^{144m}Pr – Comments on evaluation of decay data
by A. L. Nichols

Evaluated: May/June 2013 and March/April 2014

Evaluation Procedures

Limitation of Relative Statistical Weight Method (LWM) and other analytical techniques were applied to average numbers throughout the evaluation. The uncertainty assigned to the average value was always greater than or equal to the smallest uncertainty of the values used to calculate the average.

Decay Scheme

^{144m}Pr ($T_{½}$ = 7.2 min) undergoes 99.94% IT decay (Q_{IT} = 59.03 (3) keV) and 0.06% β^- decay ($Q(\beta^-)$ = 3056.4 (24) keV) via various excited levels to the ground state of ^{144}Nd. The decay scheme is dominated by a simple IT decay mode consisting of a single 59.03-keV gamma transition, whereas the small β^- decay mode is poorly characterized. Despite the latter inadequacies, a reasonably well-defined decay scheme can be derived primarily from 1960Ge05 and 1985Da16 in terms of three low-intensity β^- transitions and six gamma transitions, in which the conversion-electron emissions identified with the 59.03-keV M3 gamma transition play a dominant role.

Nuclear Data

^{144m}Pr constitutes a minor branch in the ^{144}Ce-^{144}Pr-^{144}Nd decay chain. A limited number of reasonably high-energy gamma rays of low intensity are generated in the β^- decay mode of ^{144m}Pr.

Half-life

Only half-life measurements by Fasching *et al*. (1970Fa03) and Chatterjee-Das *et al*. (1976Ch33) have been published, of which the value reported by 1976Ch33 was described as being tentative.

Reference	Half-life (min)
1970Fa03	7.2 ± 0.2
1976Ch33	6.6 ± 1.0*
Recommended value	7.2 ± 0.2

* Half-life assigned tentatively to ^{144m}Pr.

Although such a small data set still permits analysis by both the limitation of relative statistical weight method (LWM) and the normalised residual method (NRM), weighted uncertainty adjustments have not been implemented because of the nature of the 1976Ch33 measurement. Thus, a half-life value of (7.2 ± 0.2) minutes is recommended, as determined by 1970Fa03.

Q values

Q_{IT}-value of 59.03 (3) keV and Q_{β}-value of 3056.4 (24) keV were adopted for the ^{144m}Pr decay modes (2012Wa38).

Gamma-ray energies and emission probabilities

Energies

The well-defined nuclear level energies of 2001So16 were used to calculate the gamma transition energies and their uncertainties. This approach was adopted because of the more wide-ranging origins of the level energies compared with the measured gamma-ray decay data. Nevertheless, the recommended gamma-ray energy standard proposed by 2000He14 has been adopted in the form of the 696.505(4)-keV gamma ray. Various nuclear-level half-lives were adopted and calculated from the half-life and mean lifetime measurements of 1976CoZX, 1994Ro13 and 1998Hi09.

Adopted energies, spins and parities for the nuclear levels of ^{144}Pr and ^{144}Nd (2001So16).

	Nuclear level number	Nuclear level energy (keV)	Spin and parity	
^{144}Pr	0	0.0	0 −	17.29 (4) min
^{144m}Pr	1	59.03 ± 0.03	3 −	7.2 (2) min
^{144}Nd	0	0.0	0 +	2.3 (3) × 10^{15} a
	1	696.561 ± 0.010	2 +	−
	2	1314.669 ± 0.013	4 +	7.4 (9) ps
	3	1510.871 ± 0.021	3 −	0.56 (7) ps
	4	1560.920 ± 0.013	2 +	−
	(5)	2072.91 ± 0.03	2 +	59 (10) fs
	(6)	2084.68 ± 0.03	0 +	0.12 (5) ps
	(7)	2185.75 ± 0.03	1 −	15 (2)
	(8)	2368.82 ± 0.04	2 +	39 (14) fs
	(9)	2582.32 ± 0.06	(3 +)	−
	(10)	2655.54 ± 0.03	1 +	9.9 (2) fs
	(11)	2675.61 ± 0.08	0 +	0.2 (1) ps
	(12)	2742.99 ± 0.07	0 +	64 (40) fs
	(13)	2946.04 ± 0.10	(2, 3, 4) −	−

Transition and gamma-ray energies of ^{144m}Pr (2001So16).

		Transition energy (keV)	Gamma-ray energy, E_γ (keV)	Decay mode
$\gamma_{1,0}$	(Pr)	59.03 (3)	59.03 ± 0.03	IT
$\gamma_{2,1}$	(Nd)	618.108 (16)	618.107 ± 0.016	β^-
$\gamma_{1,0}$	(Nd)	696.561 (10)	696.559 ± 0.010*	β^-
$\gamma_{3,1}$	(Nd)	814.310 (23)	814.308 ± 0.023	β^-
$\gamma_{(13,2)}$	(Nd)	1631.37 (10)	1631.36 ± 0.10	β^-
$\gamma_{(9,1)}$	(Nd)	1885.76 (6)	1885.75 ± 0.06	β^-

* Subsequently modified in line with the recommended energy standard of Helmer and van der Leun (2000He14).

Emission Probabilities

The gamma-ray emission probabilities were only partially obtained from the measurements of 1979Pr11 and 1985Da16. Thus, the emission probabilities of the 1631.36- and 1885.75-keV gamma rays were adopted in this manner, while the emission probability of the 618.107-keV gamma ray was arbitrarily adjusted from a measured value of 0.016 (7) to 0.030 (3) to achieve a population-depopulation balance of the 1314.67-keV nuclear level of ^{144}Nd. Equivalent emission probabilities for the 696.505- and 814.308-keV gamma rays were assigned to be 0.06 (2) and 0.02 (1), respectively, after due consideration of the β^--decay mode in which zero β^- feeding of the 1314.67-, 696.561-keV and ground states of ^{144}Nd were assumed on the basis of spin-parity considerations or balanced γ population-depopulation of these particular nuclear levels.

Studies of the β^- feeding of the 1510.87-keV nuclear level of ^{144}Nd have led to values of 0.05 (3) % (1970Fa03) and < 0.02 (1) % (1985Da16) – after careful consideration, a value of 0.02 (1) % has been recommended. An approximate normalization factor of (1.00 ± 0.10) was adopted in conjunction with these recommended gamma-ray emission probabilities. Under these somewhat unsatisfactory circumstances, a β^--decay mode with a branching fraction of 0.0006 (2) has been derived to give a matching IT branching fraction of 0.9994 (2). Finally, the absolute emission probability of the 59.03-keV M3 gamma transition was calculated from the IT branching fraction and the total internal conversion coefficient to be 0.0818 (12) %.

Multipolarities, Internal-Conversion and Internal-Pair Formation Coefficients

The nuclear level scheme specified by Sonzogni has been used to define the multipolarities of the gamma transitions on the basis of the known spins and parities (2001So16). Adopted multipolarities are 100%M3 for the 59.03-keV gamma ray constituting the IT decay mode, 100%E2 for the 618.107- and 696.505-keV gamma rays, and 100%E1 for the 814.308-keV gamma rays. Evidence for the mixing ratio and multipolarity of the 1885.75-keV (98.3%M1 + 1.7%E2) gamma transition arises from γ−γ correlation studies of 1998Hi09.

Measured and recommended gamma-ray energies.

Eγ (keV)										
1968Ra01	**1968Sa05**	**1970An15**	**1970Fa03**	**1974Be09**	**1976Ra22**	**1979Gr01**	**1979Pr11**	**1985Da16**	**2000He14**	**Recommended**[#]
−	−	59.0 (3)	−	−	58.5 (2)	−	−	−	−	59.03 ± 0.03
−	−	−	−	−	−	−	618.2 (5)	617.8 (2)	−	618.107 ± 0.016
696.3 (4)	696.48 (9)	−	696.43 (6)	696.49 (2)	696.4 (1)	696.510 (6)	696.50 (2)	696.50 (5)	696.505 (4)	696.505 ± 0.004[*]
813.7 (6)	−	−	813.8 (3)	814.15 (15)	813.6 (2)	−	814.03 (10)	814.10 (10)	−	814.308 ± 0.023
−	−	−	−	−	−	−	−	1631.36 (10)	−	1631.36 ± 0.10
−	−	−	−	−	−	−	−	1885.3 (2)	−	1885.75 ± 0.06

[#] Determined from the nuclear level energies of 2001So16 unless stated otherwise.
[*] Gamma-ray energy adopted from the recommended energy standards published by Helmer and van der Leun (2000He14).

Published relative gamma-ray emission probabilities.

E_γ (keV)	P_γ^{rel}			
	1970An15[†]	**1976Ra22**[‡]	**1979Pr11**[§]	**1985Da16**[§]
59.03 (3)	~ 0.01	0.003 (2)	−	−
618.107 (16)	−	−	0.015 (7)	0.016 (7)
696.505 (4)	−	−	−	−
814.308 (23)	−	−	−	−
1631.36 (10)	−	−	−	0.030 (3)
1885.75 (6)	−	−	−	0.010 (3)

[†] Emission probability expressed relative to P_γ(133.515 keV) of 100 % in ^{144}Ce β^- decay.
[‡] Emission probability expressed relative to P_γ(133.515 keV) of 10.0 (1) % in ^{144}Ce β^- decay.
[§] Emission probability expressed relative to P_γ(696.505 keV) of 100 % in ^{144}Pr β^- decay.

Recommended absolute gamma-ray emission probabilities and transition probabilities.

E_γ (keV)	P_γ^{abs}(%) [*]	Transition probability (%)
59.03 ± 0.03	0.0818 ± 0.0012[†]	99.94 ± 0.02
618.107 ± 0.016	0.030 ± 0.003[‡]	0.030 ± 0.003
696.505 ± 0.004	0.06 ± 0.02[#]	0.06 ± 0.02
814.308 ± 0.023	0.02 ± 0.01[§]	0.02 ± 0.01
1631.36 ± 0.10	0.030 ± 0.003	0.030 ± 0.003
1885.75 ± 0.06	0.010 ± 0.003	0.010 ± 0.003

[*] Absolute emission probabilities either adopted directly from 1979Pr11 and 1985Da16, or adjusted and derived on the basis of the proposed decay scheme, with an estimated normalization factor of (1.00 ± 0.10) applied to the relative gamma-ray emission probabilities as originally quoted.
[†] Determined from a calculated branching fraction for the IT-decay mode of 0.9994 (2) and total ICC of 1221 (18) for the 59.03-keV M3 gamma transition.
[‡] Arbitrarily assigned a value of 0.030 (3) to achieve a population-depopulation balance involving the 618.107- and 1631.36-keV gamma emissions identified with the 1314.67-keV nuclear level of ^{144}Nd to which β^- feeding was assumed to be negligible.
[#] Arbitrarily assigned a value of 0.06 (2) to achieve a population-depopulation balance involving the populating 618.107-, 814.31- and 1885.75-keV gamma emissions and the depopulating 696.505-keV gamma emissions identified with the 696.56-keV nuclear level of ^{144}Nd to which β^- feeding was assumed to be negligible.
[§] Arbitrarily assigned a value of 0.02 (1) based on β^- feeding to the 1510.87-keV nuclear level of ^{144}Nd, as determined to be 0.05 (3) % by Fasching *et al*. (1970Fa03) and < 0.02 % by Dalmasso *et al*. (1985Da16).

Gamma-ray emissions: multipolarities, and theoretical internal-conversion (frozen orbital approximation) and internal-pair formation coefficients.

E_γ (keV)		Multipolarity	α_K	α_L	α_{L1}	α_{L2}	α_{L3}	α_{M+}	$\alpha_{ICCtotal}$	α_{IPF}	α_{total}
59.03 (3)	(Pr)	M3	408 (6)	618 (9)	233 (4)	34.9 (5)	351 (5)	195	1221 (18)	−	1221 (18)
618.107 (16)	(Nd)	E2	0.005 68 (8)	0.000 869 (13)	0.000 673 (10)	0.000 123 1 (18)	0.000 072 7 (11)	0.000 241	0.006 79 (10)	−	0.006 79 (10)
696.505 (4)	(Nd)	E2	0.004 27 (6)	0.000 631 (9)	0.000 508 (8)	0.000 078 5 (11)	0.000 045 1 (7)	0.000 169	0.005 07 (7)	−	0.005 07 (7)
814.308 (23)	(Nd)	E1	0.001 198 (17)	0.000 152 8 (22)	0.000 140 7 (20)	0.000 005 46 (8)	0.000 006 56 (10)	0.000 040 2	0.001 391 (20)	−	0.001 391 (20)
1631.36 (10)	(Nd)	−	−	−	−	−	−	−	−	−	−
1885.75 (6)	(Nd)	(98.3%M1 + 1.7%E2) δ = 0.13 (5) (1998Hi09)	0.000 686 (10)	0.000 087 8 (13)	0.000 084 3 (13)	0.000 002 59 (4)	0.000 000 926 (17)	0.000 023 3	0.000 797 (10)	0.000 255 (4)	0.001 052 (15)

The detailed conversion-electron measurements of Geiger *et al*. for the 59.03-keV gamma transition are particularly noteworthy (1960Ge05, 1969Ge01) − this M3 gamma transition constitutes the IT-decay mode of ^{144m}Pr.

Recommended internal conversion coefficients have been determined from the frozen orbital approximation of Kibédi *et al*. (2008Ki07), based on the theoretical model of Band *et al*. (2002Ba85, 2002Ra45). The (98.3%M1 + 1.7%E2) 1885.75-keV gamma transition also undergoes internal-pair formation, and the coefficient for this process has also been quantified from the tabulations of 2008Ki07.

β− energies and emission probabilities

Energies

All β^- energies were derived from the structural details of the proposed decay scheme. The nuclear level energies of 2001So16 and evaluated Q-value of 3056.4 (24) keV (2012Wa38) were used to determine the recommended energies and uncertainties of the β^- emissions.

Emission Probabilities

Absolute emission probabilities were derived for the population-depopulation balances of the relative gamma-ray emission probabilities, their theoretical internal-conversion coefficients, and a normalization factor of (1.00 ± 0.10) for the gamma-ray emissions, as proposed above. β^- decay to the 1314.67-, 696.561-keV and ground-state levels of ^{144}Nd were assumed to be zero on the basis of the limited and rather questionable gamma-ray emission probabilities involved in the population-depopulation of these particular nuclear levels. Log*ft* values and average $E_{\beta-}$ energies were determined by means of the LOGFT code.

Recommended energies and emission probabilities for the β− decay of ^{144m}Pr.

	E_β (keV)*	Av. $E_{\beta-}$ (keV)	P_β	^{144}Pr	^{144}Nd	transition type	log *ft*
$\beta^-_{(1,13)}$	110.4 (24)	29.0 (7)	0.030 (3)	3 −	(2, 3, 4) −	(allowed)	4.65
$\beta^-_{(1,9)}$	474.1 (24)	143.0 (8)	0.010 (3)	3 −	(3 +)	(first forbidden non-unique)	7.15
$\beta^-_{1,3}$	1545.5 (24)	570.0 (11)	0.02 (1)	3 −	3 −	allowed	8.7
			Σ 0.06 (2)				

* Determined from the nuclear level energies of 2001So16 and Q-value of 3056.4 (24) keV (2012Wa38).

Energies and emission probabilities of noteworthy internal-conversion electrons.

		Energy (keV)	Electrons per 100 disint.
$ec_{1,0\ T}$	(Pr)	17.04 – 59.03	99.86 (2)
$ec_{1,0\ K}$	(Pr)	17.04 (3)	33.37 (1)
$ec_{1,0\ L}$	(Pr)	52.20 – 53.07	50.54 (1)
$ec_{1,0\ M}$	(Pr)	57.52 – 58.10	12.68 (1)
$ec_{1,0\ N+}$	(Pr)	58.73 – 59.03	3.27 (1)

A consistent decay scheme was derived that contains three low-intensity β^- transitions and six gamma-ray emissions (one gamma transition constitutes the main IT-decay mode, and the other five gamma rays are associated with the small β^--decay mode).

Atomic Data

The X-ray and Auger-electron data have been calculated using the evaluated gamma-ray data, and atomic data from 1996Sc06, 1998ScZM and 1999ScZX. Both the X-ray and Auger-electron emission probabilities were determined by means of the EMISSION computer program (version 4.02, 28 February 2012), as described in 2000Sc47. This program incorporates atomic data from 1996Sc06 and the evaluated gamma-ray data.

K and L X-ray energies and emission probabilities of ^{144m}Pr.

			Energy (keV)	Photons per 100 disint.	Relative probability
XL		(Pr)	4.453 – 6.617	10.5 (5)	
	XL_l	(Pr)	4.453	0.227 (7)	
	XL_α	(Pr)	5.013 – 5.033	5.74 (16)	
	XL_η	(Pr)	4.929	0.0498 (15)	
	XL_β	(Pr)	5.489 – 5.851	3.89 (7)	
	XL_γ	(Pr)	6.327 – 6.617	0.625 (13)	
XK_α	$XK_{\alpha2}$	(Pr)	35.5506 (2)	8.66 (19)	54.8
	$XK_{\alpha1}$	(Pr)	36.0267 (2)	15.8 (4)	100
$XK'_{\beta1}$	$XK_{\beta3}$	(Pr)	40.6533 (7)	)	
	$XK_{\beta1}$	(Pr)	40.7487 (5)	) 4.81 (12)	30.4
	$XK''_{\beta5}$	(Pr)	41.050	)	
$XK'_{\beta2}$	$XK_{\beta2}$	(Pr)	41.774 (2)	)	
	$XK_{\beta4}$	(Pr)	41.877	) 1.23 (4)	7.78
	$XKO_{2,3}$	(Pr)	41.968	)	
XL		(Nd)	4.633 – 6.901	0.000 067 (8)	
XK_α	$XK_{\alpha2}$	(Nd)	36.8478 (3)	0.000 119 (23)	54.1
	$XK_{\alpha1}$	(Nd)	37.3614 (2)	0.000 22 (5)	100
$XK'_{\beta1}$	$XK_{\beta3}$	(Nd)	42.1670 (4)	)	
	$XK_{\beta1}$	(Nd)	42.2717 (3)	) 0.000 067 (13)	30.5
	$XK''_{\beta5}$	(Nd)	42.580	)	
$XK'_{\beta2}$	$XK_{\beta2}$	(Nd)	43.335 (3)	)	
	$XK_{\beta4}$	(Nd)	43.451	) 0.000 017 (4)	7.73
	$XKO_{2,3}$	(Nd)	43.548	)	

Auger-electron energies and emission probabilities of ^{144m}Pr.

	Energy (keV)	Electrons per 100 disint.	Relative probability
e_{AK} (Pr)		2.87 (15)	
KLL	28.162 – 29.890	1.85 (10)	100
KLX	33.576 – 36.004	0.91 (5)	49.2
KXY	38.97 – 41.95	0.113 (7)	6.11
e_{AL} (Pr)	2.90 – 4.91	69 (10)	3730
e_{AK} (Nd)		0.000 038 (8)	
KLL	29.154 – 30.978	0.000 024 (5)	100
KLX	34.798 – 37.340	0.000 012 0 (24)	50
KXY	40.42 – 43.53	0.000 001 5 (3)	6.25
e_{AL} (Nd)	3.01 – 5.10	0.000 40 (5)	1667

Pr: ω_K = 0.914 (4); ϖ_L = 0.132 (5); n_{KL} = 0.871 (4), and Nd: ω_K = 0.918 (4); ϖ_L = 0.140 (6); n_{KL} = 0.866 (4) were taken from 1996Sc06.

Electron energies were determined from electron binding energies tabulated by Larkins (1977La19) and the evaluated gamma-ray energies. Absolute electron emission probabilities were calculated from the evaluated absolute gamma-ray emission probabilities and associated internal conversion coefficients.

Data Consistency

An effective Q-value has been calculated from the Q_{IT}-value of 59.03 (3) keV and $Q_{\beta-}$-value of 3056.4 (24) keV derived and adopted from the atomic mass evaluation of Wang *et al*. (2012Wa38), and their recommended branching fractions formulated during the evaluation of the decay scheme of ^{144m}Pr:

$$\text{effective Q-value} = \sum (Q_i \; x \; BF_i) = [59.03\ (3) \times 0.9994\ (2)] + [3056.4\ (24) \times 0.0006\ (2)]$$

$$= 59.00\ (12) + 1.8\ (6) = 60.8\ (6)\ \text{keV}$$

This value has been compared with the Q-value calculated by summing the contributions of the individual emissions to the ^{144m}Pr decay processes (i.e. β^-, conversion electrons, γ, etc.):

$$\text{calculated Q-value} = \sum (E_i \times P_i) = 60.9\ (5)\ \text{keV}$$

Percentage deviation from the effective Q-value is − (0.2 ± 1.3) %, which supports the derivation of a consistent decay scheme with a reasonably significant variant.

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