^{147}Nd β^- decay: evaluation

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^{147}Nd decay: significance

Prominent long-lived fission product: 11 d half-life.

Used in studies of absolute fission yields, fuel burnup indicators, stockpile stewardship, and other related measurements through the monitoring of photon intensity of an intense (13% absolute intensity) gamma ray of 531 keV emitted in this decay, e.g. see

PRC: **91**, 064604 (2015); PRC **100**, 014606; 014608 (2019).

In the world-wide monitoring (by the CTBTO) of radioactivity from nuclear test explosions, ^{147}Nd is in the list of ~40 most important long-lived fission products. About a year or so ago CTBTO asked the IAEA-NDS to provide recommended data for the decay of these fission products. This evaluation is also connected with an ongoing evaluation project at the IAEA-NDS.

^{147}Nd β^- decay to ^{147}Pm : Experimental studies

Activity of ~10 d half-life known since ~ 1941, Ohio State Univ.; U of M, cyclotron.

1941La01: PR **59**, 936 (1941); 1942Ku03: PR **61**, 106A (1942): meeting abstracts.

1946Bo25: Z. Naturforsch. **1**, 179 (1946): $T_{1/2}$=11.1(2) d: Heidelberg

1947Ma28: J. Am. Chem. Soc. **69**, 2781 (1947): Oak Ridge: confirmed isotopic assignment, $T_{1/2}$=11.0(3) d in 1951MaZZ. (Manhattan Project)

About 70 primary publications: β and γ spectroscopy, conversion electrons, angular distributions/correlations, etc. Latest articles:

1997Sa53: PRC **56**, 2468 (1997): γ and conversion electron measurements.

2019Br01: ARI 144, 54 (2019): ORNL-HFIR: Half-life measurement.

Two experiments aimed at determining precise %Iγ for the main gamma rays have been done during the last 2-3 years:

1. LLNL+UC-Irvine+Texas A&M+ANL: data analysis in progress: preliminary results in a Ph.D. thesis by A.M. Hennessy, UC-Irvine, 2018.

2. CEA, LNE-LNHB, Saclay. Results not yet available.

^{147}Nd β^- decay to ^{147}Pm: evaluations

ENSDF: Nov 2008: NDS **110**, 749: some corrections done Dec 2013, in the ENSDF database, but seems no erratum to the published version.

Updated evaluation of this decay and the daughter nucleus ^{147}Pm, as part of the evaluation of A=147 nuclei (by Ninel Nica, Texas A&M), submitted Sept 2019 for ENSDF and NDS.

Earlier ENSDF/NDS evaluations:

1992De38: NDS **66**, 705: NNDC

1978Ha22: NDS **25**, 113: ORNL

1967Ew01: NDS-**B2**, No. 4, 35: ORNL

DDEP (Saclay): March 2011: 2013BeZP: Monographie BIPM-5, vol.7 (2013).

NUDAT, ENDF/B-VIII.0: data adapted from 2008 / 2013 ENSDF evaluation.

Other Reaction data libraries: probably from DDEP and/or ENSDF

TOI (LBNL)-1978 (TOI-1996: data adapted from ENSDF)

TORI (LBNL)-1986

Why another evaluation of ^{147}Nd decay?

Alejandro Sonzogni mentioned to me ~3 years back that a re-evaluation of this decay is needed as there seemed some discrepancies between different evaluations in the photon emission probability of one of the main gamma rays (531 keV) from this long-lived fission product, which is used as a monitor in studies of absolute fission yields

I have been waiting for new results from the two recent experiments, but looks like it will still be sometime before these are made available in journal articles.

Brief overview of ^{147}Nd decay

Half-life: 10.98(1) d in ENSDF: re-evaluated now to 11.03(3) d.

Q value: 895.5(5) keV (2017Wa10, AME-2016)

Spin-parity of the g.s. of ^{147}Nd is $5/2^-$

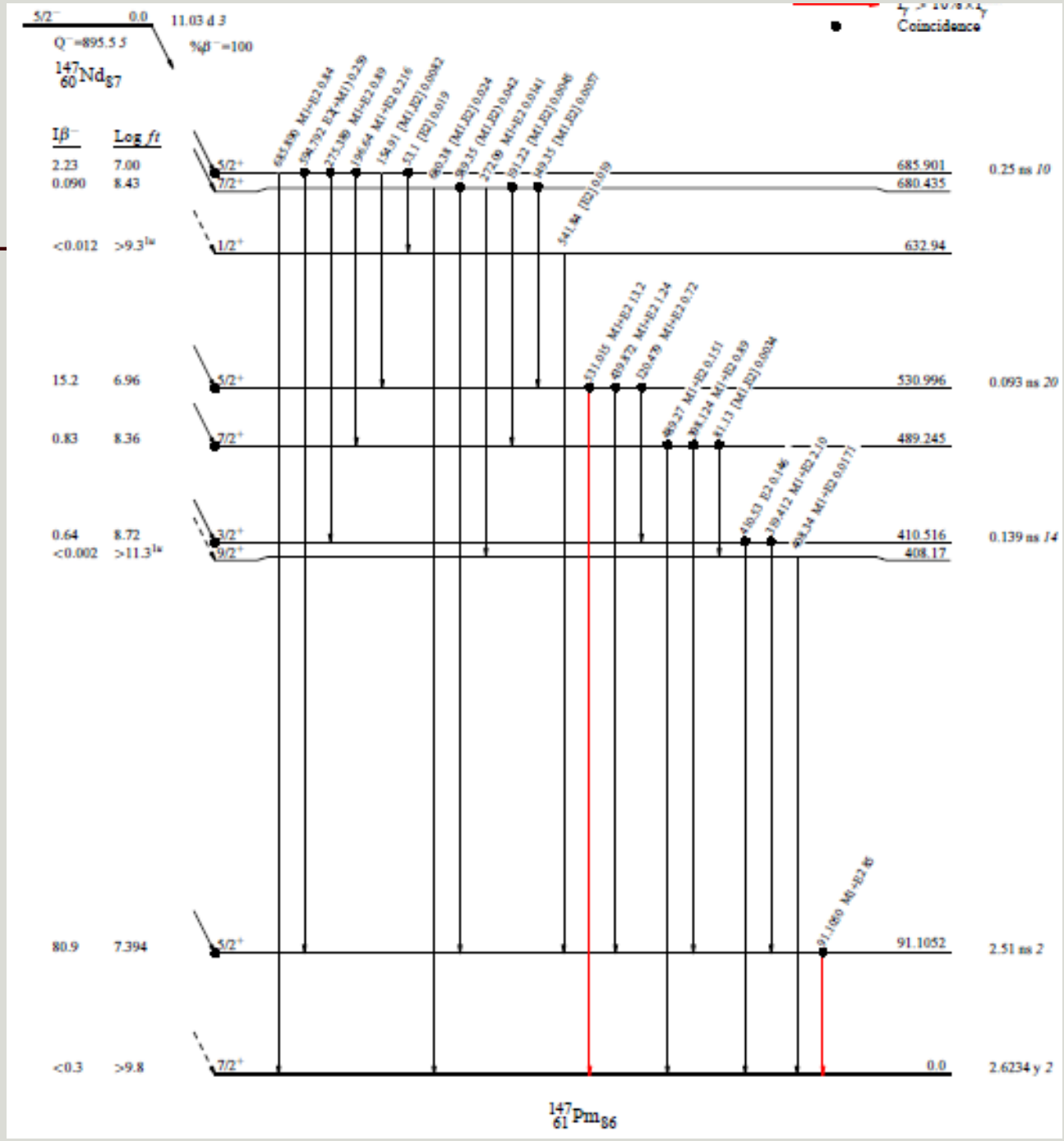
The decay scheme is well known through the measurement of energies and intensities of 22 γ rays populating 8 levels in ^{147}Pm up to an excitation energy of 685.9 keV, with confirmed β feedings to 6 levels.

Most intense β feedings: 80.9% to 91.1, $5/2^+$ level, and 15.2% to 531, $5/2^+$ level.

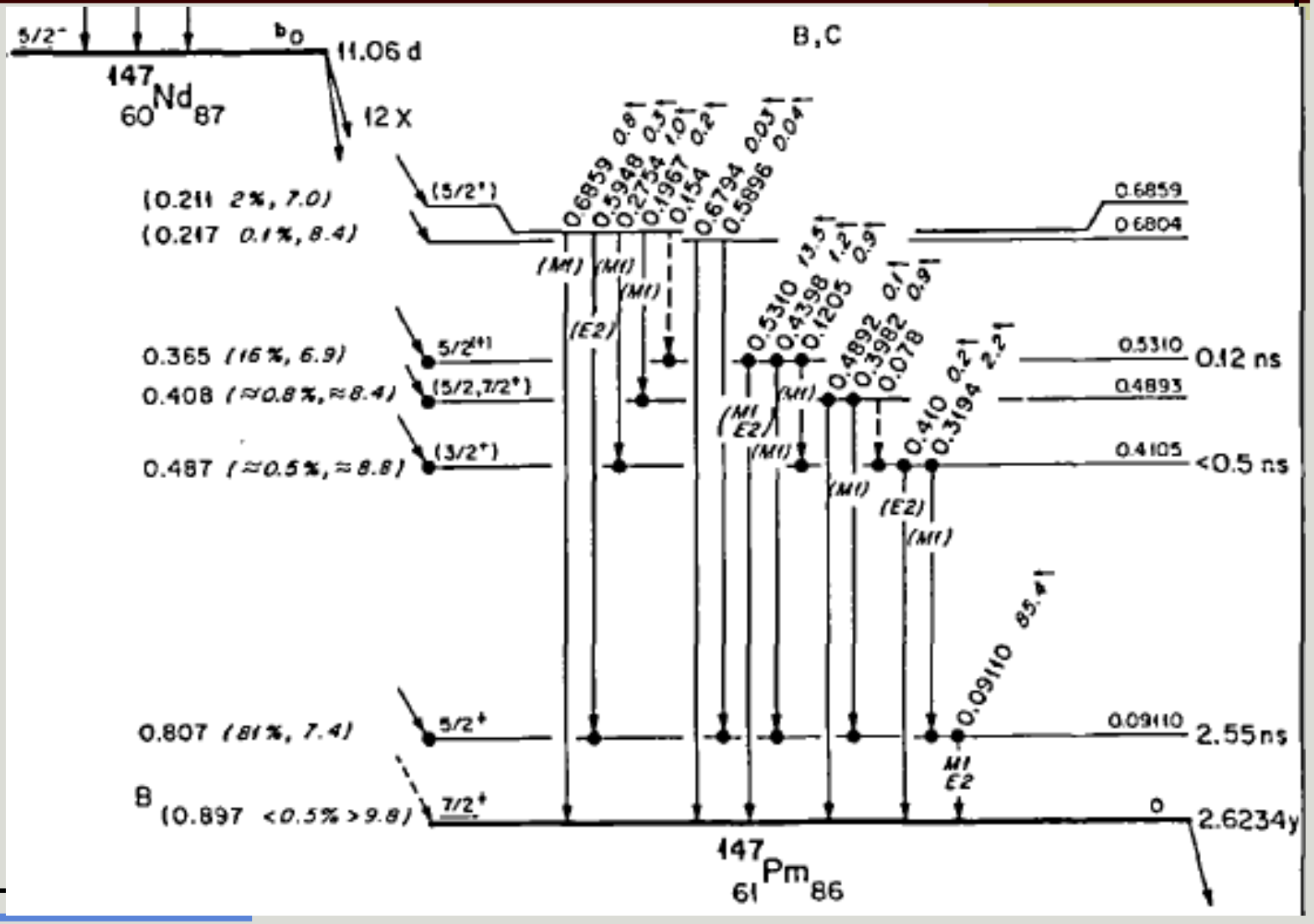
Most intense γ rays: 91.1 keV: Iγ=28.2%, and 531.0 keV: Iγ=13.0%.

For high-precision photon emission probabilities, intensities of both these gamma rays are of importance.

^{147}Nd Decay Scheme (evaluated)



^{147}Nd Decay scheme: 1967Ew01: NDS-**B2**, No. 4, 36



^{147}Nd decay: 531-keV gamma

Lack of consistency in %Iγ of 531-keV transition in evaluated ENSDF, published NDS, and DDEP:

Reference	%Iγ (531)	%β$^-$ (g.s.)
Published 2009Ni02:NDS	13.4(11) (typo)	0.08(7)
Corrected in ENSDF-2013	13.4(3)	≤0.15
DDEP: 2011	12.7(9)	0±5
1992De38: NDS	13.1(9)	<0.15
1978Ha22: NDS	13.1(7)	<0.15
1986-TORI	13.1(7)	

Recent articles on fission yields where %Iγ of 531γ used

2015Bh09: PRC **91**, 064604 (2015): from TUNL: fission yields.

Table III: footnote 'a' about %Iγ(531) : *"In the literature numbers vary from 2% to 8% [11], and they are different from the present ENDF/B-VII.1 evaluation [10]".* [11]: DDEP. [10]: NNDC. Authors used 13.37(11). 2013-corrected value in ENSDF is 13.4(3). The two are slightly different but shouldn't be.

2019Kr10: PRC **100**, 014608 (2019): from TUNL: fission yields for ~45 isotopes.

Table III: cite %Iγ=28.1(7) for 531.0-keV transition, value taken from NNDC. But ENSDF doesn't give this value for 531γ. However, %Iγ=28.08(25) for 91-keV transition in 2013-corrected version, and 28.1(5) in 2009-NDS publication. Hope it is just a typo in 2019Kr10 paper and not a mistake.

2019Na12: PRC **100**, 014606 (2019): from BARC: fission yields:

Table I: cite %Iγ=13.4(3) for 531.0-keV transition, same as in current ENSDF.

^{147}Nd decay: %Iγ of 531-keV gamma

As no direct measurement of the absolute photon intensity of the 531-keV γ seems available in literature, it can only be deduced from the decay scheme characteristics, intensity balance arguments, etc.

Crucial information needed for decay scheme analysis:

1. Direct β feeding to the ground state.
2. Photon intensity of the most intense 91-keV transition, relative to that of the 531-keV transition.
3. Multipolarity and mixing ratio of the 91-keV transition, as it is heavily converted.

^{147}Nd decay: g.s. β feeding

The β transition involves 5/2- (^{147}Nd g.s.) to 7/2$^+$ (^{147}Pm g.s.): first-forbidden non-unique.

Measurements:

Reference	%I_β to g.s.
1960We06: NP **20**, 169	<1.0: mag. spec.
1962Sh08: PR **125**, 2071	<0.25: mag. spec.
1966Be09: NP **79**, 220	<0.15: mag. spec.
1967Ja05: NP-A **99**, 411	<0.5: scint. det.
1971Na11: Nuovo Cim. **3A**, 689	<0.15: mag. spec,
1978Ma51: Izv. Akad. Nauk. **42**, 2302	<1.1(7): mag. spec.
1984Wa23: Jour. Jilin Univ. **4**, 61: Reference added in NSR in 2019	0.21(8): mag. Spec.

For this evaluation used <0.3%.

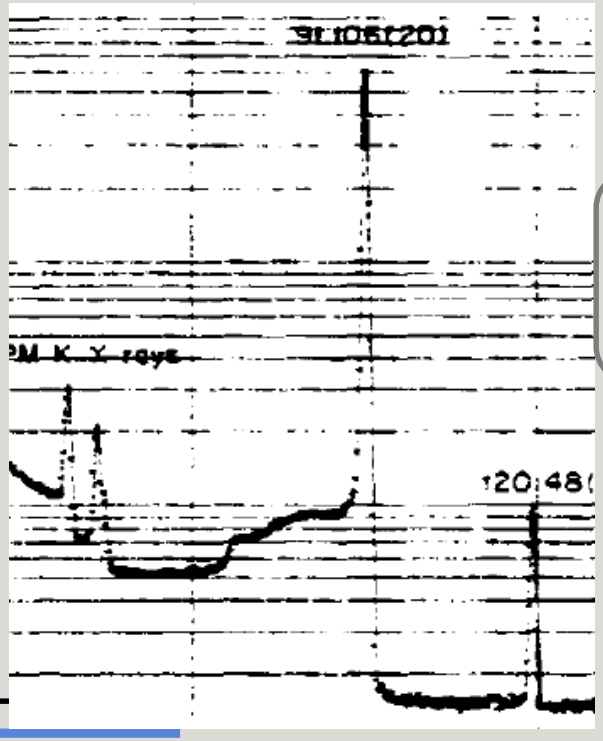
ENSDF-2009+2013 used <0.15%, DDEP used 0(5)%

^{147}Nd decay:

Intensity of 91-keV γ relative to 100.0(10) for the 531-keV γ

Below ~120 keV, the efficiency curve for a general purpose Ge detector is known to only 2-4% or so, as the calibration curve turns over and also there are not enough calibration points.

The 91-keV peak is sitting on a high Compton continuum, introduces additional uncertainty in computing the area of the photo peak.



1974HeYW: R.L. Heath, Gamma-Ray Spectrum Catalogue

Need HPGe detector whose detection efficiency response is known with high precision.

Intensity of 91-keV γ

Minimum uncertainty of 5% assigned in a value

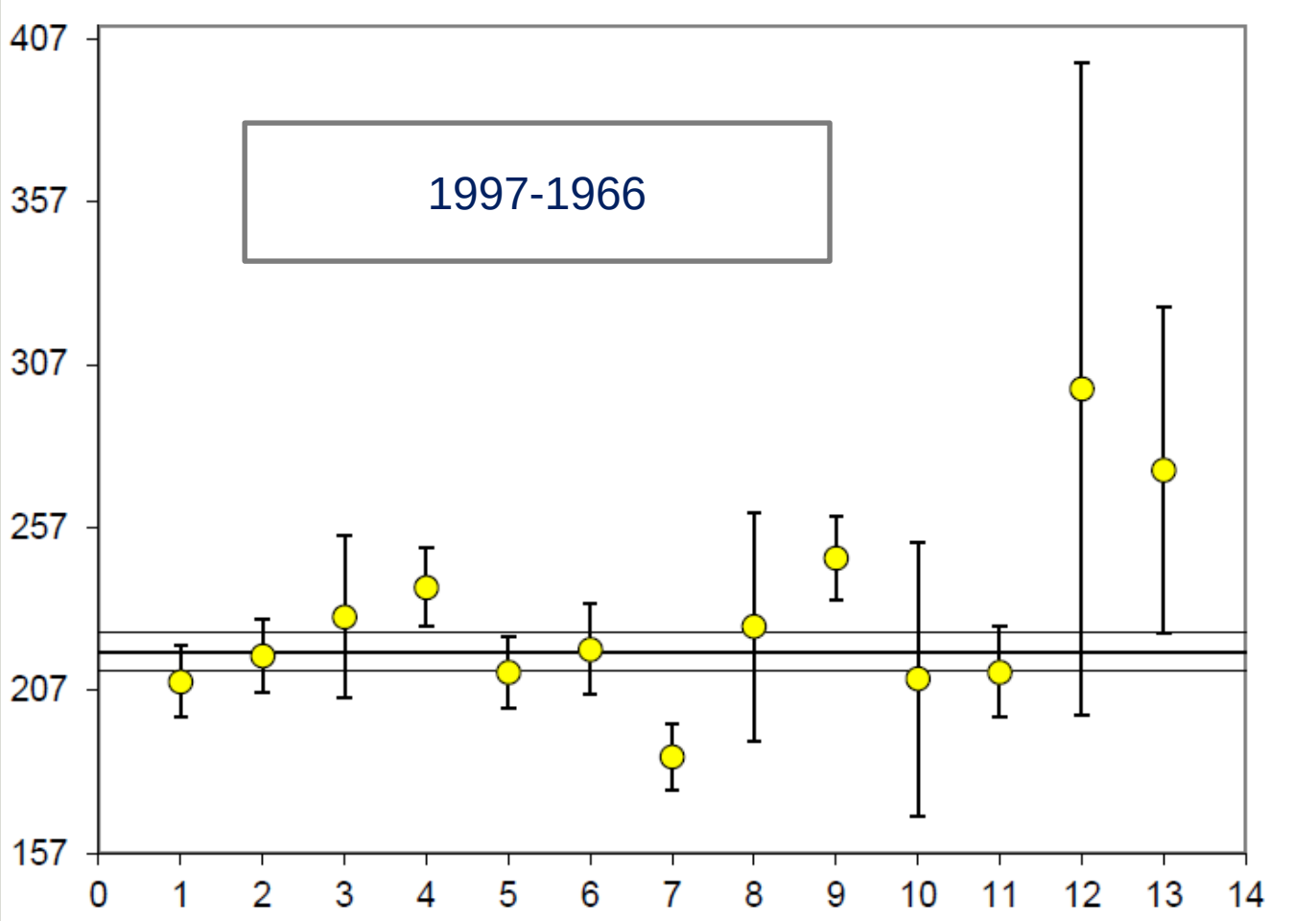
Reference	Value	Adjusted Δlγ
1997Sa53: PRC	210(4)	11
1995Go44:	218(2)	11
1979Se05:	230(25)	
1979Vo09:	239(5)	12
1974HeYW:	213	11
1974Ra30:	220(14)	
1971Si20:	187	10
1967Hi04:	227(35)	
1967Do07:	248(13)	
1967Ca18	211(42)	
1967Ba21:	213(14)	
1967Ja05	300(100)	
1966Ar16	275(50)	
1967Ki08	290(20)	Not used

Wt. avg.=217(6)

ENSDF: 210(4) from 1997Sa53 only

DDEP: 224(14) from 6 references

Relative Iγ: 91-KeV



91-keV gamma: Multipolarity and mixing ratio

Multipolarity=M1+E2 from L-subshell ratios: 1965Ew03: 1967Ba21.

Also K-shell conversion coefficient: 1997Sa53, 2003Zh47.

Mixing ratio=+0.089(5) from low-temperature nuclear orientation: 1969Ba32: PR 184, 1181.

0.092(5), 0.082(10) from L-subshell ratios: could be some nuclear penetration effect.

CC(theory from BrIcc): M1: 2.02(2); E2: 3.17(3)

%Iγ of 531-keV gamma ray

Using the g.s. β feeding, relative Iγ for 91-keV transition as discussed, and fairly well-known data for other (weaker) transitions, one obtains:

%Iγ=13.00(34)

Compared to 13.4(3) in ENSDF-2013 (corrected), 13.4 (11) in NDS (2009) where there was a typo; 12.7(9) in DDEP (2011).

Other matters of evaluation

Checking consistency with in-beam gamma-ray data

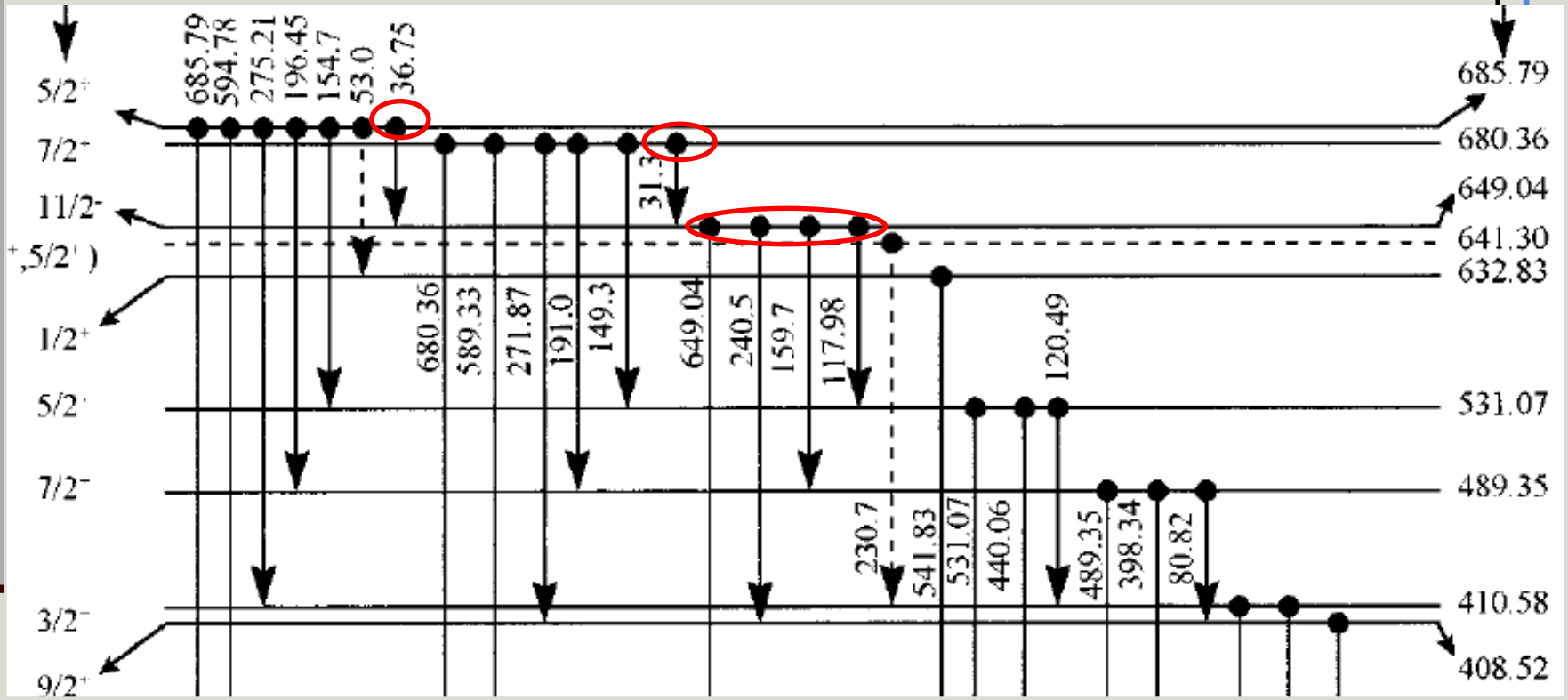
1997Sa53: PRC **56**, 2468, latest paper on this decay, singles γ and ce study:

Claimed 6 new gamma rays in this decay, connecting these to population of an $11/2^-$ level at 649 keV, that is very strongly populated in reaction gamma-ray spectroscopy: (p,2nγ); (^{15}N,4nγ). Four gamma rays of 117.98, 159.07, 240.5, and 649.0 keV were claimed by 1997Sa53 to deexcite the 649 level, whereas in-beam gamma-ray studies showed only the 240 and 649 gamma rays.

Branching ratios of these two gamma rays in 1997Sa53 also disagree with those from reaction data.

Double-checked by Alejandro Sonzogni in the γγ-coin matrices for from MNT in ^{136}Xe + ^{208}Pb reaction work at ANL: 2015Ba20: PRC **91**, 064615; where ^{147}Pm was populated. No sign of the other two gamma rays in the prompt spectra.

^{147}Nd decay scheme: 1997Sa53: PRC 56, 2468
Bringing it back to its ~1980 version !



ENSDF and DDEP kept the 6 gamma rays even when there were valid reasons to reject these, especially, the 36.7 and 31.3 transitions which cause havoc in the decay scheme.

^{147}Nd decay: half-life: needs re-evaluation

Reference	Value (days)	Method
2019Br01: ARI **144**, 54	11.26(1)	Gamma decay curves
1971Ba28: JINC **33**, 589	10.98(1)	Proportional counter
1963Ho15: JINC **25**, 1196	11.02(5)	Proportional counter
1960Al33: JINC **15**, 222	11.14(6)	Beta counting
1957Wr37: Nuc. Sci. Eng. **2**, 427	11.06(4)	Ionization chamber
1999Po32: Radiokhimya **41**, 25	11.2(1)	Gamma decay curve
1960Wi10: PR **118**, 242	11.5(5)	Proportional counter
1952Ru10: PR **86**, 775	11.9(3)	Beta, mag. spect.
1951Em23: PR **83**, 40	11.1(5)	Beta, mag. spect.
1951Ko01: PR **81**, 1056	11.6(3)	Beta, mag. spect.
1951MaZZ: NNES **9**, 1229	11.0(3)	Beta counting
1946Bo25: Z. Naturforsch. 1, 179	11.1(2)	Beta counting

^{147}Nd β^- decay: half-life re-evaluation

11.03(3) d

Weighted average (Normalized Residuals Method: NIM-A 313, 277 (1992)), of 5 most-precisely quoted results: 11.26(1) (2019Br01), 10.98(1) (1971Ba28), 11.02(5) (1963Ho15), 11.14(6) (1960Al33), 11.06(4) (1957Wr37) : discrepant dataset: some uncertainties adjusted.

ENSDF: 10.98(1) d from 1971Ba28.

DDEP: 10.987(11) d, 1971Ba28 + 7 older measurements, but missed 1960Al33; 90% weight for 1971Ba28.

Evaluation of Eγ, Iγ data, mixing ratios, J^{π} etc.

About 15 references from 1966-1997 considered for Iγ data, and 6 from 1961 to 1997 for Eγ in the re-evaluation. Present (2008, 2013) ENSDF evaluation uses only 1 reference for Iγ data and 2 for Eγ.

Beta-Shape code by Xavier Mougeot (Saclay) will be used for log *ft* values and beta radiation data.

Atomic radiation data: yet to be included, when

BrIcc-Emis code by Tibor Kibedi (ANU) becomes available.

Details of evaluation are in the attached data file in NDS-format. Critical comments are welcome. This evaluation still needs to go through a formal review procedure.

Epilogue

Sunday Nov 3, 2019: in response to my request, received from Dr. Xavier Mougeot (Saclay) copy of an abstract of ICRM-2019 with some results of LNHB-Saclay experiment: Absolute intensity of 531-keV gamma ray: 13.11(13) using $4\pi\beta\gamma$-coin and $4\pi\gamma$ methods.

This result can be compared with 13.00(34) in this evaluation.

Need to re-visit this evaluation after detailed results from Saclay as well as from Livermore become available.

Acknowledgments:

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