	^x 1973.9 5		0.10 2
1705.12# 10	1789.61	1.22# 21	1992.4# 4	2077.3	0.47# 8
1712.30# 10	1796.75	1.55# 26	2013.4 5	2229.4	0.10 2
1736.19# 25	1736.3	0.95# 16	2030.5 5	2246.5	0.74 12
1753.93 10	1969.92	0.59 10	2033.2 5	2117.4	0.22 4
^x 1779.1 5		0.12 3	2117.3 5	2117.4	0.34 5
1784.3 3	2000.2	0.30 5	^x 2123.2 5		0.17 3
1789.4 2	1789.61	1.90 30	2145.2 5	2229.4	0.11 2
^x 1798.4 5		0.18 3	2152.5 5	2368.7	0.19 3
1801.3 5	2052.3	0.27 5	2162.0 5	2246.5	0.69 11
1811.6 5	1896.3	0.13 3	^x 2169.7 5		0.29 5
^x 1816.2 5		0.11 2	^x 2214.8 5		0.22 4
1827.05# 27	2043.2	0.56# 10	2246.6 5	2246.5	0.10 2
1836.5 5	2052.3	0.17 5	2368.8 5	2368.7	0.10 2
^x 1847.1 5		0.40 7	^x 2372.6 5		0.20 2
1862.0 5	2077.3	0.22 4	^x 2388.0 5		0.11 3
1919.3 5	2135.3	0.26 4			

[†] From 1980KuZL unless otherwise stated.[‡] From 1977Ku25 (^{228}Th α decay) and adopted by 1981Ku02.§ From $\gamma\gamma$ coin spectra.

Weighted average of values from 1980KuZL and 1979Va20.

@ Unweighted average of values from 1980KuZL and 1979Va20.

& From $\alpha(K)\text{exp}=\text{Ice}(1979\text{Va20})/I\gamma(\text{listed here})$, normalized to $\alpha(K)(216\gamma, E1)=0.0600$.^a From Adopted Gammas.^b For absolute intensity per 100 decays, multiply by 0.174 20.^c Placement of transition in the level scheme is uncertain.^x γ ray not placed in level scheme.

^{224}Fr β^- Decay (3.33 min) 1981Ku02,1980KuZL,1979Va20 (continued)

Decay Scheme

 $^{224}_{87}\text{Fr}_{137}$ 3.33 min

 $\% \beta^- = 100$
 $Q^-(\text{g.s.}) = 2968^{13}$

 Intensities: I(γ +ce) per 100 parent decays

 $^{224}_{88}\text{Ra}_{136}$

3.6319 d

^{224}Fr β^- Decay (3.33 min) 1981Ku02,1980KuZL,1979Va20 (continued)

Decay Scheme (continued)

 $1(-)$ 0.0 3.33 min

 $^{224}\text{Fr}_{137}$
 $\% \beta^- = 100$
 $Q^-(\text{g.s.}) = 2968^{13}$

 Intensities: I(γ +ce) per 100 parent decays

 $^{224}\text{Ra}_{136}$

3.6319 d

^{224}Ac ϵ Decay (2.78 h) $^{1976}\text{MiZR}$

Parent ^{224}Ac : $E=0$; $J\pi=(0-)$; $T_{1/2}=2.78$ h 17; $Q(\text{g.s.})=1408$ 4; $\%\epsilon+\%\beta^+$ decay=90.9 17.

$^{224}\text{Ac}-J, T_{1/2}$: From ^{224}Ac Adopted Levels.

$^{224}\text{Ac}-Q(\epsilon)$: From 2012Wa38.

$^{1976}\text{MiZR}$ (a short conference report): measured $E\gamma$, ϵ feedings. Authors present $E\gamma$ values of three γ rays and ϵ feeding mainly to 216 level.

Other: 1958Hi78 report $\epsilon(217 \text{ level})/\Sigma\epsilon\geq 80\%$ from $I(\text{K x ray})/I\gamma$.

 ^{224}Ra Levels

$E(\text{level})$	$J\pi^\dagger$	$T_{1/2}^\dagger$
0.0	0+	3.6319 d 23
84.4	2+	
215.75	1-	
251	4+	
290	3-	

† From adopted levels.

 β^+, ϵ Data

$E\epsilon$	$E(\text{level})$	$I\epsilon^\#$	$\text{Log } ft$	$I(\epsilon+\beta^+)^\dagger^\#$
(1118@ 4)	290	≤ 0.6	≥ 8.0	$\leq 0.6^\S$
(1157@ 4)	251	≤ 0.6	≥ 8.0	$\leq 0.6^\S$
(1192 4)	215.75	90	5.9	90
(1324@ 4)	84.4	≤ 0.7	≥ 8.1	$\leq 0.7^\ddagger$
(1408@ 4)	0.0	≤ 0.7	≥ 8.1	$\leq 0.7^\ddagger$

† From $^{1976}\text{MiZR}$, per 100 ^{224}Ac decays. Estimated upper limits of ϵ branchings to 84, 251 and 290 levels are presumably based on $I(\text{K x ray})/I\gamma$ data. In the absence of a detailed study of this decay, and with no information available in the excitation energy region between 290 and 1400 keV, evaluators consider the decay scheme to be incomplete. The ϵ feeding to 216 level and associated $\log ft$ should be considered as approximate.

‡ Combined feeding of g.s. and 84 level is $\leq 0.7\%$.

§ Combined feeding of 251 and 290 levels is $\leq 0.6\%$.

$^\#$ For intensity per 100 decays, multiply by 1.000 19.

@ Existence of this branch is questionable.

 $\gamma(^{224}\text{Ra})$

$E\gamma^\dagger$	$E(\text{level})$	$I\gamma^\ddagger^\@$	Mult.	α
(74.4)	290	≤ 0.006	[E2]	38.5
84.4	84.4	1.52 6	E2	21.2
131.35 §	215.75	26.9 $^\#$ 6	E1	0.248
(166.4)	251	≤ 0.27	E2	1.164
(205.9)	290	≤ 0.32	E1	0.0842
215.75 §	215.75	52.3 $^\#$ 12	E1	0.0754

† From level-energy differences unless otherwise stated.

‡ Not given by authors. Values are deduced by the evaluator from the authors' ϵ branches and known γ branching and conversion coefficients (see Adopted Gammas).

§ From $^{1976}\text{MiZR}$.

$^\#$ 1958Hi78 report $I\gamma(216\gamma)/I\gamma(131\gamma)=2.24$ compared to 1.94 4 from Adopted Gammas.

@ For absolute intensity per 100 decays, multiply by 1.000 19.

²²⁴Ac ε Decay (2.78 h) 1976MiZR (continued)

²²⁸Th α Decay (1.9125 y) 1977Ku15,1984Ge07

Parent ²²⁸Th: E=0; Jπ=0+; T_{1/2}=1.9125 y 9; Q(g.s.)=5520.08 22; %α decay=100.

²²⁸Th-Q(α): From 2012Wa38.

²²⁸Th-T_{1/2}: 698.54 d 32 or 1.9125 Y 9 (using 1 tropical year=365.2422 d). This value is the weighted average of 698.3 d 6 (2014Un01, revision of their previous values reported in 2002Un02 and 1992Un01); 698.77 d 32 (1971Jo14, also 1964Ei01), 697.8 d 7 (1956Ki16). Others: 1964Ei01 give T_{1/2}=1.91313 y 44, a value also quoted in 1971Jo14 with an internal uncertainty of 0.00044 y but with a final uncertainty of 0.00088 y; 1956Ki16, 1964Ei03 and 1971Jo14 are from the same laboratory; 696.9 d 15, 703 d 7 (1962Ma57), 695.8 d 70 (1918Me01, uncertainty of 1% mentioned by 1956Ki16). Note that in ²²⁸Th Adopted Levels, T_{1/2}=1.9116 y 16 is taken from 1991BaZS compilation.

²²⁸Th-%α decay: %α=100. Cluster decay: measured %²⁰O=1.13×10⁻¹¹ 22 (1993Bo20).

1977Ku15 (also 1977Ku25): measured Eγ, Iγ, γγ-coin using Ge(Li) detectors. Deduced levels, J, π, half-life, α hindrance factors.

1984Ge07: measured Iγ, absolute Iγ using 4π-γ counting system. Precise Eγ values were not measured in this work.

1970Ba20: measured Eα, Iα using a magnetic spectrograph. Deduced levels, J, π. See also 1976BaZZ.

1989Po19: measured γγ-coin, αγ(θ), ce, total-conversion coefficients from αγ-coin data.

Others:

1973He13: measured g factor of first 2+ state.

1970SpZW: measured subshell ratios.

1968Du06, 1966Co40: measured total-conversion coefficient from αγ-coin data.

α measurements: 1971Gr17, 1953As31, 1949Ro02. Evaluation: 1991Ry01.

γ ray measurements: 1982Sa36, 1974HeYW, 1973Ta25, 1972DaYV, 1957St92, 1954Ne01, 1953Ri23, 1953Bo45.

αγ(θ) measurements: 1954St02, 1953Ba07, 1951Be42.

1982Sa36: measured Iγ for four γ rays. The values are systematically lower than in 1977Ku15 and 1984Ge07, thus not used here.

The decay scheme is from 1977Ku15.

²²⁴Ra Levels

E(level) [†]	Jπ [‡]	T _{1/2} [‡]	Comments
0.0	0+	3.6319 d 23	
84.373 3	2+	0.748 ns 19	g=+0.46 11 (1973He13). g: αγ(θ,H) (1973He13). T _{1/2} : weighted average of (α)(ce)(t) values: 0.748 ns 20 (1970To08), 0.744 ns 19 (1965Ne03), 0.76 ns 3 (1960Be25).
215.985 4	1-		
250.783 5	4+	0.181 ns 9	Jπ: 4+ from αγ(θ) from 0+ parent (1989Po19). T _{1/2} : (α)(ce)(t) (1965Ne03).
290.32 5	3-		
432.89 19	(5)-		
479.28 20	(6+)		
916.39 19	0+		
992.50 10	(2+)		

²²⁸Th α Decay (1.9125 y)   ¹⁹⁷⁷Ku15,1984Ge07 (continued)

²²⁴Ra Levels (continued)

† From least-squares fit to E_γ data.

‡ From Adopted Levels.

α radiations

Eα [†]	E(level)	Iα [‡] #	HF [§]	Comments
(4448.15 24)	992.50	≈4.6×10 ⁻⁶	≈7.1	
(4522.9 3)	916.39	1.7×10 ⁻⁵ 3	7 1	
(4952.4 3)	479.28	2.4×10 ⁻⁵ 5	5×10 ³ 1	
(4997.9 3)	432.89	1.0×10 ⁻⁵ 3	2.1×10 ⁴ 7	
5138	290.32	0.036 6	44 8	Iα: ≈0.05 (1970Ba20).
5173	250.783	0.218 8	12.5 5	Eα: other: 5173 (1953As31).
				Iα: 0.2 (1953As31), 0.18 (1970Ba20).
5211	215.985	0.408 14	10.7 4	Eα: other: 5208 (1953As31).
				Iα: 0.4 (1953As31), 0.36 (1970Ba20).
5340.36 15	84.373	26.0 10	0.96 4	Eα: measured values: 5339.2 10 (1976BaZZ), 5340.54 15 (1971Gr17), 5338.6 (1970Ba20), 5338.5 10 (1953As31), 5338 (1949Ro02).
				Iα: 26.7 2 (1969Pe17), 26.7 (1970Ba20), 28 (1953As31), 28 (1949Ro02).
5423.15 22	0.0	73.4 5	1.0	Iα: from DDEP evaluation (published in 2013BeZP); based on measurements by 1976BaZZ and 1993Ba72.
				Eα: measured values: 5420.6 10 (1976BaZZ), 5423.33 22 (1971Gr17), 5420.0 (1970Ba20), 5421 1 (1953As31), 5423 (1949Ro02).
				Iα: others: 74.0 6 (1993Ba72), 72.4 10 (1976BaZZ), 72.7 (1970Ba20) 71 (1953As31), 72 (1949Ro02).

† Data for the ground-state and 84-level branches are from 1991Ry01 evaluation. Others are from 1970Ba20, but increased by 2 keV by the evaluators to account for changes in calibration as deduced from a comparison of authors' values for the two strong branches with those of 1991Ry01 evaluation.

‡ From I(γ+ce) imbalance at each level, unless stated otherwise.

§ HF(5423.15α)=1.0 yields r₀(²²⁴Ra)=1.5339 fm 3.

Absolute intensity per 100 decays.

γ(²²⁴Ra)

I_γ normalization: From absolute Iα=73.4 5 (2013BeZP evaluation based on measured values in 1976BaZZ and 1993Ba72), and summed γ transition intensity to g.s.=100-73.4 5. Others: measured values: 0.0121 6(1969Pe17), 0.01248 29 (1984Ge07), 0.019 1 (1982Sa36, this value is discrepant). Evaluation: 0.0122 2 (1991BaZS and 1986LoZT).

Eγ [†]	E(level)	Iγ [§] @	Mult.	α	Comments
74.4 1	290.32	0.033 12	[E2]	38.5	
84.373 [‡] 3	84.373	100.0 16	E2	21.2	Mult.: L1:L2:L3=5.19 21:134.3 10:100; M1:M2:M3=5.7 6:121.9 9:100 (1970SpZW); theory(E2): L1:L2:L3=4.8:129.7:100. From αγ: α(exp)=21.4 9 (1969Pe17), 19.6 14 (1968Du06), 18 4 (1966Co40).
131.613 [‡] 4	215.985	10.70 15	E1 [#]	0.247	
142.0 5	432.89	0.00011 4	[E2]	2.18 5	Iγ: I _g (142.0)/I _γ (182.2)=0.26 10 is in disagreement with 0.56 13 from Adopted Gammas.
166.410 [‡] 4	250.783	8.49 12	E2	1.164	αγ(θ): A ₂ =+0.55 6, A ₄ =-0.48 18 (1989Po19). Mult.: from I(γ+ce)(161γ)=Iα(5173)=0.18 (1970Ba20), α(exp)(166γ)=0.73.
182.2 2	432.89	0.00043 15	[E1]	0.1127	Iγ: see comment for 142.0γ.
205.93 5	290.32	1.61 5	E1	0.0842	Mult.: α(K)exp<0.19, α(L)exp<0.05, α(M)exp<0.014 (1989Po19).
215.983 [‡] 5	215.985	20.78 25	E1 [#]	0.0752	Iγ: absolute Iγ/100 decays=0.261 3 (1984Ge07).
228.5 2	479.28	0.0015 3	[E2]	0.366	
700.5 5	916.39	≈0.00025	[E1]	0.00611	
742.2 5	992.50	0.00012 4	[E2]	0.01624	
832.0 2	916.39	0.0012 2	[E2]	0.01289	
908.10 10	992.50	≈0.00014	[M1,E2]	0.024 13	Eγ,Iγ: from Iγ/I(742γ)=1.14 26 in ²²⁴ Fr β ⁻ decay in later work of these authors (1981Ku02). Spectrum in present work shows 911.2γ labeled as a background peak.
992.9 10	992.50	≈0.00012	[E2]	0.00913	

Footnotes continued on next page

²²⁸Th α Decay (1.9125 y)   1977Ku15,1984Ge07 (continued)
γ(²²⁴Ra) (continued)

† From 1977Ku15 unless otherwise noted.

‡ The value in 1977Ku25 has been adjusted by the evaluators for change in calibration of ¹⁹⁸Au line from 411.794 keV 7 (used by 1977Ku25) to 411.80205 keV 17 recommended by 2000He14.

§ Relative to 100 for the 84γ. Values for the strong lines (>1) are from 1984Ge07. Others are from 1977Ku15.

From an intensity balance at the 216 level, using Iα(5211α)=0.36 (1970Ba20), both the 131γ and 216γ must be E1.

@ For absolute intensity per 100 decays, multiply by 0.01188 34.

Coulomb Excitation   2013Ga23,2012GaZV

2013Ga23, 2012GaZV: Beam=²²⁴Ra, E=631.68 MeV (for ⁶⁰Ni target), 633.92 MeV (for ¹¹²Cd and ¹²⁰Sn targets) produced by bombardment of thick Uranium carbide target by 1.4 GeV protons from CERN PS booster facility. Ions of ²²⁴Ra were accelerated in REX-ISOLDE. Targets: 2.1 mg/cm² thick ⁶⁰Ni, 2.0 mg/cm² thick ¹¹²Cd, 2.0 mg/cm² thick ¹²⁰Sn. Measured E_γ, I_γ, (particle)γ coin using MINIBALL array of 24 HPGe detectors, each with six-fold segmentation and arranged in eight triple clusters. Scattered particles (beam and target recoils) were detected in a highly segmented Si detector. Measured yields of γ rays for two ranges of recoil angles of the target nucleus: 23.10°–39.87° and 39.30°–53.23° for ⁶⁰Ni target; 23.94°–40.32° and 40.43°–54.32° for ¹¹²Cd and ¹²⁰Sn targets. Data analyzed using GOSIA computer code, by providing known lifetimes and branching ratios for low-lying levels as input parameters to this code. A total of 23 free parameters (16 matrix elements as stated in 2012GaZV) for each combination of target and recoil angle range) were determined from 57 independent data points. Deduced E1, E2, E3 matrix elements, and intrinsic quadrupole and octupole moments. Evidence for strong octupole deformation, stronger than in ²²⁰Rn.

²²⁴Ra Levels

Data are from 2013Ga23, except when stated otherwise.

Magnitude of matrix elements are listed, sign is unknown. Units are in eb^{L/2}, where L=multipole order.

Q₁, Q₂ and Q₃ are intrinsic dipole, quadrupole and octupole moments, respectively, and are from 2012GaZV with some also listed in 2013Ga23.

E(level) [†]	Jπ	T _{1/2}	Comments
0.0 §	0+		
84.4 § 2	2+		Q ₂ =6.32 10 in eb units. β ₂ =0.154 (2012GaZV). E2 matrix element (from g.s.,0+)=1.99 3.

Continued on next page (footnotes at end of table)

Coulomb Excitation 2013Ga23,2012GaZV (continued)
²²⁴Ra Levels (continued)

E(level) [†]	J π	T _{1/2}	Comments
216.0 # 2	1-		Dipole moment Q ₁ <0.002, <0019 in eb ^{1/2} units. Octupole moment Q ₃ =3.20 30 in eb ^{3/2} units. E1 matrix element (from g.s.,0+)<0.0018. E1 matrix element (from 85,2+)<0.003. E3 matrix element (from 85,2+)=1.37 14.
250.5 § 4	4+		Q ₂ =6.23 11 in eb units. E2 matrix element (from 85,2+)=3.15 6.
290.5 # 3	3-		Octupole moment Q ₃ =2.52 9 in eb ^{3/2} units. Octupole moment Q ₃ <8.0 in eb ^{3/2} units. Q ₂ =5.40 30 in eb units. Dipole moment Q ₁ =0.00030 6 in eb ^{1/2} units. β_3 =0.097 (2012GaZV). E1 matrix element (from 85,2+)=0.0026 5. E2 matrix element (from 216,1-)=2.30 11. E3 matrix element (from g.s.,0+)=0.940 30. E3 matrix element (from 85,2+)<4.00.
432.7 # 4	5-		Q ₂ =7.1 11 in eb units. Octupole moment Q ₃ =2.40 30 in eb ^{3/2} units. Dipole moment Q ₁ =0.00026 8 in eb ^{1/2} units. E1 matrix element (from 251,4+)=0.0030 10. E2 matrix element (from 291,3-)=4.10 60. E3 matrix element (from 241,2+)=1.41 19.
478.9 § 4	6+	52.7 ps [‡] 42	Q ₂ =6.30 20 in eb units. E2 matrix element (from 251,4+)=4.05 15.
640.6 # 4	7-		Dipole moment Q ₁ <0.010 in eb ^{1/2} units. E1 matrix element (from 480,6+)<0.010.
754.5 § 5	8+	20.8 ps [‡] +49-55	Q ₂ =6.6 8 in eb units. E2 matrix element (from 480,6+)=5.00 60.
905.9 # 5	9-		
965.49 @ 24	2+		Q ₂ =0.73 12 in eb units. E2 matrix element (from g.s.,0+)=0.23 4.
1067.1 § 6	10+		

[†] From least-squares fit to E γ values, assuming 0.3 keV uncertainty for each γ -ray energy.

[‡] Deduced in 2012GaZV from relevant matrix elements, assuming 100% E2 decay from each level. Note that 8+ level decays also by a weak 113.8 keV, E1 transition.

§ (A): The g.s. band.

(B): Octupole band.

@ (C): K π =2+ γ band.

 $\gamma(^{224}\text{Ra})$

B(E1)(W.u.), B(E2)(W.u.) and B(E3)(W.u.) values are from 2013Ga23, deduced from measured matrix elements.

E γ	E(level)	I γ [†]	Mult. [‡]	α [§]	Comments
74.4	290.5		(E2)	38.5	B(E2)(W.u.)=93 9.
84.4	84.4	53 3	E2	21.2	B(E2)(W.u.)=98 3.
113.8	754.5		[E1]	0.351	
131.6	216.0	1.46 13	E1	0.247	I γ (131.6)/I γ (216.0)=0.48 5. B(E1)(W.u.)<1.3 $\times 10^{-4}$. B(E3)(W.u.)=210 40.
142.0	432.7	0.44 10	E2	2.18	B(E2)(W.u.)=190 60. E γ : from 2012GaZV, listed as 142.6 in 2013Ga23.
151.5	905.9		[E1]	0.176	
161.7	640.6		[E1]	0.150	B(E1)(W.u.)<3 $\times 10^{-4}$.
166.4	250.5	81.5 19	E2	1.164	B(E2)(W.u.)=137 5.
182.3	432.7	0.78 9	E1	0.1126	B(E1)(W.u.)=4 $\times 10^{-5}$ +3-2. I γ (182.3)/I γ (142.0)=1.8 4.
205.9	290.5	2.49 17	E1	0.0842	B(E1)(W.u.)=3.9 $\times 10^{-5}$ +17-14. B(E3)(W.u.)<600.
207.7	640.6	0.38 15	[E2]	0.511	E γ : from Figure 2 in 2013Ga23 and Figure 4.11 in 2012GaZV; 207.6 in Table B.2 in 2012GaZV.

Continued on next page (footnotes at end of table)

Coulomb Excitation 2013Ga23,2012GaZV (continued)
 $\gamma(^{224}\text{Ra})$ (continued)

E γ	E(level)	I $\gamma^{\dagger}$	Mult. ‡	$\alpha^{\S}$	Comments
216.0	216.0	3.03 12	E1	0.075	B(E1)(W.u.) $<5\times 10^{-5}$.
228.5	478.9	13.6 4	[E2]	0.366	B(E2)(W.u.)=156 12. E γ : from 2012GaZV, listed as 228.4 in 2013Ga23.
265.3	905.9	0.18 6	[E2]	0.223	
275.7	754.5	1.26 9	[E2]	0.197	B(E2)(W.u.)=180 60.
(290.5)	290.5		[E3]	1.084	B(E3)(W.u.)=42 3.
312.6	1067.1	0.09 5	[E2]	0.1345	
(348.5)	432.7		[E3]	0.508	B(E3)(W.u.)=61 17.
881.1	965.49	0.41 8			
965.5	965.49	0.36 9	(E2)	0.0096	Mult.: Coulomb excitation of 965 level suggests mult=E2. B(E2)(W.u.)=1.3 5.

† From 2012GaZV for "total statistics, (particle)- γ data. Listed intensities are divided by a factor of 1000 by the compiler.
Values are also given in 2012GaZV for individual six experiments.

‡ From Adopted Gammas unless otherwise stated.

§ From BrIcc computer code.

²²⁶Ra(p,t) 1974Fr01

1974Fr01: E(p)=16.5 MeV. Measured triton spectra and $\sigma(\theta)$ using Enge split-pole magnetic spectrograph at FN-tandem-ANL facility. Target= 25 $\mu\text{g}/\text{cm}^2$ on 30-40 $\mu\text{g}/\text{cm}^2$ carbon layer. DWBA analysis.

²²⁴Ra Levels

E(level)	L †	d $\sigma/\text{d}\Omega$ $\mu\text{b}/\text{sr}^{\S}$	Comments
0.0	0	198 26	Reduced d $\sigma/\text{d}\Omega$ =155 $\mu\text{b}/\text{sr}$ 25 at 60°. $\sigma(\text{exp})/\sigma(\text{DWBA})$ =0.85.
84 2	(2) ‡	31 4	
251 3	(4) ‡	19 3	
477 2		6 1	
918 3	0	16 3	Reduced d $\sigma/\text{d}\Omega$ =8 $\mu\text{b}/\text{sr}$ 2 at 60°. $\sigma(\text{exp})/\sigma(\text{DWBA})$ =0.07.
1223 4	0 ‡	12	Reduced d $\sigma/\text{d}\Omega$ =13 $\mu\text{b}/\text{sr}$ 2 at 60°. $\sigma(\text{exp})/\sigma(\text{DWBA})$ =0.14.
1627 3		13 3	
1761 4		8 1	
1949 4		2 1	

† Authors state that only the L=0 angular distributions are reliable. L=2 and L=4 are listed for the 84 and 251 levels based probably on the assumed J π values.

‡ The $\sigma(\theta)$ distribution curves not shown by 1974Fr01. Authors state that while L=0 assignments are unambiguous, this is not the case for L=2 and 4 transitions. For this reason, L=2 and 4 are listed here in parentheses.

§ Values at 15°.

²²⁶Ra(α , α' 2n γ) 1990Ma20

1990Ma20: E α =55 MeV; measured (ce(L))(ce)- and (ce) γ -coin using iron-free double-orange magnetic spectrometer for electrons and four Compton-suppressed Ge detectors for γ rays. Target ≈ 200 $\mu\text{g}/\text{cm}^2$ RaBr₂ placed between ≈ 40 $\mu\text{g}/\text{cm}^2$ carbon and Be. Deduced high-spin levels, J, π , band structures.

²²⁴Ra Levels

E(level) †	J $\pi^{\ddagger}$	Comments
0.0 §	0+	
84.4 §	2+	
215.0 #	1-	
250.8 §	4+	
290.4 #	3-	B(E1)(205.9)/B(E2)(74.4)=1.3E-9 b ₁ 4.

Continued on next page (footnotes at end of table)

²²⁶Ra($\alpha, \alpha' 2n\gamma$) ¹⁹⁹⁰Ma20 (continued)

²²⁴Ra Levels (continued)

E(level) [†]	J $\pi^{\ddagger}$	Comments
433.1 [#]	5-	B(E1)(182.3)/B(E2)(142.7)=3.0E-9 b ₁ 14.
479.3 [§]	6+	
640.9 [#]	7-	
754.9 [§]	8+	
906.2 [#]	9-	
1068.5 [§]	10+	
1220.8 [#]	11-	
1413.6 ^{?§}	(12+)	

[†] From least-squares fit to E γ data.

[‡] Assignments for levels up to 6+ are from Adopted Levels. Assignments for higher levels are from energy systematics of rotational bands (1990Ma20).

[§] (A): K π =0+ g.s. band.

[#] (B): K π =0-, octupole band.

 $\gamma(^{224}\text{Ra})$

E γ	E(level)	I γ	E γ	E(level)	I γ	E γ	E(level)	I γ
74.4 [‡]	290.4		166.4 [‡]	250.8	46	265.3 2	906.2	13
84.4 [‡]	84.4		182.3 [‡]	433.1	27	275.6 2	754.9	27
131.6 [‡]	215.0		205.9 [‡]	290.4	37	313.6 2	1068.5	18
142.7 [‡]	433.1		207.8 2	640.9	15	314.6 2	1220.8	5
151.5 [§]	906.2	<2	216.0 [‡]	215.0		345.1 [§] 2	1413.6?	8
161.8 ^{†§}	640.9		228.4	479.3	39			

[†] No intensity obtained since line is masked by a strong γ in ²²⁵Th.

[‡] From Adopted Gammas.

[§] Placement of transition in the level scheme is uncertain.

²²⁶Ra(⁵⁸Ni, ⁶⁰Ni γ) ¹⁹⁸⁹Po19

E(⁵⁸Ni)=315 MeV; measured E γ , I γ , γ -coin, $\alpha\gamma$ (θ) using POLYTESSA array of 22 escape-suppressed Ge detectors for γ rays, and two Si detectors for α particles at Daresbury accelerator facility. Deduced high-spin levels, J π .

²²⁴Ra Levels

E(level) [†]	J $\pi^{\ddagger}$	Comments
0.0 [§]	0+	
84.4 [§] 1	2+	
215.9 [#] 1	1-	
250.7 [§] 1	4+	
290.3 [#] 1	3-	Intrinsic dipole moment=0.027 3 (1989Po19).
433.00 [#] 12	(5-)	Intrinsic dipole moment=0.040 10 (1989Po19).
478.9 [§] 2	(6+)	
640.7 [#] 3	(7-)	Intrinsic dipole moment<0.05 (1989Po19).
754.6 [§] 3	(8+)	Intrinsic dipole moment<0.11 (1989Po19).
906.0 [#] 3	(9-)	Intrinsic dipole moment<0.08 (1989Po19).
1067.2 [§] 4	(10+)	
1220.5 [#] 4	(11-)	
1412.5 [§] 4	(12+)	
1569.0 [#] 5	(13-)	

[†] From least-squares fit to E γ data.

[‡] From 1989Po19; based on ²²⁸Th α -decay measurements (for levels with J $\leq$ 4), level decay properties and band structure.

[§] (A): The g.s. band.

[#] (B): Octupole band.

²²⁶Ra(⁵⁸Ni,⁶⁰Ni) γ 1989Po19 (continued)

 $\gamma(^{224}\text{Ra})$

E(level)	E γ	I $\gamma^{\dagger}$	Mult.	α	Comments
84.4	84.4 1	100	E2	21.2 4	Mult.: from Adopted Gammas.
215.9	131.5 1	22.3 3			I γ : I γ (131.5)/I γ (215.9)=0.287 4 is in disagreement with 0.514 6 from Adopted Gammas.
	215.9 1	77.7 3			I γ : see comment for 131.5 γ .
250.7	166.3 1	100	E2	1.167	Mult.: from $\gamma(\theta)$ and RUL. A ₂ =+0.55 6; A ₄ =-0.48 18.
290.3	74.4 1	2.6 6			
	205.9 1	97.4 6	E1	0.0842	$\alpha(\text{K})\text{exp}<0.19$; $\alpha(\text{L})\text{exp}<0.05$; $\alpha(\text{M})\text{exp}<0.014$. Mult.: from $\alpha(\text{K})\text{exp}$, $\alpha(\text{L})\text{exp}$, $\alpha(\text{M})\text{exp}$ estimates (1989Po19).
433.00	142.7 1	35 12			
	182.3 1	65 12			
478.9	228.2 1	100			
640.7	(161.8 2)	<30			
	207.7 2	85 15			
754.6	113.9 $\ddagger$	<10			
	275.7 2	95 5			
906.0	151.4 $\ddagger$	<15			
	265.3 2	93 7			
1067.2	312.6 2	100			
1220.5	314.5 2	100			
1412.5	345.3 2	100			
1569.0	348.5 $\ddagger$ 2				

 $\dagger$ Absolute photon branching ratio.

 $\ddagger$ Placement of transition in the level scheme is uncertain.

²³²Th(¹³⁶Xe,X γ) 1999Co02

1999Co02: E=833 MeV. Measured E γ , I γ , $\gamma\gamma$ -coin, $\gamma(\theta)$ using GAMMASPHERE array with 73 HPGe detectors at LBNL accelerator facility. Target=36 mg/cm². Deduced levels, J π , bands.

²²⁴Ra Levels

E(level) $\dagger$	J π	E(level) $\dagger$	J π	E(level) $\dagger$	J π
0.0 $\ddagger$	0+	1069.3 $\ddagger$ 4	10+	3060.1 $\ddagger$ 12	(20+)
84.372 $\ddagger$ 3	2+	1221.3 $\S$ 7	11-	3294.2 $\S$ 13	(21-)
215.985 $\S$ 4	1-	1414.6 $\ddagger$ 7	12+	3527.2 $\ddagger$ 13	(22+)
250.9 $\ddagger$ 2	4+	1578.0 $\S$ 9	(13-)	3774.0 $\S$ 14	(23-)
290.4 $\S$ 2	3-	1788.4 $\ddagger$ 8	(14+)	4012.3 $\ddagger$ 14	(24+)
432.9 $\S$ 4	5-	1969.1 $\S$ 10	(15-)	4270.8 $\S$ 15	(25-)
479.5 $\ddagger$ 3	6+	2188.6 $\ddagger$ 10	(16+)	4513.1 $\ddagger$ 15	(26+)
640.6 $\S$ 4	7-	2388.5 $\S$ 11	(17-)	4782.4 $\S$ 16	(27-)
755.6 $\ddagger$ 4	8+	2613.0 $\ddagger$ 11	(18+)	5031.3 $\S$ 16	(28+)
906.5 $\S$ 4	9-	2831.4 $\S$ 12	(19-)		

 $\dagger$ From least-squares fit to E γ data.

 $\ddagger$ (A): g.s. band.

 $\S$ (B): Octupole band.

 $\gamma(^{224}\text{Ra})$

E $\gamma^{\dagger}$	E(level)	I γ	Mult.	$\alpha^{\S}$	Comments
(74.4)	290.4				E γ : from Adopted Gammas.
84.373 $\ddagger$ 3	84.372		E2 $\ddagger$	21.2	
131.613 $\ddagger$ 4	215.985		E1 $\ddagger$	0.247	
142.6 5	432.9	39 11	[E2]	2.15 5	I γ : I γ (142.6)/I γ (182.2)=1.39 39 is in disagreement with 0.56 13 from Adopted Gammas.

Continued on next page (footnotes at end of table)

$^{232}\text{Th}(^{136}\text{Xe},\text{X}\gamma)$ 1999Co02 (continued) $\gamma(^{224}\text{Ra})$ (continued)

$E\gamma^\dagger$	E(level)	I_γ	Mult.	$\alpha^\S$	Comments
151.2 5	906.5				
160.5 5	640.6	15 4	[E1]	0.1530 25	
166.5 2	250.9	100 5	(E2) ‡	1.162	
182.2 5	432.9	28 8	[E1]	0.1127 18	I_γ : see comment for 142.6 γ .
206.0 2	290.4	54 12	E1 ‡	0.0841	
207.9 5	640.6	113 21	[E2]	0.509 9	
215.983 ‡ 5	215.985		E1 ‡	0.0752	
228.6 2	479.5	146 28	[E2]	0.365	
265.9 2	906.5	94 26	[E2]	0.221	
276.1 2	755.6	156 19	[E2]	0.197	
313.7 2	1069.3	151 15	[E2]	0.1331	
314.8 5	1221.3	98 22	[E2]	0.1317	
345.3 5	1414.6	121 4	[E2]	0.1008	
356.7 5	1578.0	83 15	[E2]	0.0920	
373.8 5	1788.4	87 4	[E2]	0.0809	
391.1 5	1969.1	55 14	[E2]	0.0717	
400.2 5	2188.6	77 8	[E2]	0.0674	
419.4 5	2388.5	37 9	[E2]	0.0597	
424.4 5	2613.0	57 8	[E2]	0.0579	
442.9 5	2831.4	29 9	[E2]	0.0520	
447.1 5	3060.1	31 6	[E2]	0.0508	
462.8 5	3294.2	24 7	[E2]	0.0466	
467.1 5	3527.2	23 5	[E2]	0.0456	
479.8 5	3774.0	21 7	[E2]	0.0427	
485.1 5	4012.3	17 5	[E2]	0.0416	
496.8 5	4270.8	7 3	[E2]	0.0393	
500.8 5	4513.1	4 2	[E2]	0.0385	
511.6 $^\#$ 5	4782.4?				
518.2 $^\#$ 5	5031.3?				

† Uncertainties of 0.2 and 0.5 keV are assigned by evaluators based on a general statement in caption of Figure 7 in 1999Co02.

‡ From Adopted Gammas.

§ Theoretical values from BrIcc code with implicit uncertainty of 1.4%, when not stated.

$^\#$ Placement of transition in the level scheme is uncertain.

Adopted Levels, Gammas

Q(β⁻)=241 11; S(n)=5663 8; S(p)=4289 5; Q(α)=6326.9 7 2012Wa38.

S(2n)=12529 6, S(2p)=10693 22 (2012Wa38).

²²⁴Ac identified and produced by 1948Gh01 in Th(d,X) at 80 MeV, with an estimated half-life of ≈2.5 h. Later studies of ²²⁴Ac decay: 1951Me10, 1958Hi78, 1968LE17, 1976MiZR, 1987Mi10, 1992LI31.

2008Sh18: theoretical calculations of level energies, Jπ.

2004Sh25: theoretical calculations of parity doublet splitting, configuration assignments.

All data are from ²²⁸Pa α decay.

In this evaluation, the level scheme is essentially that proposed by 1994Ah03 with some modifications suggested in 2004Sh25. The band structures are taken essentially from 2004Sh25, but considered tentative at this stage. As pointed out in 1994Ah03 and 2004Sh25, the level scheme of ²²⁴Ac is very complex and many additional levels are expected. Thus the level scheme presented here is considered as incomplete. Information about confirmed multipolarities, mixing ratios and other spectroscopic details is lacking. Further experiments on the decay of ²²⁸Pa, and involving nuclear reactions are needed to confirm and elucidate the structure of this nucleus.

2004Sh25 suggest five other bands, not listed here, for which only one or two levels each are known.

²²⁴Ac Levels

Cross Reference (XREF) Flags

A ²²⁸Pa α Decay (22 h)

E(level)	Jπ [†]	XREF	T _{1/2}	Comments
0.0 [‡]	(0-)	A	2.78 h 16	%ε=90.9 +14-20; %α=9.1 +20-14 (1951Me10). %ε,%α: from ε/α=10 2 (1951Me10). %β⁻: No β⁻ branch observed; %β⁻<1.6 from log ft>5.9 expected for a 0- to 0+ ²²⁴Th g.s. β⁻ transition. Jπ: log ft=5.9 (1976MiZR) to 1- level in ²²⁴Ra suggest probable allowed β⁻ transition; large hindrance factors (or non-observation) of α transitions to levels in ²²⁰Fr which are connected by γ transitions implying change of one or two units of spin between these levels; possible Kπ=0- bandhead of an octupole band. See also several arguments given in previous NDS evaluation (1986Ma45; same arguments in 1997Ar05) where Jπ=0- was assigned. Based on theoretical considerations 1988Sh01 deduce Jπ=0- or 3- for 3/2 proton and 3/2 neutron coupling with octupole deformation, and 2+ or (2-) with quadrupole deformation only. T_{1/2}: weighted average of 2.55 h 28 (1987Mi10) and 2.9 h 2 (1951Me10; their previous value ≈2.5 h reported in 1948Gh01).
17.60 [‡] 15	(1-)	A		
23.40 11	(2-)	A		
29.83 [§] 9	(1+)	A		Jπ: E1 γ to (0-).
34.2? 8		A		
37.17 [‡] 9	(2-)	A		
44.2? 3		A		
45.8? 4	(-)	A		
47.4? 4		A		
49.08 13	(3-)	A		
52.20 [§] 11	(2+)	A		
64.47 14	(3+)	A		
65.2? 6		A		
75.9? 6		A		
78.51 [‡] 12	(3-)	A		A 48.6γ is omitted here due to unlikely M2 multipolarity implied from assigned Jπ values.
80.49 [§] 10	(3+)	A		
84.1? 4		A		
90.56 13	(+)	A		
92.6? 4		A		
100.44? 23		A		
103.31 13	(4+)	A		
105.1? 6		A		
109.33 17	(4-)	A		
110.53 15	(+)	A		
116.46 [‡] 13	(4-)	A		
130.30 [§] 11	(4+)	A		
133.4? 4		A		
142.5 3	(5+)	A		
146.6 4		A		E(level): this level may be the same as 142.4 level, but the energy matching is poor.
159.3 4		A		

Continued on next page (footnotes at end of table)

Adopted Levels, Gammas (continued)
²²⁴Ac Levels (continued)

E(level)	Jπ [†]	XREF	E(level)	Jπ [†]	XREF	E(level)	Jπ [†]	XREF
169.2		A	252.68 [§] 17	(6+)	A	360.25 [@] 11	(3+)	A
176.72 [§] 14	(5+)	A	283.48 13	(3-)	A	380.80 16	(+)	A
183.40 [‡] 13	(5-)	A	300.2		A	395.84 [#] 19	(4-)	A
212.2		A	317.2 5		A	402.92 [@] 16	(4+)	A
219.7 4		A	333.04 12	(3+)	A	448.08 [#] 20	(5-)	A
236.5 [‡] 4	(6-)	A	353.89 [#] 11	(3-)	A	452.1 [@] 4	(5+)	A

[†] Assignments are mainly from 2004Sh25 based on interpretation of parity-doublets (reflection asymmetric) structures in ²²⁴Ac. Some of the assignments are supported by transition multiplicities from conversion electron data for high energy transitions and E1 assignments from I(K-x ray)/I_γ ratios. For the Kπ=0 and 1 bands, two scenarios are presented in their figures 4 and 5 of 2004Sh25. See detailed discussion by the authors. Assignments given here are arbitrarily taken from figure 4 in 2004Sh25. Kπ=3+ and 3- parity- doublet bands are also supported by 1994Ah03 with minor differences in level assignments at high energy.

[‡] (A): Band based on (0-). Mixture of Kπ=0- and Kπ=1- bands from π3/2⊗v3/2 and π5/2⊗v3/2 configurations (2004Sh25).

[§] (B): Band based on 1+. Mixture of Kπ=0+ and Kπ=1+ bands from π3/2⊗v3/2 and π5/2⊗v3/2 configurations (2004Sh25).

[#] (C): Band based on (3-). Mixture of Kπ=2- and Kπ=3- bands from π5/2⊗v1/2 configuration (2004Sh25).

[@] (D): Band based on (3+). Mixture of Kπ=2+ and Kπ=3+ bands from π5/2⊗v1/2 configuration (2004Sh25).

^γ(²²⁴Ac)

E(level)	E _γ	I _γ	Mult.	δ	α	Comments
29.83	29.8 1	100	E1		2.83 5	
37.17	37.2 [†] 1	100	[E2]		1200 24	
52.20	(22)					
	28.8 1	42 7	E1		3.10 6	
	34.6 1	100 11	E1		1.91	A 52.1γ is omitted here due to unlikely M2 multipolarity implied from assigned J _π values.
64.47	41.1 1	100				Mult.: (M1) listed in 1993Sh07, but no argument given.
78.51	26.3 1	100 14	E1		3.93 7	
80.49	28.3 1	≈4.2				
	43.3 1	100 13	E1		1.054 17	
90.56	67.2 1	100	(E1)		0.327	
103.31	54.2 1	100	(E1)		0.580	
109.33	60.3 [‡] 2	100 [‡]				
110.53	61.5 1	100				
116.46	36.0 1	100 15	(E1)		1.72 3	
	52.0 2	87 15				
130.30	49.8 1	20 4				
	51.8 1	100 11	(E1)		0.654	
	78.6 [†] 3	8 4				
	81.2 1	89 15				
146.6	62.5 [†] 1	100 17				
159.3	66.3 [†] 3	≈50				
	75.5 [†] 3	≈100				
176.72	46.5 2	≈30				
	60.3 [‡] 2	<125 [‡]	(E1)		0.436 8	
	67.4 2	100 15				
	73.4 2	21 9				
183.40	53.1 1	100 15	(E1)		0.612	
	74.1 3	38 10				
	80.1 1	85 15	(E1)		0.205	
219.7	77.2 2	≈100				
	86.3 [†] 2	≈67				
236.5	59.8 3	100				
252.68	69.3 2	100 17	(E1)		0.301	
	76.0 2	43 12				
	110.3 4	86 17				
	122.5 5	≈23				
283.48	140.8 4	20 5				
	193.0 2	11 4				
	237.7 [†] 3	26 5	(M1)		1.473	
	246.2 2	36 8				

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Adopted Levels, Gammas (continued) $\gamma(^{224}\text{Ac})$ (continued)

E(level)	E γ	I γ	Mult.	δ	α
283.48	260.1 1	100 11			
317.2	280.0 5	$\approx$ 100			
	283.0 [†] 5	$\approx$ 100			
333.04	202.7 1	88 13	M1 (+E2)	<0.6	2.07 23
	222.7 2	$\approx$ 16			
	232.6 [†] 2	59 9			
	242.6 2	47 8	(M1)		1.392
	252.6 2	63 13	(M1)		1.244
	267.8 [†] 5	33 11			
	280.8 4	$\approx$ 31			
	283.4 4	$\approx$ 47			
	285.8 [†] 5	$\approx$ 16			
	288.9 [†] 5	$\approx$ 47			
	295.5 4	$\approx$ 31			
	303.2 2	100 18			
353.89	237.5 2	18.9 23	(M1)		1.476
	244.7 5	9.6 23	(M1)		1.359
	248.8 [†] 5	7.7 27			
	269.1 [†] 4	13 3			
	278.0 [†] 5	$\approx$ 9			
	290.0 5	$\approx$ 23			
	309.6 [†] 3	$\approx$ 23			
	316.8 1	100 14	(M1)		0.666
	330.4 [‡] 1	<50 [‡]	(M1)		0.593
360.25	230.0 1	45 8	M1 (+E2)	<0.7	1.41 21
	268.7 [†] 5	9 2			
	279.5 4	9.3 23			
	308.0 1	100 10	M1 (+E2)	<0.4	0.68 4
	312.8 [†] 4	$\approx$ 5.0			
	330.4 [‡] 1	<28 [‡]			
380.80	250.5 2	59 12	(M1)		1.273
	300.3 3	$\approx$ 17			
	328.6 2	100 14			
	351.0 4	$\approx$ 17			
395.84	212.5 5	$\approx$ 42			
	253.4 5	$\approx$ 67			
	317.2 2	$\approx$ 580			
	347.0 3	100 42			
402.92	226.3 2	$\approx$ 17			
	299.5 3	$\approx$ 33			
	312.3 3	$\approx$ 17			
	322.4 2	100 13	M1 (+E2)	<0.7	0.55 9
448.08	195.5 2	100 30			
	317.8 3	$\approx$ 300			
	344.3 4	$\approx$ 100			
452.1	335.6 3	100			

[†] Placement of transition in the level scheme is uncertain.[‡] Multiply placed; undivided intensity given.

²²⁸Pa α Decay (22 h) 1994Ah03,1993Sh07,1958Hi78

Parent ²²⁸Pa: E=0; J π =3+; T_{1/2}=22 h 1; Q(g.s.)=6264.5 15; % α decay=2.0 2.

²²⁸Pa-J, T_{1/2}: From ²²⁸Pa Adopted Levels in ENSDF database (half-life taken from 1951Me10). 1989He07 discuss $\pi/2[633]@v1/2[631]$ configuration for this state and conclude that it is not probable due to energy mismatch even though the measured magnetic moment is in agreement with theoretical value for this configuration, and that $\pi 5/2@v1/2$ octupole deformed configuration is more likely.

²²⁸Pa-Q(α): From 2012Wa38.

²²⁸Pa-% α decay: From measured I α /(I α +I ϵ)=0.020 2 (1994Ah03). Other: I ϵ /I α =53 5 (1951Me10).

1994Ah03: ²²⁸Pa produced in ²³²Th(p,5n) at 45 MeV followed by chemical separation. Measured E α , I α , E γ , I γ , ce, $\alpha\gamma$ -, and α (x ray)-coin, $\alpha\gamma$ -coin, α (ce)-coin using Ge, LEPS and SI(Li) detectors. Deduced levels, J, π , conversion coefficients, multipolarity, α hindrance factors, octupole deformation.

1993Sh07 (also 1991Sh14,2004Sh25,2008Sh18): ²²⁸Pa produced in ²³²Th(p,5n) at 200 MeV followed by chemical separation. Measured E α , I α , E γ , I γ , ce, $\alpha\gamma$ -, and α (ce)-coin using Ge and SI(Li) detectors. Deduced levels, J, π , multipolarity, α hindrance factors, octupole deformation and reflection asymmetry. 2004Sh25 (also 2008Sh18) discuss differences in the level schemes, bands and interpretation presented in 1993Sh07 and those in 1994Ah03.

1958Hi78: ²²⁸Pa formed in ²³⁰Th(d,4n) reaction; measured E α , I α , E γ . Deduced levels, hindrance factors.

Levels in ²²⁴Ac were first proposed in 1958Hi78 from α decay of ²²⁸Pa to levels in ²²⁴Ac. 1993Sh07 first observed γ rays in singles and coincidence modes, and proposed a level scheme incorporating 34 γ rays out of a total of 45 γ rays observed. The authors interpreted level scheme in terms of parity-doublet (or reflection asymmetric) structures composed of K π =0-, 0+, 3+, 3-, (1+) and (1-) bands. 1994Ah03 investigated in detail γ , ce and α spectra in singles and coincidence modes using a much stronger source than in 1993Sh07, and reported 86 γ rays with 73 γ rays incorporated in a level scheme based essentially on coincidence data. For most levels the authors assigned only the parities based on gamma-ray multiplicities, but did not agree with K π =0- and 0+ parity-doublet bands proposed by 1993Sh07. Although energies and relative intensities of most γ rays reported in 1993Sh07 agreed with those in 1994Ah03, yet there were several differences in γ -ray placements. 2004Sh25 (also 2008Sh18) have further discussed these differences and proposed revised level schemes and band structures.

In this evaluation, the level scheme is essentially that proposed by 1994Ah03 with some modifications suggested in 2004Sh25. The band structures are taken essentially from 2004Sh25, but considered tentative at this stage. As pointed out in 1994Ah03 and 2004Sh25, the level scheme of ²²⁴Ac is very complex and many additional levels are expected. Thus the level scheme presented here is considered as incomplete. Information about confirmed multiplicities, mixing ratios and other spectroscopic details is lacking. Further experiments on the decay of ²²⁸Pa and involving nuclear reactions are needed to confirm and elucidate the structure of this nucleus.

²²⁴Ac Levels

Levels at 66.0, 89.3, (117.2), 132.9, 184.2, 397.5, (453.2) keV reported by 1993Sh07 have not been included here.

The γ rays from these levels have been reassigned to other levels in 1994Ah03 from their detailed $\alpha\gamma$ and $\alpha\gamma\gamma$ coincidence data. Some of the levels are close in energy to the ones given here but transitions from them are different.

Band assignments are proposed in 2004Sh25. For the K π =0 and 1 bands, two scenarios are presented in their figures 4 and 5. See detailed discussion by the authors. Assignments given here are arbitrarily taken from figure 4 in 2004Sh25. K π =3+ and 3- parity-doublet bands are also supported by 1994Ah03 with minor differences in level assignments at high energy. 2004Sh25 suggest 5 other bands, not listed here, for which only one or two levels each are known.

E(level) [†]	J π [‡]	T _{1/2}	Comments
0.0#	0-	2.78 h 16	T _{1/2} : from Adopted Levels.
17.60# 15	(1-)		
23.40 11	(2-)		
29.83@ 9	(1+)		
34.2? 8			
37.17# 9	(2-)		
44.2? 3			
45.8? 4	(-)		
47.4? 4			
49.08 13	(3-)		
52.20@ 11	(2+)		
64.47 14	(3+)		
65.2? 6			E(level): a level at 66.0 was suggested by 1993Sh07 with 28.8, 49 and 66.0 deexciting γ rays. These γ rays were placed elsewhere by 1994Ah03.
75.9? 6			
78.51# 12	(3-)		
80.49@ 10	(3+)		
84.1? 4			
90.56 13	(+)		J π : parity assigned in 1994Ah03.
92.6? 4			
100.44? 23			
103.31 13	(4+)		

Continued on next page (footnotes at end of table)

²²⁸Pa α Decay (22 h) 1994Ah03,1993Sh07,1958Hi78 (continued)

²²⁴Ac Levels (continued)

E(level) [†]	Jπ [‡]	Comments
105.1? 6		
109.33 17	(4-)	
110.53 15	(+)	Jπ: parity from 1994Ah03.
116.46# 13	(4-)	
130.30@ 11	(4+)	
133.4? 4		
142.5 3	(5+)	
146.6§ 4		E(level): this level may be the same as 142.4 level, but the energy matching is poor.
159.3§ 4		
169§ 2		
176.72@ 14	(5+)	
183.40# 13	(5-)	
212§ 2		
219.7 4		
236.5# 4	(6-)	
252.68@ 17	(6+)	
283.48 13	(3-)	
300§ 2		
317.2 5		
333.04 12	(3+)	
353.89& 11	(3-)	
360.25 ^a 11	(3+)	
380.80 16	(+)	
395.84& 19	(4-)	
402.92 ^a 16	(4+)	
448.08& 20	(5-)	
452.1 ^a 4	(5+)	

[†] From least squares fit to E_γ data, unless otherwise noted.

[‡] Jπ and band assignments are generally from 2004Sh25 (also 1993Sh07), Kπ=3+ and 3- bands are supported also by 1994Ah03. For low-lying levels (below 254 keV), 1994Ah03 assign only parities based on γ-ray multiplicities. See also Adopted Levels.

§ From Eα.

(A): Band based on 0-. Mixture of Kπ=0- and Kπ=1- bands from π3/2⊗v3/2 and π5/2⊗v3/2 configurations (2004Sh25).

@ (B): Band based on 1+. Mixture of Kπ=0+ and Kπ=1+ bands from π3/2⊗v3/2 and π5/2⊗v3/2 configurations (2004Sh25).

& (C): Band based on (3-). Mixture of Kπ=2- and Kπ=3- bands from π5/2⊗v1/2 configuration (2004Sh25).

^a (D): Band based on (3+). Mixture of Kπ=2+ and Kπ=3+ bands from π5/2⊗v1/2 configuration (2004Sh25).

α radiations

Eα [†]	E(level)	Iα ^{‡a}	HF [§]	Eα [†]	E(level)	Iα ^{‡a}	HF [§]
5711& 2	448.08	1.00& 12		5981 2	176.72	2.6 2	460 60
5711& 2	452.1	&		5988 2	169	1.0 1	1.3×10 ³ 2
5758 2	402.92	3.00 22	31 5	5997 2	159.3	≈0.3	≈4824
5765 2	395.84	2.6 2	39 6	6010 2	146.6	0.8 1	2.2×10 ³ 4
5780 2	380.80	1.30 14	9 2	6027 2	130.30	8.5 4	240 30
5800 2	360.25	10.7 6	14 2	6040 2	116.46	2.2 3	1.1×10 ³ 2
5806 2	353.89	6.9 4	24 3	6047@ 3	109.33	@	
5827 2	333.04	5.8 7	36 6	6047@ 3	110.53	≈0.3@	
5844 2	317.2	≈0.4	≈625	6052 3	103.31	≈0.7	≈3816
5859 2	300	≈0.3	≈1013	6065 2	90.56	1.0 2	3.1×10 ³ 7
5875 2	283.48	1.30 11	280 40	6076# 2	78.51	#	
5905 2	252.68	1.0 1	520 80	6076# 2	80.49	19.5# 7	
5921 2	236.5	0.8 1	800 100	6089 2	64.47	2.2 3	1.9×10 ³ 3
5940 2	219.7	0.5 1	1.5×10 ³ 4	6104 2	52.20	11.3 6	410 50
5946 2	212	0.6 1	1.4×10 ³ 3	6117 2	37.17	9.9 5	550 70
5974 2	183.40	2.5 2	450 60	6126 3	29.83	≈1.0	≈5879

[†] From 1994Ah03. Values from 1993Sh03 and 1958Hi78 are given under document records in ENSDF data file. Uncertainties in 1958Hi78 are stated by 1994Ah03 as 0.5 keV, but systematic uncertainties are 3-4 keV. A 6142α group in 1958Hi78 was later assigned by 1964Mc21 to ²²⁴Ac α decay.

[‡] From 1994Ah03, renormalized intensities in α-spectrum of 1958Hi78.

Footnotes continued on next page

^{228}Pa α Decay (22 h) 1994Ah03,1993Sh07,1958Hi78 (continued) **α radiations (continued)**

§ $r_0(^{224}\text{Ac})=1.532$ fm 4; deduced from interpolation of $r_0=1.5383$ fm 8 for ^{222}Ra ; 1.524 fm 9 for ^{224}Th , 1.5332 fm 8 for ^{224}Ra , 1.531 fm 5 for ^{226}Th ; taken from 1998Ak04 for α -daughter nuclides.

Doublet feeding 78 and 80 levels; total $I_\alpha=19.5$ 7.

@ Doublet feeding 109 and 110 levels; total $I_\alpha=0.3$.

& Doublet feeding 448 and 451 levels; total $I_\alpha=1.00$ 12.

a For α intensity per 100 decays, multiply by 0.020 2.

 $\gamma(^{224}\text{Ac})$

Measured $I(K\alpha_1 \text{ x ray})=6.7$ 7, $I(K\alpha_2 \text{ x ray})=4.0$ 4, $I(K \text{ x ray})=13.6$ 15 (1994Ah03).

Measured $I(K \text{ x ray})=12.5$ 11, $I(L \text{ x ray})=55$ 10 (1993Sh07).

Experimental K-conversion coefficients are from 1994Ah03.

I_γ normalization: 1994Ah03 and 1993Sh07 give photon intensities per 100 α decays.

$E\gamma^\dagger$	E(level)	$I_\gamma^{\ddagger b}$	Mult.#	δ	α	Comments
(22)	52.20		[M1]		291	$E\gamma$: γ required by the $\alpha\gamma$ results of 1993Sh07; γ not in 1994Ah03.
$\times 23.3^\ddagger$ 2		0.12 ‡ 5				Placed from an 89.3 level, and mult=(E1) (1993Sh07).
$\times 24.9^\ddagger$ 2		0.10 ‡ 5				
26.3 1	78.51	0.36 5	E1&		3.93 7	
28.3 1	80.49	=0.1	[M1]		138.9 25	
28.8 1	52.20	0.76 12	E1&		3.10 6	$E\gamma$: 1993Sh07 placed 28.8 γ from a 66.0 and 80.5 levels. 1994Ah03 reported two γ rays at 28.3 and 28.8, former from 80.4 level, and the latter from 52.1 level based on coincidence data.
29.8 1	29.83	2.8 3	E1&		2.83 5	
34.6 1	52.20	1.8 2	E1&		1.91	
36.0 1	116.46	0.52 8	(E1)		1.72 3	
37.2 ^c 1	37.17	=0.2	[E2]		1200 24	γ placed from 37.2 and 89.3 levels (1993Sh07).
41.1 1	64.47	0.54 9	[E1]		1.211 19	$E\gamma$: 1993Sh07 placed 41.1 γ from 78.4 level.
						Mult.: (M1) in 1993Sh07, but no argument given.
43.3 1	80.49	2.4 3	E1&		1.054 17	
46.5 2	176.72	=0.2	[M1]		32.1 6	
48.6 $^\S c$ 1	78.51	0.80 13	[M2]		1320 23	2004Sh25 suggest that this γ may belong to ^{220}Fr from ^{224}Ac α decay, yet $\alpha\gamma$ coincidence data in figure 3 of 1994Ah03 clearly show this γ ray, and this γ is also listed in $\alpha\gamma\gamma$ coin data in table 4 of 1994Ah03. Its implied M2 multipolarity is, however, problematic, for $J\pi=3-$ for 78 level and $1+$ for 29.8 level
49.8 1	130.30	0.27 5	[M1]		26.3	
51.8 1	130.30	1.35 15	(E1)		0.654	
52.0 2	116.46	0.45 8	[E1]		0.647 12	
52.1 ^c 2	52.20	0.30 6	[M2]		963 22	$E\gamma$: 2004Sh25 argue against the placement or existence of this γ ray in 1994Ah03, and suggest that its appearance in $\alpha\gamma$ coincidence data of 1994Ah03 may be due to $\alpha+ce$ sum line. Its implied M2 multipolarity is also problematic for $J\pi=2+$ for 52 level and $0-$ for g.s.
53.1 1	183.40	0.40 6	(E1)		0.612	$E\gamma$: 1993Sh07 placed 53.1 γ from a 90.3 levels.
54.2 1	103.31	1.2 2	(E1)		0.580	$E\gamma$: 1993Sh07 placed 54.2 γ from a 184.2 level.
59.8 3	236.5	0.14 5	[E1]		0.446 9	
60.3 ^{ad} 2	109.33	0.84 ^d 13	[M1]		15.0 3	
	176.72	0.84 ^d 13	(E1)		0.436 8	
61.5 1	110.53	0.30 5				$E\gamma$: 1993Sh07 placed 61.4 γ from 78.4 level.
62.5 ^c 1	146.6	0.36 6				
66.3 ^c 3	159.3	=0.05				
67.2 1	90.56	1.7 3	(E1)		0.327	
67.4 2	176.72	0.67 10	[E1]		0.324 6	
69.3 2	252.68	0.35 6	(E1)		0.301	
73.4 2	176.72	0.14 6	[M1]		8.43 14	$E\gamma$: 1993Sh07 placed 73.3 γ from a 90.3 level.
74.1 3	183.40	0.15 4	[M1]		8.20 15	
75.5 $^\S c$ 3	159.3	=0.10				
76.0 § 2	252.68	0.15 4	[M1]		7.62 13	
77.2 § 2	219.7	=0.3				

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²²⁸Pa α Decay (22 h) 1994Ah03,1993Sh07,1958Hi78 (continued)

 $\gamma(^{224}\text{Ac})$ (continued)

$E_{\gamma}^{\dagger}$	E(level)	$I_{\gamma}^{\dagger b}$	Mult.#	δ	α	Comments
78.6 ^c 3	130.30	0.11 5	[E2]		32.2 8	E γ : γ from 1993Sh07 only.
80.1 1	183.40	0.34 6	(E1)		0.205	E γ : 1993Sh07 placed 79.9 γ from a tentative 117.2 level.
81.2 1	130.30	1.2 2	[E1]		0.198	E γ : 1993Sh07 placed 81.1 γ from a 132.9 level.
86.3 ^{§c} 2	219.7	$\approx$ 0.2				
110.3 [§] 4	252.68	0.30 6	[M1]		12.82 22	
122.5 [§] 5	252.68	$\approx$ 0.08	[E2]		4.34 10	
140.8 [§] 4	283.48	0.15 4	[M2]		36.9 7	
193.0 [§] 2	283.48	0.08 3				
195.5 [§] 2	448.08	0.10 3	[E1]		0.0974	
202.7 1	333.04	0.56 8	M1 (+E2)	<0.6	2.07 23	$\alpha(K)\text{exp}=1.8$ 4.
212.5 [§] 5	395.84	$\approx$ 0.05				
222.7 [§] 2	333.04	$\approx$ 0.1				
226.3 [§] 2	402.92	$\approx$ 0.1	[M1]		1.689	
230.0 1	360.25	1.8 3	M1 (+E2)@	<0.7	1.41 21	$\alpha(K)\text{exp}=1.3$ 3.
232.6 ^c 2	333.04	0.38 6				
237.5 2	353.89	0.40 5	(M1)		1.476	$\alpha(K)\text{exp}(237.5\gamma+237.7\gamma)=1.1$ 3 (1994Ah03).
237.7 ^c 3	283.48	0.20 4	(M1)		1.473	$\alpha(K)\text{exp}(237.5\gamma+237.7\gamma)=1.1$ 3 (1994Ah03).
242.6 2	333.04	0.30 5	(M1)		1.392	$\alpha(K)\text{exp}(242.6\gamma+244.7\gamma)=1.2$ 4.
244.7 5	353.89	0.21 5	(M1)		1.359	$\alpha(K)\text{exp}(242.6\gamma+244.7\gamma)=1.2$ 3 (1994Ah03).
246.2 [§] 2	283.48	0.27 6	[M1]		1.336	
248.8 ^c 5	353.89	0.17 6				
250.5 2	380.80	0.34 7	(M1)		1.273	$\alpha(K)\text{exp}(250.5\gamma+252.6\gamma)=0.95$ 26 (1994Ah03).
252.6 2	333.04	0.40 8	(M1)		1.244	$\alpha(K)\text{exp}(250.5\gamma+252.6\gamma)=0.95$ 26 (1994Ah03).
253.4 [§] 5	395.84	$\approx$ 0.08				
260.1 1	283.48	0.76 8	[M1]		1.147	
267.8 ^c 5	333.04	0.21 7				
268.7 ^c 5	360.25	0.36 8				
269.1 ^c 4	353.89	0.29 7				
278.0 ^c 5	353.89	$\approx$ 0.2				
279.5 4	360.25	0.37 9	[M1]		0.940	
280.0 ^a 5	317.2	$\approx$ 0.2				
280.8 ^a 4	333.04	$\approx$ 0.2				
283.0 ^c 5	317.2	$\approx$ 0.2				
283.4 4	333.04	$\approx$ 0.3				
285.8 ^{§c} 5	333.04	$\approx$ 0.1				
288.9 ^{§c} 5	333.04	$\approx$ 0.3				
290.0 5	353.89	$\approx$ 0.5				
295.5 [§] 4	333.04	$\approx$ 0.2				
299.5 [§] 3	402.92	$\approx$ 0.2	[M1]		0.777	
300.3 [§] 3	380.80	$\approx$ 0.1				
303.2 2	333.04	0.64 11	[E2]		0.1550	
308.0 1	360.25	4.0 4	M1 (+E2)@	<0.4	0.68 4	$\alpha(K)\text{exp}=0.63$ 12.
309.6 ^{§c} 3	353.89	$\approx$ 0.5				
312.3 [§] 3	402.92	$\approx$ 0.1				
312.8 ^{§c} 4	360.25	$\approx$ 0.2				
316.8 1	353.89	2.2 3	(M1)@		0.666	$\alpha(K)\text{exp}(316.8\gamma+317.2\gamma+317.8\gamma)=0.50$ 11 (1994Ah03).
317.2 2	395.84	$\approx$ 0.7	[M1]		0.663	$\alpha(K)\text{exp}(316.8\gamma+317.2\gamma+317.8\gamma)=0.50$ 11 (1994Ah03).
317.8 [§] 3	448.08	$\approx$ 0.3	[E1]		0.0318	$\alpha(K)\text{exp}(316.8\gamma+317.2\gamma+317.8\gamma)=0.50$ 11 (1994Ah03).
322.4 [§] 2	402.92	0.60 8	M1 (+E2)	<0.7	0.55 9	$\alpha(K)\text{exp}=0.45$ 10.
328.6 [§] 2	380.80	0.58 8				
330.4 ^d 1	353.89	1.1 ^d 1	(M1)		0.593	E γ ,Mult.: 2004Sh25 suggest placement of 330.4 γ from 354 level based on $\alpha\gamma$ coincidence displayed in top panel of figure 7 in 1994Ah03. This placement is consistent with M1 multipolarity from experimental K-conversion coefficient in 1994Ah03. Evaluators suggest double placement of this γ ray based on $\alpha\gamma$ coincidence with α groups to both the 354 and 360 levels (see $\alpha\gamma$ coin figure 7 in 1994Ah03).
	360.25	1.1 ^d 1	[E2]		0.1202	$\alpha(K)\text{exp}=0.57$ 12.
335.6 [§] 3	452.1	0.16 4	[E1]		0.0282	
344.3 [§] 4	448.08	$\approx$ 0.1	[E1]		0.0267	

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^{228}Pa α Decay (22 h) 1994Ah03,1993Sh07,1958Hi78 (continued) $\gamma(^{224}\text{Ac})$ (continued)

$E\gamma^{\dagger}$	E(level)	$I\gamma^{\ddagger b}$	Mult.#	α
347.0 § 3	395.84	0.12 5	[M1]	0.519
351.0 § 4	380.80	=0.1		

† From 1994Ah03, unless otherwise noted. $I\gamma$ and $I(\text{ce(K)})$ are given per 100 α decays.

‡ From 1993Sh07.

§ γ not reported in 1993Sh07.

The E1 assignments are based on intensity considerations, the M1 assignments are based on experimental results as indicated. In addition, 1994Ah03 have deduced, from a comparison of (L x ray)(α) and (23< $E\gamma$ <87)(α) spectra that the major transitions deexciting the 52, 80, 130, 177 and 183 levels have E1 multipolarity.

@ M1 assignment confirmed by 1993Sh07 from measured $I(\text{K x ray})/I\gamma$ ratio.

& M1, E2 or higher multipolarities are rejected since these imply unreasonably high transition intensities.

a 1993Sh07 placed a 281.0 γ from 397.5 level. 1994Ah03 reported two γ rays at 280.0 and 280.8, former from 317 level, and the latter from 333 level based on coincidence data.

b For absolute intensity per 100 decays, multiply by 0.020 2.

c Placement of transition in the level scheme is uncertain.

d Multiply placed; undivided intensity given.

x γ ray not placed in level scheme.

^{228}Pa α Decay (22 h) 1994Ah03,1993Sh07,1958Hi78 (continued)

Decay Scheme

Intensities: I γ per 100 parent decays
& Multiply placed; undivided intensity given

3+ 0.0 22 h
 $^{228}_{91}\text{Pa}_{137}$ $\downarrow$ $\alpha=2.0$ 2
 $Q_{\alpha}(\text{g.s.})=6264.5^{15}$

 $^{224}_{89}\text{Ac}_{135}$

^{228}Pa α Decay (22 h) 1994Ah03,1993Sh07,1958Hi78 (continued)

Decay Scheme (continued)

Intensities: I γ per 100 parent decays
 & Multiply placed; undivided intensity given

$^{228}_{91}\text{Pa}_{137}$ 3+ 0.0 22 h
 $Q_{\alpha}(\text{g.s.})=6264.5^{15}$

Adopted Levels, Gammas

Q(β⁻)=-3869 13; S(n)=7463 14; S(p)=5122 12; Q(α)=7298 6 2012Wa38.

S(2n)=13352 16, S(2p)=8906 11 (2012Wa38).

²²⁴Th isotope identified and produced by Meinke, Ghiorso and Seaborg, Phys. Rev, 75, 314 (1949) in Th(α,X) at 100-120 MeV, with an estimated half-life of ≈1 s. Later studies of ²²⁴Th decay: 1958To25, 1961Ru06, 1970Va13, 1978IbZZ, 1989An13, 2000He17.

2015Bo05, 2015Na11, 2014De43, 2014No01, 2006Mi05, 2003Sh02, 2000Bo34: theoretical calculations of level energies, Jπ, B(E2), deformation, band structures.

²²⁴Th Levels

D₀/Q₀=electric dipole moment to electric quadrupole moment ratio deduced by 1993Ac02 from B(E1)/B(E2) ratios determined in (α,6nγ) reaction.

Cross Reference (XREF) Flags

A ²²⁸U α Decay (9.1 min)

B ²⁰⁸Pb(¹⁶O,Fγ): GDR

C ²⁰⁸Pb(¹⁸O,2nγ)

D ²²⁶Ra(α,6nγ)

E(level) [†]	Jπ [‡]	XREF	T _{1/2}	Comments
0.0 #	0+	A CD	1.04 s 2	%α=100. T _{1/2} : weighted average of 0.812 s 99 (2000He17 from α decay), 1.05 s 2 (1978IbZZ), 1.03 s 5 (1970Va13, from α decay curve), 1.05 s 5 (1958To25, detection of integral α particles with pulsed beam).
98.1 # 3	2+	A CD	0.590 ns 40	Jπ: E2 γ to 0+.
251.0 ? @ 3	(1-)	A D		T _{1/2} : (186 ce(L2))(98 ce(L2))(t) in ²²⁶ Ra(α,6nγ) (1986Sc18). XREF: D(?). Jπ: possible member of Kπ=0- band.
284.1 # 5	4+	A CD		Jπ: stretched E2 γ to 2+.
305.3 @ 5	(3-)	CD		
464.5 @ 5	(5-)	CD		
534.7 # 5	6+	CD		D ₀ /Q ₀ =7.3E-4 fm ⁻¹ 11.
699.5 @ 5	(7-)	CD		
833.9 # 6	8+	CD		D ₀ /Q ₀ =6.7E-4 fm ⁻¹ 7.
997.7 @ 6	(9-)	CD		
1173.8 # 6	10+	CD		D ₀ /Q ₀ =7.3E-4 fm ⁻¹ 4.
1347.3 @ 6	(11-)	CD		XREF: C(?). D ₀ /Q ₀ =8.8E-4 fm ⁻¹ 6.
1549.8 # 6	12+	D		D ₀ /Q ₀ =8.4E-4 fm ⁻¹ 4.
1738.7 @ 6	(13-)	D		D ₀ /Q ₀ =8.0E-4 fm ⁻¹ 4.
1958.9 # 7	14+	D		D ₀ /Q ₀ =9.3E-4 fm ⁻¹ 5.
2164.7 @ 7	(15-)	D		D ₀ /Q ₀ =8.9E-4 fm ⁻¹ 6.
2398.0 # 7	16+	D		
2620.2 ? @ 7	(17-)	D		D ₀ /Q ₀ =10.0E-4 fm ⁻¹ 13.
2864 ? #	18+	D		
10.8×10 ^{3‡} 3		B	4.4 MeV 6	
14.1×10 ^{3‡} 6		B	5.9 MeV 10	

[†] From least squares fit to Eγ data.

[‡] GDR.

[§] Based on multipolarities for selected transitions in in-beam γ-ray studies, band structures and systematics of neighboring nuclides, unless specific arguments are given.

(A): Kπ=0+ g.s. band.

@ (B): Kπ=0- band.

γ(²²⁴Th)

E(level)	Eγ [†]	Iγ [†]	Mult. [‡]	α	Comments
98.1	98.1 3	100	E2 [§]	12.33 25	B(E2)(W.u.)=96 7.
251.0 ?	152.9 3	50 13	[E1]	0.179	Iγ: from ²²⁸ U α decay.
	246 3	100 25	[E1]	0.059	Eγ,Iγ: γ seen in ²²⁸ U α decay only.
284.1	186.0 3	100	E2 [§]	0.863	
305.3	207.2 3	100	(E1)	0.0868	
464.5	180.4 3	100	(E1)	0.1204	

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Adopted Levels, Gammas (continued) $\gamma(^{224}\text{Th})$ (continued)

E(level)	$E_{\gamma}^{\dagger}$	$I_{\gamma}^{\dagger}$	Mult. [‡]	α	E(level)	$E_{\gamma}^{\dagger}$	$I_{\gamma}^{\dagger}$	Mult. [‡]	α
534.7	70.2 3	85 25	[E1]	0.299 6	1549.8	376.0 3	29 3	[E2]	0.0880
	250.6 3	100	(E2)	0.299	1738.7	188.9 3	100	[E1]	0.1080
699.5	164.8 3		(E1)	0.151		391.4 3	50 5	[E2]	0.0790
	235.0 3				1958.9	220.2 3	100	[E1]	0.0753
833.9	134.4 3	100	(E1)	0.243		409.0 3	29 3	[E2]	0.0703
	299.2 3	50 10	[E2]	0.170	2164.7	205.8 3	100	[E1]	0.0882
997.7	163.8 3					426.1 3	45 6	[E2]	0.0633
	298.2 3				2398.0	233.3 3			
1173.8	176.1 3	100	(E1)	0.1276		439.1 3			
	339.9 3	36 4	[E2]	0.1166	2620.2?	222.3 [#]	100	[E1]	0.0737
1347.3	173.4 3	100	(E1)	0.1323		455.4 [#] 3	42 11	[E2]	0.0535
	349.6 3	30 4	[E2]	0.1076	2864?	466 [#]			
1549.8	202.5 3	100	[E1]	0.0916					

[†] From $^{226}\text{Ra}(\alpha,6n\gamma)$, where data are more extensive and generally given with uncertainties. The E_{γ} and γ branching ratios available from $^{208}\text{Pb}(^{18}\text{O},2n\gamma)$ are in agreement with those from $(\alpha,6n\gamma)$ reaction but are less complete. The only exception is 251,(1-) level, where energy of one γ ray and intensities are taken from α decay.

[‡] From $\gamma(\theta)$ data in $(^{18}\text{O},2n\gamma)$, unless otherwise stated.

[§] Intensities of L1, and L2+L3 peaks in $(^{18}\text{O},2n\gamma)$ displayed in spectral figure 1 of 1986Sc12 are consistent with E2.

[#] Placement of transition in the level scheme is uncertain.

Adopted Levels, Gammas (continued)

^{228}U α Decay (9.1 min) $^{1961}\text{Ru06}$

Parent ^{228}U : $E=0$; $J\pi=0+$; $T_{1/2}=9.1$ min 2; $Q(\text{g.s.})=6803$ 10; $\% \alpha$ decay=97.5 25.

$^{228}\text{U}-T_{1/2}$: From ^{228}U Adopted Levels in ENSDF database (taken from 1961Ru06).

$^{228}\text{U}-Q(\alpha)$: From 2012Wa38.

$^{228}\text{U}-\% \alpha$ decay: $\% \alpha=97.5$ 25 (from $\% \epsilon < 5\%$ measured by 1961Ru06). Other: $\% \alpha > 80$ (1951Me10).

1961Ru06: ^{228}U produced from bombardment of ^{232}Th target with He ion beam of 300 MeV from Berkeley synchrocyclotron facility, followed by chemical separation. Measured $E\alpha$, $E\gamma$, $\alpha\gamma$ -coin, $\gamma\gamma$ -coin. Other: 1951Me10, also from Lawrence Berkeley laboratory.

 ^{224}Th Levels

E(level)	$J\pi^\dagger$
0.0	0+
98 4	2+
246 3	(1-)
280 6	4+

† From Adopted Levels.

 α radiations

$E\alpha$	E(level)	$I\alpha^\#$	HF §
6409 † @	280	0.56 † 20	8 3
6442 † @	246	0.66 † 11	9.9 18
6590 ‡ 10	98	29 ‡ 4	0.96 15
6680 ‡ 10	0.0	70 ‡ 4	1.000

† Energy based on level energy determined from γ -ray data, and intensity from γ -transition intensities.

‡ From 1961Ru06.

§ $\text{HF}(6680\alpha)=1.00$ yields $r_0(^{224}\text{Th})=1.524$ fm 5.

$^\#$ For α intensity per 100 decays, multiply by 0.975 25.

@ Existence of this branch is questionable.

 $\gamma(^{224}\text{Th})$

$I\gamma$ normalization: $I\gamma$ data of 1961Ru06 are given as photons per 100 α particles.

$E\gamma$	E(level)	$I\gamma^\ddagger$	Mult. †	α	$I(\gamma+\text{ce})^\ddagger$	Comments
(98)	98	2.1 3	E2	12.6	29 4	$E\gamma$: rounded value from Adopted Gammas. $E\gamma=93$ (1961Ru06). $I(\gamma+\text{ce})$: from $I\alpha$ imbalance at 93 level. $I\gamma$: from $I(\gamma+\text{ce})$ and α . α : α is for $E\gamma=98.1$ keV, the adopted energy for this γ .
152 3	246	0.20 5	[E1]	0.184		
187 3	280	0.3 1	E2	0.88		
246 3	246	0.40 10	[E1]	0.059		

† From Adopted Gammas.

‡ For absolute intensity per 100 decays, multiply by 0.975 25.

Decay Scheme

²⁰⁸Pb(¹⁸O,2n γ) ¹⁹⁸⁶Sc12

¹⁹⁸⁶Sc12: E(¹⁸O)=78,79 MeV; target=140 μ g/cm² placed between thin carbon foils. Measured $\gamma\gamma$ (recoil)- and (ce) γ (recoil)-coin, $\gamma(\theta)$ at 145° and 90°.

The level scheme is constructed on the basis of coincidence data, energy sums and systematics.

²²⁴Th Levels

E(level) [†]	J $\pi^{\ddagger}$	Comments
0.0 §	0+	
98.8 § 5	2+	
251.0 ? # 3	1-	E(level),J π : from Adopted Levels. ¹⁹⁸⁶ Sc12 list 246 keV 5, but this level is probably not populated in this reaction.
284.5 § 7	4+	
305.7 # 7	3-	
464.9 # 9	5-	
534.9 § 9	6+	
699.6 # 10	7-	
834.0 § 10	8+	
996.9 # 11	9-	
1172.8 § 12	10+	
1346.2 ? # 13	11-	

[†] From least-squares fit to E γ data, assuming 0.5 keV uncertainty for each E γ .

[‡] From ¹⁹⁸⁶Sc12 based on band structures.

§ (A): K π =0+ g.s. band.

(B): K π =0- band.

$\gamma(^{224}\text{Th})$

E $\gamma^{\dagger}$	E(level)	I $\gamma^{\ddagger}$	Mult.§	α	I(γ +ce) [†]	E $\gamma^{\dagger}$	E(level)	I $\gamma^{\ddagger}$	Mult.§	α	I(γ +ce) [†]
70.1	534.9	15	[E1]	0.300	19	180.4	464.9	28	(E1)	0.1204	31
98.8	98.8	10	E2#	11.92	135	185.7	284.5	54	E2#	0.868	100
134.5	834.0	16	(E1)	0.243	20	206.9	305.7	23	(E1)	0.0871	25
162.9	996.9	10	[E1]	0.1536	12	250.4	534.9	18	(E2)	0.300	23
164.8	699.6	26	(E1)	0.1494	30	297.3@	996.9	3.4	[E2]	0.1734	4
173.4@	1346.2?	3.5	(E1)	0.1323	4	298.9	834.0	10	[E2]	0.1706	12
175.9	1172.8	5	(E1)	0.1279	6	339@	1172.8		[E2]	0.1175	

[†] From level scheme figure 3 in ¹⁹⁸⁶Sc12.

[‡] Deduced by evaluators from I γ +ce and conversion coefficients.

§ From I γ (145°)/I γ (90°) ratios displayed in figure 2 of ¹⁹⁸⁶Sc12, and interpreted as stretched quadrupoles and stretched dipoles, unless otherwise noted. Based on band structures stretched quadrupoles are assumed as E2 and stretched dipoles as E1.

Intensities of L1, and L2+L3 peaks displayed in spectral figure 1 of ¹⁹⁸⁶Sc12 are consistent with E2.

@ Placement of transition in the level scheme is uncertain.

²⁰⁸Pb(¹⁶O,F γ): GDR ¹⁹⁸⁷Th07,1992Di03

¹⁹⁸⁷Th07: E(¹⁶O)=100,120,140 MeV; measured GDR γ spectra, s(E γ), $\gamma(\theta)$, yield ratios. Deduced giant dipole resonance, level density parameters, fission hindrance factors.

¹⁹⁹²Di03: E(¹⁶O)=140 MeV; also W(³²S,FG),E(³²S)=185-230 MeV; measured fission (fragment) $\gamma(\theta)$, GDR γ spectra in 5-22 MeV region, total kinetic energy distributions. Deduced shape features, quasifission T_{1/2}, GDR decay.

²²⁴Th Levels

E(level)	Γ	Comments
10.8 $\times 10^3$ 3	4.4 MeV 6	E(level): average of 10.3, 11.2 and 11.0 MeV (¹⁹⁸⁷ Th07). Value is $\approx$ 10 MeV in ¹⁹⁹² Di03.
		Γ : average of 4.0, 4.2 and 5.0 MeV (¹⁹⁸⁷ Th07).
14.1 $\times 10^3$ 6	5.9 MeV 10	E(level): average of 14.0, 14.2 and 14.0 MeV (¹⁹⁸⁷ Th07).
		Γ : average of 5.4, 5.8 and 6.5 MeV (¹⁹⁸⁷ Th07).

²²⁶Ra(α,6nγ) 1993Ac02

1993Ac02 (also 1986Sc18): Eα=55 MeV from Bonn cyclotron facility, target=300 μg/cm² sandwiched between 40 μg/cm carbon and beryllium; measured Eγ, Iγ, ce, γ(ce)-coin, αγ(ce)-coin, (ce)(ce)(t) using Ge detectors and double orange spectrometer. Deduced levels, Jπ, multipolarity, level half-life, B(E1)/B(E2) ratios, intrinsic electric dipole to quadrupole moments.

1993Ac02 state that a large number of additional γ rays at higher higher energies were observed but were not assigned to rotational bands. The authors further cite Ph.D. theses by M. Marten-Tolle and B. Ackermann, University of Bonn (1992) for details of data. The evaluators of the current evaluation obtained copies of both the theses through McMaster University library, but could not find any more details than given in the paper by 1993Ac02.

²²⁴Th Levels

Ratios of magnitude of electric dipole moment D₀ to electric quadrupole moment Q₀ deduced by 1993Ac02 from experimental B(E1)/B(E2) ratios are listed under comments as D₀/Q₀.

The level scheme is that proposed by 1993Ac02 based on coincidence relations and energy sums.

E(level) [†]	Jπ [‡]	T _{1/2}	Comments
0.0 §	0+		
98.1 § 3	2+	0.590 ns 40	T _{1/2} : from (186 ce(L2))(98 ce(L2))(t) (1986Sc18).
251.0 ? # 3	1-		
284.1 § 5	4+		
305.3 # 5	3-		
464.5 # 5	5-		
534.7 § 5	6+		D ₀ /Q ₀ =7.3E-4 fm ⁻¹ 11.
699.5 # 5	7-		
833.9 § 6	8+		D ₀ /Q ₀ =6.7E-4 fm ⁻¹ 7.
997.7 # 6	9-		
1173.8 § 6	10+		D ₀ /Q ₀ =7.3E-4 fm ⁻¹ 4.
1347.3 # 6	11-		D ₀ /Q ₀ =8.8E-4 fm ⁻¹ 6.
1549.8 § 6	12+		D ₀ /Q ₀ =8.4E-4 fm ⁻¹ 4.
1738.7 # 6	13-		D ₀ /Q ₀ =8.0E-4 fm ⁻¹ 4.
1958.9 § 7	14+		D ₀ /Q ₀ =9.3E-4 fm ⁻¹ 5.
2164.7 # 7	15-		D ₀ /Q ₀ =8.9E-4 fm ⁻¹ 6.
2398.0 § 7	16+		
2620.2 ? # 7	17-		D ₀ /Q ₀ =10.0E-4 fm ⁻¹ 13.
2864 ? §	18+		

[†] From least squares fit to Eγ data.

[‡] As proposed by 1993Ac02, based on multipolarity assignments, band structure and systematics.

§ (A): Kπ=0+ g.s. band.

(B): Kπ=0- band.

γ(²²⁴Th)

E(level)	Eγ [†]	Iγ [§]	Mult. [‡]	α	Comments
98.1	98.1 3		E2	12.33 25	
251.0 ?	152.9 @ 3				
284.1	186.0 3		E2	0.863	
305.3	207.2 3				
464.5	180.4 3				
534.7	70.2 3	85 25	[E1]	0.299 6	Iγ(70)/Iγ(251)=0.85 25 (1993Ac02).
	250.6 3	100	(E2)	0.299	
699.5	164.8 3				
	235.0 3				
833.9	134.4 3	100	[E1]	0.243	
	299.2 3	50 10	[E2]	0.1700	Iγ(134)/Iγ(299)=2.0 4 (1993Ac02).
997.7	163.8 3				
	298.2 3				
1173.8	176.1 3	100	[E1]	0.1276	
	339.9 3	36 4	[E2]	0.1166	Iγ(176)/Iγ(340)=2.8 3 (1993Ac02).
1347.3	173.4 3	100	[E1]	0.1323	
	349.6 3	30 4	[E2]	0.1076	Iγ(173)/Iγ(350)=3.3 4 (1993Ac02).
1549.8	202.5 3	100	[E1]	0.0916	
	376.0 3	29 3	[E2]	0.0880	Iγ(202)/Iγ(376)=3.4 3 (1993Ac02).
1738.7	188.9 3	100	[E1]	0.1080	

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$^{226}\text{Ra}(\alpha, 6n\gamma)$ 1993Ac02 (continued) $\gamma(^{224}\text{Th})$ (continued)

E(level)	$E_{\gamma}^{\dagger}$	$I_{\gamma}^{\S}$	Mult. [‡]	α	Comments
1738.7	391.4 3	50 5	[E2]	0.0790	$I_{\gamma}(189)/I_{\gamma}(391)=2.01\ 20$ (1993Ac02).
1958.9	220.2 3	100	[E1]	0.0753	
	409.0 3	29 3	[E2]	0.0703	$I_{\gamma}(220)/I_{\gamma}(409)=3.5\ 4$ (1993Ac02).
2164.7	205.8 3	100	[E1]	0.0882	
	426.1 3	45 6	[E2]	0.0633	$I_{\gamma}(206)/I_{\gamma}(426)=2.2\ 3$ (1993Ac02).
2398.0	233.3 3				
	439.1 3				
2620.2?	222.3 #@	100	[E1]	0.0737	
	455.4 @ 3	42 11	[E2]	0.0535	$I_{\gamma}(222)/I_{\gamma}(455)=2.4\ 6$ (1993Ac02).
2864?	466 @ 1				

[†] 1993Ac02 state that the uncertainty varies from 0.1 keV for transitions between the lower levels to 0.3 keV for transitions between the upper levels. The evaluators assigned an uncertainty of ± 0.3 keV to all transitions.

[‡] From Adopted Gammas. 1986Sc18 state that the multipolarities of the stronger γ rays were determined from I_{γ} and $I(\text{ce})$, but do not provide experimental information.

[§] Relative branching ratios deduced from measured $I_{\gamma}(\text{E1:J to J-1})/I_{\gamma}(\text{E2: J to J-2})$.

[#] Deduced from level energies; γ not shown in level scheme figure 13, but is present in spectral figure 3 and in table 2 of 1993Ac02.

@ Placement of transition in the level scheme is uncertain.

Adopted Levels

Q(β⁻)=-1851 26; S(n)=6530 70; S(p)=2812 12; Q(α)=7694 4 2012Wa38.

S(2n)=14440 70 (syst), S(2p)=7337 9 (2012Wa38).

1958To25: ²²⁴Pa produced and identified in E=170 MeV pulsed proton bombardment of Thorium, measured Eα. Later half-life and α decay studies: 1970Bo13, 1996Li05, 1997Wi15, 2003Ni10.

²²⁴Pa Levels

Cross Reference (XREF) Flags

A ²²⁸Np α Decay (61.4 s)

E(level)	Jπ	XREF	T _{1/2}	Comments
0.0	(5-)	A	0.846 s 20	%α=100. Jπ: tentative assignment by 1996Li05, based on possible configuration= v5/2[633]⊗π5/2[523]; 5/2[633] from g _{9/2} neutron orbital, and 5/2[523] from h _{9/2} proton orbital; single-particle assignments are based on theoretical calculations by 1991Cw01 and 1984Le04. T _{1/2} : from α-decay curves; weighted average of 0.850 s 20 (1997Wi15), 0.79 s 6 (1996Li05), 0.95 s 15 (1970Bo13). Other: 0.60 s 5 (1958To25, estimated from measured Eα and Geiger-Nuttall law). %ε+%β ⁺ : =0.1 (from gross β-decay theory, 1973Ta30), >0.7 (from β and α decay theoretical half-lives in 1997Mo25). Measured Eα of the main α transition=7490 10 (1970Bo13); 7489 (1987FuZT); 7488 (1996Li05); 7522 (average of four values, 2003Ni10).

²²⁸Np α Decay (61.4 s) 2003Ni10,1994Kr13

Parent ²²⁸Np: E=0; Jπ=?; T_{1/2}=61.4 s 14; Q(g.s.)=7310 50; %α decay=40 7.

²²⁸Np-T_{1/2}: From ²²⁸Np Adopted Levels in ENSDF database, taken from 1994Kr13.

²²⁸Np-Q(α): From 2012Wa38.

²²⁸Np-%α decay: %α=40 7 from ε/α=1.5 4 (1994Kr13), based on the measured ratio of ²¹²Po/²¹⁶Fr activities. Note that

2003Ni10 measure %α=83 +17-36. Weighted average of %α values from 1994Kr13 and and 2003Ni10 is 43% 10.

2003Ni10: ²²⁸Np produced in ¹⁹⁸Pt(³⁴S,p3n),E=170,172 MeV; measured Eα, T_{1/2}. Five α decay chains reported in this study.

1994Kr13: ²²⁸Np from ²³³U(p,6n),E(p)=50 MeV; ion chem; measured half-life.

Others: 1978SoZZ, 1966Ku13 (SF decay of ²²⁸Np decay, half-life).

²²⁴Pa Levels

E(level)	Jπ	T _{1/2}	Comments
0.0	(5-)	0.846 s 20	Jπ,T _{1/2} : from Adopted Levels.

α radiations

Eα [†]	E(level)	Comments
7063		Eα: average of 7062 and 7065.
7126		
7180§	0.0	Eα: average of 7177 and 7183.

[†] From 2003Ni10.

§ Existence of this branch is questionable.

Adopted Levels

Q(β^-)=-6160 SY; S(n)=8200 80; S(p)=3900 80; Q(α)=8620 12 2012Wa38.

Estimated uncertainty=200 for Q β^- (2012Wa38).

S(2n)=14650 100 (syst), S(2p)=6067 28 (2012Wa38).

1991An10 (also 1991An13, 1994Ye08): ²²⁴U produced and identified in ²⁰⁸Pb(²⁰Ne,4n) reaction at E=100-125 MeV, in-flight kinematic separation, and genetic relationships. Measured E α , T_{1/2}. In 1994Ye08, ¹⁹⁷Au+²⁷Al reaction was used to produce ²²⁴U.

1992To02: ²²⁴U produced in ²⁰⁹Bi(¹⁹F,4n) at E=102-115 MeV, velocity filter; measured E α , T_{1/2}.

²²⁴U Levels

Cross Reference (XREF) Flags

A ²²⁸Pu α Decay (1.1 s)

E(level)	J π	XREF	T _{1/2}	Comments
0.0	0+	A	0.84 ms +40-22	% α =100. T _{1/2} : from α -decay curves; weighted average of 0.7 ms +5-2 (1991An10, also 1991An13 and 1994Ye08) and 1.0 ms 4 (1992To02). ϵ, β^+ decay mode has not been observed. Theoretical calculations predict % ϵ +% β^+ <0.00012 (gross β -decay theory,1973Ta30), LT 0.34 (QRPA,1997Mo25). Measured E α =8470 15 (1991An10), 8458 20 (1992To02).

²²⁸Pu α Decay (1.1 s) 2003Ni10,1994An02

Parent ²²⁸Pu: E=0; J π =0+; T_{1/2}=1.1 s +20-5; Q(g.s.)=7940 18; % α decay=100.

²²⁸Pu-T_{1/2}: From ²²⁸Pu Adopted Levels (from 2003Ni10).

²²⁸Pu-Q(α): From 2012Wa38.

²²⁸Pu-% α decay: % α =100, based on % ϵ +% β^+ <0.5 from Gross theory of β decay (1973Ta30) and <0.1 from QRPA calculations in 1997Mo25.

2003Ni10: ²²⁸Pu produced in ¹⁹⁸Pt(³⁴S,4n),E=170,172 MeV; measured E α , T_{1/2}.

1994An02, 1994Ye08: ²⁰⁸Pb(²⁴Mg,4n) at beam energy E=5.50 MeV/nucleon, genetic correlations with the α decay of ²²⁴U and its daughter products; measured E α . Half-life could not be measured in this work.

Deduced r₀=1.480 fm 6 for T_{1/2}=1.1 s, 1.435 fm 6 for T_{1/2}=3.1 s, 1.506 fm 6 for T_{1/2}=0.6 s. These values are somewhat lower than the systematics value of 1.525 fm 15 from local trend.

²²⁴U Levels

E(level)	J π
0.0	0+

α radiations

E α	E(level)	Comments
7810 20	0.0	E α : from 1994An02. Other: 7772 35 (2003Ni10).

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