Adopted Levels, Gammas

History			
Type	Author	Citation	Literature Cutoff Date
Full Evaluation	Balraj Singh	ENSDF	26-Jun-2023

S(n)=8510 *syst*; S(p)=2610 *syst*; Q(α)=9210 *syst* 2021Wa16

Estimated uncertainties (2021Wa16): 500 for S(n), 330 for S(p), 200 for Q(α).

Q(ε)=3560 *300*, S(2p)=4250 *280*, Q(εp)=1550 *280* (syst, 2021Wa16). S(2n)=15890 (theory, 2019Mo01).

A dataset in the XUNDL database, compiled from 2015Da12 by J. Chen (NSCL, MSU) was used in this evaluation.

1997He29: ^{254}Rf produced and identified in ^{206}Pb(^{50}Ti,2n) reaction, followed by measurement of $T_{1/2}$ from SF decay.

Later measurements of half-lives: 2008Dr05, 2015Da12.

2008Dr05: ^{208}Pb(^{48}Ti,2n),E=4.6-4.8 MeV/nucleon; the beam provided by 88-Inch cyclotron at LBNL. Detected charged particles using a focal plane detector and a double-sided silicon strip detector. Half-life of ^{254}Rf and production cross section measured based on subsequent α decay of ^{254}Rf.

2015Da12: two experiments were performed using ^{206}Pb(^{50}Ti,2n) reaction: 1. E=242.5 MeV ^{50}Ti beam produced at ATLAS-ANL facility was incident on a 0.5 mg/cm^2 99.948% enriched ^{206}Pb target. Recoiling residues were separated and selected using the Fragment Mass Analyzer (FMA) and implanted into a 100 μm-thick, double-sided silicon strip detector (DSSD) at the focal plane. Spontaneous-fission (SF) events were identified based on spatial and temporal correlations between implanted residues and high-energy (>100 MeV) decay events in DSSD. Measured energies of reaction products, conversion electrons, implant-decay correlations. 2. E=244 MeV ^{50}Ti beam produced at the LBNL cyclotron facility was incident on a 0.5 mg/cm^2 ^{206}Pb target. Recoiling residues were separated and selected by the Berkeley Gas-filled Separator (BGS) and implanted into three 1-mm-thick, double-sided silicon-strip detectors (DSSDs), with emitted γ rays detected with a clover HPGe detector behind each DSSD. Measured energies of reaction products, Eγ, Iγ, conversion electrons, implant-decay correlations. Deduced evidence and $T_{1/2}$ for two isomers in ^{254}Rf using a novel approach involving a pulse-shape analysis of data acquired with a digital data acquisition system. Comparison with multi-quasiparticle calculations. A total of 28 and 723 SF events from ^{254}Rf were identified in the two experiments, respectively. The two isomers were identified based on observed electron-SF and/or electron-electron-SF correlations following the decay of the isomers, with 82 electrons associated with the shorter-lived 2-qp isomer and 11 electrons with the longer-lived 4-qp isomer. The absence of sizable fission branches from either of the isomers implies unprecedented fission hindrance relative to the ground state.

2020Kh01: E(^{50}Ti)=242.5 MeV pulsed beam from the UNILAC-GSI facility. This beam energy corresponds E(^{256}Rf*)=23.3 MeV excitation energy for the compound nucleus. The evaporation residues passed through the gas-filled recoil separator TASCA at GSI. The focal plane detector of TASCA consisted of a multi-wire proportional counter (MWPC) and double-sided silicon strip detectors (DSSDs), and eight DSSDs (box detectors) to detect the backward escaping α particles and fission fragments. Measured energy spectrum of the fission events of ^{256}Rf compound nucleus, spatially and time correlated events from implanted evaporation residues (ERs), fission fragments, α particles, and conversion electrons from the decay of isomeric activity. A total of 22 (ERs)(fission fragment)-correlated events were detected within a time range of 50 μ to 10 s, out of which 20 events were in the correlated time of much less than 1 ms. Small-energy signals were interpreted as arising from the detection of conversion electrons.

2020Kh01 reported one ER-trace, correlated to the fission of ^{254}Rf, with additional two small signals detected, corresponding to the first and second electrons, registered at 0.65 μs and 13.5 μs after the preceding signals, which might indicate decays of two short-lived isomeric states, but with no definite conclusion for the presence of such isomers.

2020SvZZ: ^{254}Rf produced in ^{206}Pb(^{50}Ti,2n) reaction at the U400 cyclotron of FLNR, JINR, and fragments separated using SHELS separator. Investigated characteristics of spontaneous fission with measurement of mean number of neutrons per fission for ^{254}Rf ν=3.87 *34*.

Theoretical nuclear structure calculations:

2022Ma70: calculated negative-parity energy levels, transition dipole, quadrupole and octupole moments using the cluster model of a dinuclear system.

2021Ya34: calculated energy levels, J^π, deformation parameters, S(2n), charge and neutron radii, neutron skin using the relativistic Hartree-Bogoliubov (RHB) framework.

2020Ta21: calculated superdeformed minima, β_2, β_3, second fission barrier using covariant density functional theory (CDFT).

2018Re07: calculated energies of 2$^-$ phonon levels, B(E3) using QRPA with Gogny D1M parametrization.

2015Ag09: calculated binding energies, proton and neutron quadrupole deformations, charge radius, root-mean square (rms) proton radius, neutron skin thickness, S(2n), S(2p) using relativistic Hartree-Bogoliubov theory with DD-PC1 and PC-PK1 interactions, and covariant energy density functionals.

Adopted Levels, Gammas (continued)

2014Af04: calculated kinematic moments of inertia for g.s. rotational band using covariant density functional theory.
2014Li15: calculated level energies, Q(α) values, β_2, β_4 and β_6 for ground and two- and four-quasiparticle high-K isomers, and configuration-constrained potential energy surfaces (PES).
2014Wa25: calculated single-particle levels, deformation parameters, moment of inertia, band crossing using total Routhian surface method.
2012Jo05: calculated level energies and configurations of 2^+ γ-vibrational states using quasiparticle-phonon model.
2011Jo09: calculated energies, J^π for collective states using quasiparticle phonon model.
2006Sh19: calculated levels, J^π, rotational bands, transition dipole and quadrupole moments using cluster model.
2001Mu06: calculated level energy of 2^+ state, Q(α), α-decay branching ratios using macroscopic-microscopic approach.
Other theoretical calculations (levels, J^π, bands, B(Eλ), decay characteristics for α and SF: 18 references for structure and 39 for decays retrieved from the NSR database are listed in 'document' records.
Additional information 1.

^{254}Rf Levels

Cross Reference (XREF) Flags

A ^{206}Pb(^{50}Ti,2nγ)

E(level)†	J^π	$T_{1/2}$	XREF	Comments
0	0^+	22.8 μs *11*	A	%SF≈100; %α<1.5 (1997He29) Only the SF-decay mode has been detected. An upper limit of 1.5% was given by 1997He29 from non-observation of α particles and the total number of 155 SF events detected. $T_{1/2}$: weighted average of 20 μs *3* (2020Kh01, time distribution of 56 ER-fission correlated events); 23.2 μs *11* (2015Da12); and 23 μs *3* (1997He29,1999He11). Other: 29.6 μs *+7−6* (2008Dr05). If the value from 2008Dr05 is considered, then the unweighted average is 24.0 μs *20* and the weighted average is 27.7 μs *18*, but with an unacceptable reduced χ^2=12. Earlier assignments of $T_{1/2}$<3 ms in 1975Og01 and ≈5 ms in 1975Te01 (both from the same laboratory) are most likely erroneous, as e.g. assignment of SF activity to ^{254}Rf in 1975Te01 was inconclusive, as communicated privately by the first author 1975Te01 to the authors of 1997He29. Production σ=0.40 nb *+27−17* in ^{208}Pb(^{48}Ti,2n), E=4.6-4.8 MeV/nucleon (2008Dr05). Production σ=3.8 nb *4* for ^{254}Rf at E(^{50}Ti)=242.5 MeV (2020Kh01).
48‡# *calc*	(2^+)		A	
158‡# *calc*	(4^+)		A	
330#	(6^+)		A	
562#	(8^+)		A	
847#	(10^+)		A	
1186#	(12^+)		A	
1570#	(14^+)		A	
x	(8^-)	4.3 μs *10*		%IT≈100; %SF<10 (2015Da12) A cluster of three counts at 853 keV and two counts at 829 keV is seen in the spectrum of γ rays coincident with electrons, indicating two other possible transitions associated with the 2-qp isomer (2015Da12). %SF<10%, deduced by 2015Da12 assuming 10 fissions from the 2-qp isomer, which is one standard deviation departure in the time interval between 1 μs and 9 μs in the ground-state decay-time distribution. No definitive evidence was found for this fission branch. 2020Kh01 estimated 16% *5* of all the ERs assigned to the decay of ^{254}Rf were observed with conversion electrons (CEs), which indicated isomeric yield in the

Continued on next page (footnotes at end of table)

Adopted Levels, Gammas (continued)

^{254}Rf Levels (continued)

E(level)†	J^π	$T_{1/2}$	XREF	Comments
				reaction. E(level): x>1350 (2015Da12), from the sum of the 450-keV maximum energy of conversion electrons emitted from this isomer and the 893-keV γ-ray energy measured in prompt coincidence with those electrons. $T_{1/2}$: weighted average of 4 μs *1* (2020Kh01, time distributions of electron-like signals relative to ERs correlated with fission fragments); and 4.7 μs *11* (2015Da12, decay time distribution of electrons emitted by the isomer). J^π: proposed configuration=ν7/2[624]⊗ν9/2[734], $K^\pi=8^-$ (2015Da12).
y	(16^+)	247 μs *73*		%SF<40 (2015Da12); %IT≈100 %SF<40%, deduced by 2015Da12, assuming that all the six fission events in the time interval of the 4-qp isomer decays originated from this isomer, although these six fission events could also be associated with the ground-state fission events following decays of the 4-qp isomer which may have escaped detection. 2020Kh01 mentioned that with their experimental arrangement it was not possible to detect the 247−μs isomer. E(level): y>x (2015Da12), based on the longer-lived 4-qp isomer feeding the shorter-lived one, which is supported by the observed event chains of two successive electron bursts detected in between the implantation and the ^{254}Rf ground-state fission and by the measured decay times of the first and second generation electrons in these events. J^π: proposed configuration=(ν7/2[624]+ν9/2[734])⊗ (π7/2[514]+π9/2[624]), $K^\pi=16^+$ (2015Da12). $T_{1/2}$: from decay time distribution of electrons emitted by the isomer (2015Da12).

† From Eγ data, unless otherwise indicated.

‡ Deduced by 2023Se09 from fit to the 172-, 232-, 285-, 339-, and 384 keV γ-ray energies using the Harris formula. The low-energy transition from the level was not seen in the gamma spectrum as it is expected to be heavily converted.

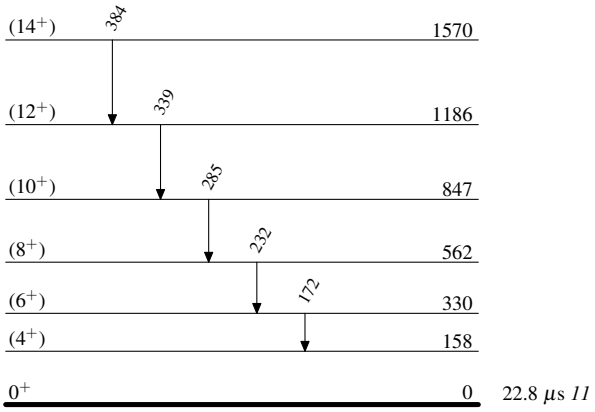
Band(A): $K^\pi=0^+$, g.s. band. Using the Harris formula, the (16^+) and 18^+ members of the band were predicted by 2023Se09 at 1992 keV and 2462 keV, respectively, the (16^+) decaying by 420-keV γ and (18^+) by 470-keV γ.

$\gamma(^{254}Rf)$

E_i(level)	J_i^π	E_γ	E_f	J_f^π
330	(6^+)	172	158	(4^+)
562	(8^+)	232	330	(6^+)
847	(10^+)	285	562	(8^+)
1186	(12^+)	339	847	(10^+)
1570	(14^+)	384	1186	(12^+)

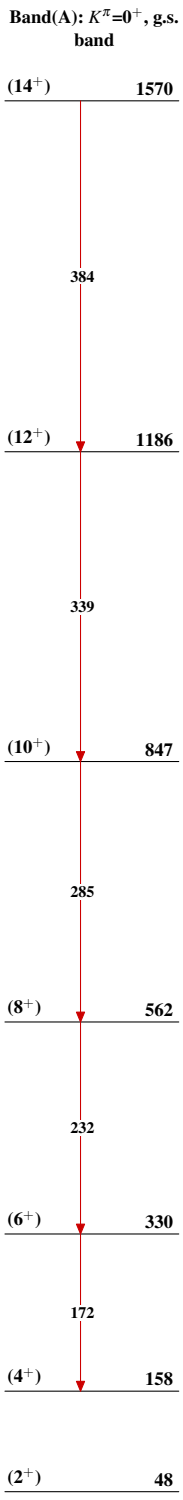
Adopted Levels, Gammas

Level Scheme



$^{254}_{104}Rf_{150}$

Adopted Levels, Gammas



$^{254}_{104}Rf_{150}$