Analysis of Long-Range Alpha-Emission Data

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Alpha barrier penetrabilities for the long-range alpha particles of Po^{212} and Po^{214} are calculated by using the diffuse exponential nuclear potential derived from optical-model analysis of alpha-particle elastic-scattering data. The calculations are made on the same basis as reported by Rasmussen in two previous publications. Partial half-lives for alpha and gamma emission are calculated on the assumption that the long-range alpha decay is unhindered with respect to the ground-state alpha decay.

INTRODUCTION

RASMUSSEN has reported alpha-decay barrier-penetration calculations using an exponential nuclear potential.[1,2] Details of the calculation were discussed,[1] and numerical results for all measured alpha-particle transitions of even-even[1] and odd-mass[2] nuclei were given. The alpha-nuclear potential used was the real part of a potential given by Igo to fit alpha elastic-

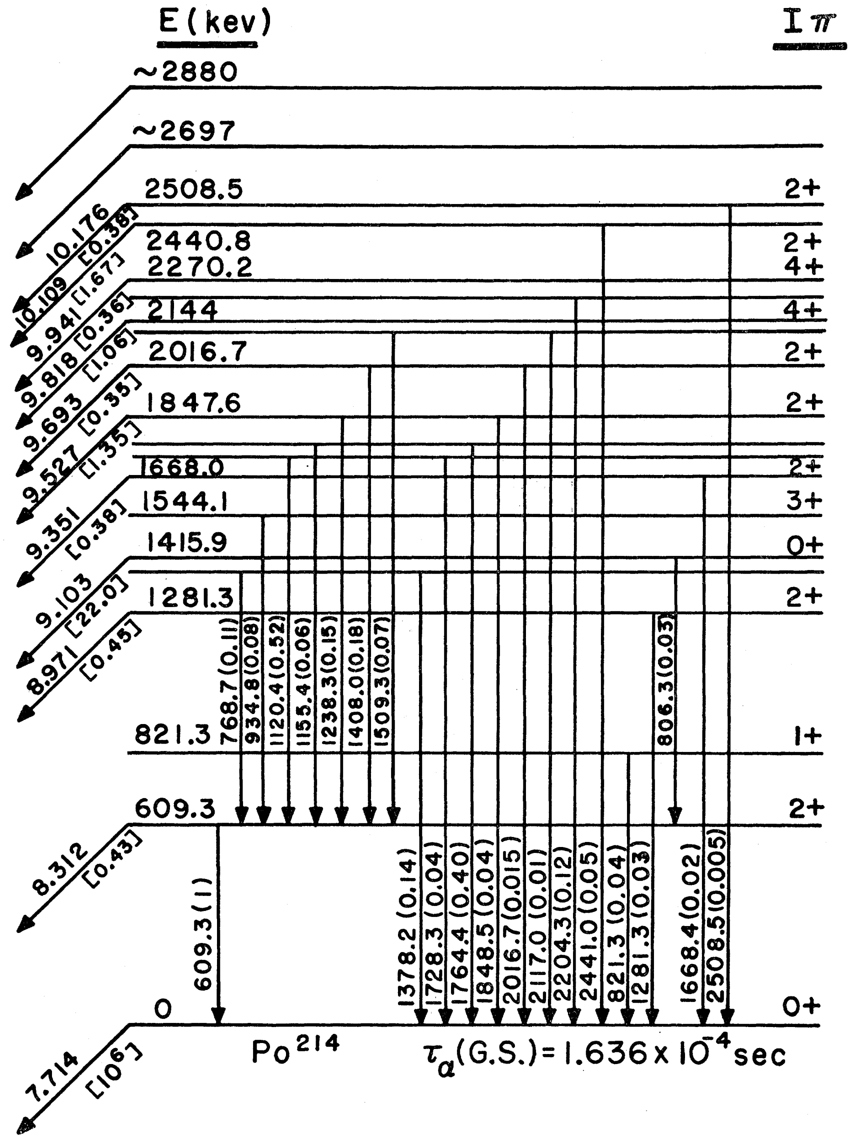

FIG. 1. Level scheme and decay scheme of Po^{214} as given by Bishop (reference 4). E_α in Mev includes electron screening correction. Alpha intensities in square brackets relative to N_α (ground state) $\equiv 10^6$. E_γ in kev. Gamma intensities in parenthesis relative to N_γ (609 kev) $\equiv 1$.

[1] J. O. Rasmussen, Phys. Rev. **113**, 1593 (1959).
[2] J. O. Rasmussen, Phys. Rev. **115**, 1675 (1959).

scattering data[3]:

$$V(r) = -1100 \exp\left\{\frac{1.17A^{\frac{1}{3}} - r}{0.574}\right\} \text{ Mev.}$$

This potential is used here to calculate with the IBM-650 computer the alpha-decay barrier-penetration factors for the long-range alpha particles from the excited states of Po^{212} and Po^{214}. The centrifugal potential for the angular momentum of the alpha particle, as determined from the decay schemes, is included in these calculations. The penetration factors are used to calculate the partial half-lives of the levels for alpha decay, assuming that the decay is unhindered with respect to the ground-state decay. The relative alpha-particle and gamma-ray abundances are then used to calculate partial half-lives for the gamma transitions from these same states.

Po^{214}

In the case of Po^{214}, two different proposed level schemes and decay schemes are used. The first of these, due to Bishop[4] (see Fig. 1), assumes that all of the long-range alpha groups arise from transitions to the ground state of Pb^{210}. The second, due to Hauser[5] (see Fig. 2), proposes that three of the long-range alpha groups arise from transitions to excited states of Pb^{210}. This proposal was made to account for the fact that

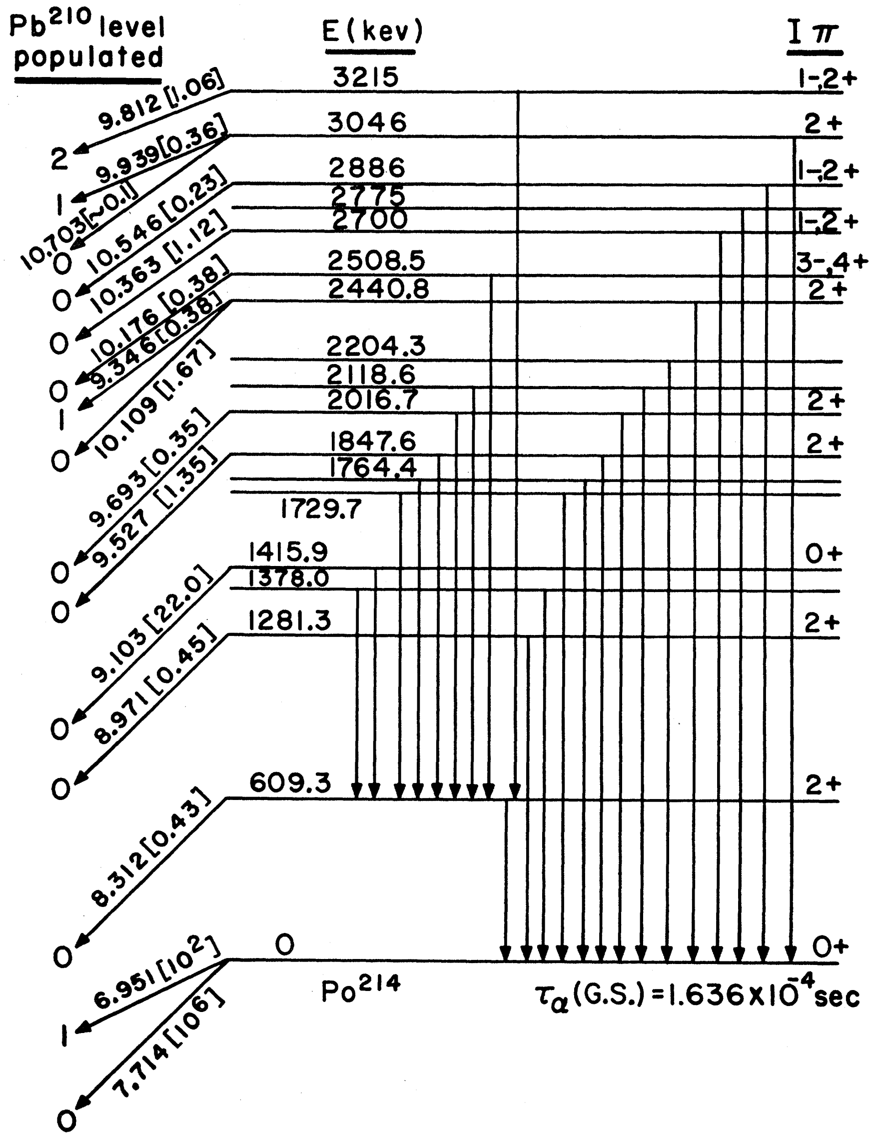

FIG. 2. Level scheme and decay scheme of Po^{214} as given by Hauser (reference 5). E_α in Mev includes electron screening correction. Alpha intensities in square brackets relative to N_α (ground state) $\equiv 10^6$. Pb^{210} level populated in alpha decay: 0 = ground state; 1 = first excited state; 2 = second excited state.

[3] G. Igo, Phys. Rev. Letters **1**, 72 (1958).
[4] G. R. Bishop, Nuclear Phys. **5**, 358 (1958).
[5] U. Hauser, Z. Physik **150**, 599 (1958).

TABLE I. Po^{214} alpha-barrier penetration factors and partial half-lives of excited states based on the decay scheme due to Bishop.[a]

Energy level (kev)	E_α with screening correction (Mev)	N_α relative to 10^6 ground-state decays[b]	α angular momentum	Barrier-penetration factor, P	Partial α half-life (sec)	N_γ relative to 10^2 ground-state decays	E_γ (kev)	Partial γ half-life, $\tau_{\frac{1}{2}}$ (sec)	Single-particle half-life,[c] τ_{sp} (sec)	$\tau_{sp}/\tau_{\frac{1}{2}}$
0	7.714	10^6	0	1.58×10^{-16}	1.636×10^{-4}	...	...	...	...	...
609.3	8.312	0.43	2	4.65×10^{-15}	5.5×10^{-6}	42	609.3	5.6×10^{-12}	$4.0\times10^{-11}(E2)$	7.1
1281.3	8.971	0.45	0	3.43×10^{-13}	7.5×10^{-8}	(1.3) (?)	1281.3	2.6×10^{-12}	...	...
1378.0	9.066	(2.7)[d]	2	3.46×10^{-13}	7.5×10^{-8}	5.9	1378	(3.4×10^{-12})[d]	$6.8\times10^{-13}(E2)$	(0.2)[d]
						4.6	769	(4.4×10^{-12})[d]	$1.3\times10^{-11}(E2)$	(3.0)[d]
									$5.5\times10^{-14}(M1)$	(0.012)[d]
1415.9	9.103	22.0	0	6.93×10^{-13}	3.7×10^{-8}	$(0.3)_K$	e	...	...	...
						1.3	806.3	6.3×10^{-11}	$9.9\times10^{-12}(E2)$	0.16
1668.0	9.351	0.38	2	1.52×10^{-12}	1.7×10^{-8}	0.8	1668.4	8.1×90^{-13}	$2.6\times10^{-13}(E2)$	0.32
1847.6	9.527	1.35	2	3.64×10^{-12}	7.1×10^{-9}	1.7 ..	1848.5	5.6×10^{-13}	$1.6\times10^{-13}(E2)$	0.29
						6.3 ..	1238.3	1.5×10^{-13}	$1.2\times10^{-12}(E2)$	8.0
									$1.3\times10^{-14}(M1)$	0.087
2016.7	9.693	0.35	2	8.11×10^{-12}	3.2×10^{-9}	0.6	2016.7	1.9×10^{-13}	$1.0\times10^{-13}(E2)$	0.53
						7.6	1408.0	1.5×10^{-14}	$6.1\times10^{-13}(E2)$	41
									$8.9\times10^{-15}(M1)$	0.59
2144	9.818	1.06	4	4.71×10^{-12}	5.5×10^{-9}	(≤1)	1534	$\geq5.8\times10^{-13}$	$4.0\times10^{-13}(E2)$	≤0.69
2270.2	9.941	0.36	4	8.34×10^{-12}	3.1×10^{-9}	(≤0.8)	1661	$\geq1.4\times10^{-13}$	$2.7\times10^{-13}(E2)$	≤1.9
2440.8	10.109	1.67	2	5.48×10^{-11}	4.7×10^{-10}	2.1	2441	3.7×10^{-14}	$3.9\times10^{-14}(E2)$	1.1
2508.5	10.176	0.38	2	7.36×10^{-11}	3.5×10^{-10}	0.21	2508.5	6.3×10^{-14}	$3.4\times10^{-14}(E2)$	0.54

[a] See reference 4.
[b] G. H. Briggs, Revs. Modern Phys. **26**, 1 (1954).
[c] Calculated from the formulas given by Moszkowski (reference 6).
[d] These values were calculated assuming that the partial γ half-life of the 1378-kev gamma is five times the single-particle gamma half-life.
[e] Conversion electrons. Strength parameter $|\rho|_K=0.035$ [see E. L. Church and J. Weneser, Phys. Rev. **103**, 1035 (1956).]

TABLE II. Po^{214} alpha-barrier penetration factors and partial half-lives of excited states based on the decay scheme due to Hauser.[a]

Energy level (kev)	E_α with screening correction (Mev)	N_α relative to 10^6 ground-state decays[b]	α angular momentum	Barrier-penetration factor, P	Partial α half-life (sec)	N_γ relative to 10^2 ground-state decays	E_γ (kev)	Partial γ half-life, $\tau_{\frac{1}{2}}$ (sec)	Single-particle half-life,[c] τ_{sp} (sec)	$\tau_{sp}/\tau_{\frac{1}{2}}$
0	7.714	10^6	0	1.58×10^{-16}	1.636×10^{-4}	...	...	...	...	($\delta^2=0.111$ Mev)
	6.951	$\sim10^2$ [d]	2	2.99×10^{-19}	8.6×10^{-2}	...	...	...	...	($\delta^2=0.0096$ Mev)
609.3	8.312	0.43	2	4.65×10^{-15}	5.5×10^{-6}	42	609.3	5.6×10^{-12}	$4.0\times10^{-11}(E2)$	7.1
1281.3	8.971	0.45	2	2.08×10^{-13}	1.2×10^{-7}	1.3	1281.3	4.3×10^{-12}	$9.8\times10^{-13}(E2)$	0.23
1415.9	9.103	22.0	0	6.93×10^{-13}	3.7×10^{-8}	$(0.3)_K$	e	...	...	...
						1.3	806.3	6.3×10^{-11}	$9.9\times10^{-12}(E2)$	0.16
1847.6	9.527	1.35	2	3.64×10^{-12}	7.1×10^{-9}	1.7	1848.5	5.6×10^{-13}	$1.6\times10^{-13}(E2)$	0.29
						6.3	1238.3	1.5×10^{-13}	$1.2\times10^{-12}(E2)$	8.0
									$1.3\times10^{-14}(M1)$	0.087
2016.7	9.693	0.35	2	8.11×10^{-12}	3.2×10^{-9}	0.6	2016.7	1.9×10^{-13}	$1.0\times10^{-13}(E2)$	0.53
						7.6	1408.0	1.5×10^{-14}	$6.1\times10^{-13}(E2)$	41
									$8.9\times10^{-15}(M1)$	0.59
2440.8	10.109	1.67	2	5.48×10^{-11}	4.7×10^{-10}	2.1	2441	3.7×10^{-14}	$3.9\times10^{-14}(E2)$	1.1
	9.346	0.38	0	2.43×10^{-12}	1.06×10^{-8}			1.9×10^{-13}		0.21
2508.5	10.176	0.38	4	2.40×10^{-11}	1.07×10^{-9}	<1.1	1900	$>3.7\times10^{-14}$	$1.4\times10^{-13}(E2)$	<3.8
			3	4.55×10^{-11}	5.7×10^{-10}			$>2.0\times10^{-14}$	$1.4\times10^{-13}(E2)$	<7.0
									$3.6\times10^{-15}(M1)$	<0.18
2700	10.363	1.12	2	1.65×10^{-10}	1.56×10^{-10}	5×10^{-2}	2700	3.5×10^{-13}	$2.4\times10^{-14}(E2)$	0.069
			1	2.27×10^{-10}	1.14×10^{-10}			2.6×10^{-13}	$2.4\times10^{-14}(E2)$	0.092
									$1.3\times10^{-15}(M1)$	0.005
2886	10.546	0.23	2	3.54×10^{-10}	7.3×10^{-11}	4.3×10^{-2}	2886	3.9×10^{-14}	$1.7\times10^{-14}(E2)$	0.44
			1	4.87×10^{-10}	5.3×10^{-11}			2.8×10^{-14}	$1.7\times10^{-14}(E2)$	0.61
									$1.0\times10^{-15}(M1)$	0.036
3046	10.703	~0.1	2	6.71×10^{-10}	3.8×10^{-11}	3.7×10^{-2}	3046	1.0×10^{-14}	$1.3\times10^{-14}(E2)$	1.3
	9.939	0.36	0	4.15×10^{-11}	6.2×10^{-10}			6.0×10^{-13}		0.022

[a] See reference 5.
[b] G. H. Briggs, Revs. Modern Phys. **26**, 1 (1954).
[c] Calculated from the formulas given by Moszkowski (reference 6).
[d] R. J. Walen and G. Bastin, *Proceedings of the International Congress on Nuclear Physics, 1958* (Dunod Publishing Company, Paris, 1959), pp. 910–916.
[e] Conversion electrons. Strength parameter is $|\rho|_K=0.035$ [see E. L. Church and J. Weneser, Phys. Rev. **103**, 1035 (1956)].

gamma rays from the levels corresponding to some of the alpha groups have not been detected.

The numerical results for Po^{214} are summarized in Tables I and II along with the decay-scheme data utilized. The alpha barrier-penetration factor, P, is given for each of the states, assuming spins and parities as indicated in Figs. 1 and 2. This penetration factor is then used to calculate the partial alpha half-life for each level:

$$t_{\alpha,\text{ excited state}} = t_{\alpha,\text{ ground state}} (P_g/P_e),$$

where P_g and P_e are penetration factors for the ground-state and excited-state alpha decay.

This partial alpha half-life and the relative alpha and gamma abundances lead to partial gamma half-lives, which are compared with single-particle gamma half-lives calculated from the formulas given by Moszkowski.[6] The value obtained by Nierhaus and Daniel[7] of 19% of the beta transitions in Bi^{214} going directly to the ground state of Po^{214} was used. The gamma-ray intensities in both cases are taken from the work of Bishop[4] and of Dzhelepov *et al.*[8]

TABLE III. Ratio of reduced width to first excited state to reduced width to ground state for Po^{214} alpha-emitting levels.

Level (kev)	δ^2 (excited state)/ δ^2 (ground state)
0	0.086
2441	5.1
3046	58

No alpha group has been detected from the 1378-kev level. By comparison with the $E2$ transitions from the 1281- and 1416-kev levels the partial gamma half-life of the 1378-kev gamma ray is assumed to be five times the single-particle value. This assumption gives a value of 2.7 alphas from this level per 10^6 ground-state transitions. This number could easily be unresolved from the abundant alpha group from the 0+ 1416-kev level; thus, the data on this level are consistent with the alpha-decay data.

The calculations also show that it is reasonable that some of the gamma rays from certain alpha-emitting states have not been detected. On the other hand, the second decay scheme allows one to calculate relative reduced transition probabilities, δ^2 (see reference 1), for the decay of a few given levels to the first excited state and to the ground state of Pb^{210}. This ratio is shown in Table III, and is seen to increase greatly as the energy increases. This would indicate that the transition to the ground state becomes quite hindered as the energy of the initial state increases.

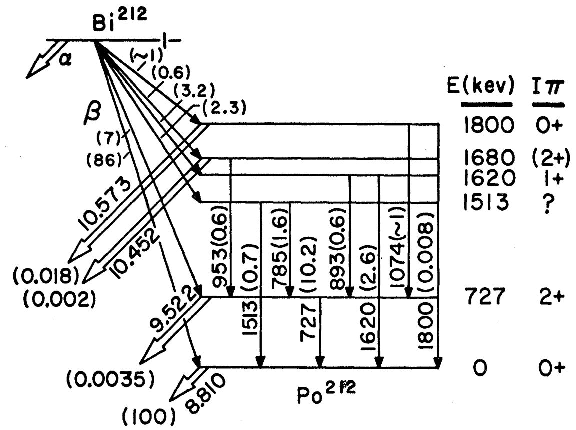

FIG. 3. Level scheme and decay scheme of Po^{212} as given by Emery and Kane (reference 9). E_α in Mev includes electron screening correction. E_γ in kev. All intensities (in parenthesis) relative to 100 Po^{212} ground-state transitions.

The results of these calculations do not differ appreciably from those of Hauser,[5] who used a simpler potential and experimental level spacings. The calculations on the groups leading to excited states are very interesting. The large variation in reduced transition probabilities shown in Table III indicates that the assumption of alpha decay to the excited states of Pb^{210} may not be valid.

Po^{212}

The level scheme and decay scheme of Po^{212} due to Emery and Kane[9] and also to Sergeev *et al.*[10] is shown

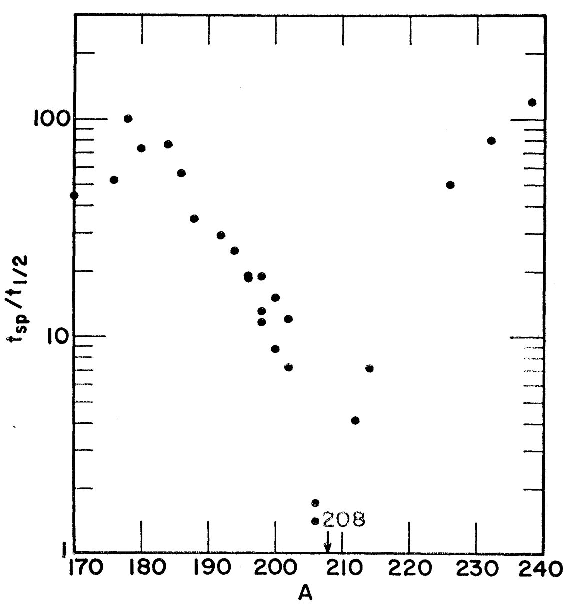

FIG. 4. Half-lives of first excited (2+) levels of even-even nuclei—ratio of single-particle to experimental half-lives.

[6] S. A. Moszkowski, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, New York, 1955), Chap. XIII.

[7] R. Nierhaus and H. Daniel, Z. Naturforsch. **12A**, 1 (1957).

[8] B. Dzhelepov, S. Shestopalova, and I. Uchevatkin, Nuclear Phys. 5, 413 (1958).

[9] G. T. Emery and W. R. Kane, Phys. Rev. **118**, 755 (1960).

[10] A. G. Sergeev, E. M. Krisyuk, G. D. Latyshev, Yu. N. Trofimov, and A. S. Remennyi, Soviet Phys.-JETP **6**, 878 (1958).

TABLE IV. Po^{212} alpha-barrier penetration factors and partial half-lives of excited states.

Energy level (kev)	E_α with screening-correction (Mev)	N_α relative to 10^6 ground-state decays[a]	α angular momentum	Barrier penetration factor, P	Partial α half-life (sec)	N_γ relative to 10^2 ground-state decays	E_γ (kev)	Partial γ half-life, $t_{\frac{1}{2}}$, (sec)	Single-particle γ half-life t_{sp}[b] (sec)	$t_{sp}/t_{\frac{1}{2}}$
0	8.810	10^6	0	1.32×10^{-13}	3.04×10^{-7}	...	...	...	...	...
727	9.522	35	2	3.30×10^{-12}	1.2×10^{-8}	10.2	727	4.1×10^{-12}	$1.7\times10^{-11}(E2)$	4.1
1680	10.452	20	2	2.24×10^{-10}	1.8×10^{-10}	0.6	953	6.0×10^{-13}	$4.4\times10^{-12}(E2)$	7.3
									$2.9\times10^{-14}(M1)$	0.048
1800	10.573	180	0	5.95×10^{-10}	6.7×10^{-11}	~1	1074	1.2×10^{-12}	$2.4\times10^{-12}(E2)$	2.0
						0.008	c			

[a] G. H. Briggs, Revs. Modern Phys. **26**, 1 (1954).
[b] Calculated from the formulas given by Moszkowski (reference 6).
[c] Conversion electrons. Strength parameter is $|\rho|_K=0.041$ [see E. L. Church and J. Weneser, Phys. Rev. **103**, 1035 (1956)].

in Fig. 3. The results for Po^{212} are summarized in Table IV. The gamma intensities and multipolarities are taken from Emery and Kane[9] and the level energies from Sergeev *et al.*[10]

Partial alpha and gamma half-lives are calculated as in the case of Po^{214} above. The results here differ by about a factor of two from those of Emery and Kane,[9] who also based their calculations on the ground-state decay while using a simpler potential.

Ratios of single-particle half-lives to experimental half-lives[11–13] for first excited (2+) states in even-even nuclei are shown in Fig. 4 as a function of mass number. The ratios calculated here for Po^{212} and Po^{214} agree very well with the general trend, indicating that the assumption of unhindered alpha decay is probably good for these first excited states.

[11] D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. **30**, 585 (1958).
[12] R. H. Davis, A. S. Divatia, D. A. Lind, and R. D. Moffat, Phys. Rev. **103**, 1801 (1956).
[13] F. K. McGowan and P. H. Stelson, Phys. Rev. **99**, 112 (1956).