Deterministic RealQM Alpha Decay: Coulomb-Barrier Tunnelling and the Geiger–Nuttall Law

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Abstract

Alpha decay is the clean case for a charge-density account of radioactivity. It is a genuine *two-body* decay — daughter nucleus plus an alpha particle of charge +2 — driven by tunnelling through the daughter's *Coulomb* barrier, with no weak interaction, *no neutrino*, and a *discrete, monoenergetic* alpha line whose sharpness is itself the proof that no third body is emitted. Everything the process needs — extended charge, a Coulomb barrier, two-body kinematics — lies inside RealQM; nothing of the chargeless carrier that a companion analysis of beta decay had to concede is present here. We make two points. First, quantitatively: a single WKB Coulomb-barrier (Gamow) calculation reproduces the Geiger–Nuttall law — $\log_{10} t_{1/2}$ linear in $Q^{-1/2}$ — across the twenty-five orders of magnitude that alpha lifetimes span, matching measured half-lives from ^{232}Th (1.4×10^{10} yr) to ^{212}Po ($0.3\,\mu$s) within a factor of a few, with the Geiger–Nuttall slope 158 against the measured 153. The timing of alpha decay is barrier tunnelling of an extended charge, entirely a charged-sector phenomenon; and the half-life follows equally from the *full* time-dependent RealQM — a metastable resonance evolved in real time decays exponentially, and the complex-energy (Siegert) width extends the Geiger–Nuttall law across the whole span — so the WKB factor is validated, not relied upon. Second, foundationally: on the reading of de Broglie and Bohm the decay is deterministic, its randomness epistemic. A concrete mechanism for this — phase coincidence among coexisting charge domains — suggests itself, but we show it does *not* in fact arise in RealQM as it stands: the escaping domain couples to its neighbours only through their phase-invariant densities across zero-flux boundaries, so the decay is plain Gamow, and gating would require an added phase-permeable (Josephson) interface. Either way alpha decay is a Coulomb process throughout, with the neutrino nowhere in sight.

1 Why alpha decay is the clean case

Radioactive decay puts two questions to a theory: *when* a nucleus decays, and *what carries* the released energy and momentum. For beta decay the second question forces a chargeless carrier — the antineutrino, which takes on average some 60% of the released energy and the momentum imbalance, and which lies outside a charge-density ontology [8]. Alpha decay is different in exactly the way that matters.

Alpha decay is parent → daughter + α, the alpha being a ^{4}He nucleus of charge +2. It is a genuine *two-body* decay: no leptons are created, no weak interaction acts, and no neutrino is emitted. The experimental signature is decisive: alpha spectra are *discrete*, each branch emitting the alpha at a sharp, fixed energy (the alpha carrying $\approx (A-4)/A$ of the release, the heavy daughter the small recoil). A two-body decay from rest is forced by conservation to send the products back-to-back with a *fixed* energy split; a continuous alpha spectrum would signal a hidden third body, as the continuous *electron* spectrum does in beta decay. The alpha line is sharp. That sharpness is the direct evidence that alpha decay has *no* missing carrier.

Every ingredient is then inside RealQM. The alpha is a charged, extended density; the barrier it must cross is the *Coulomb* repulsion of the daughter; the kinematics is two-body. A RealQM two-body decay comes out exactly back-to-back and monoenergetic [8], which is *wrong* for beta decay but *right* for alpha. Where beta decay exposed the boundary of the charge-density picture, alpha decay sits squarely within it.

2 The alpha as unit: dissociation of Be-8 and the stability of carbon

Why the alpha, and not some other fragment? Because the alpha is anomalously stable: doubly magic ($Z = N = 2$, both shells closed), bound by 28.3 MeV, a local maximum in binding per nucleon. Emitting a lone nucleon or a loose cluster is usually forbidden ($Q < 0$); emitting a *pre-bound* alpha releases energy. RealNucleus computes this exceptional stability directly, the ^{4}He binding coming out near experiment and the ^{4}He/deuteron binding ratio at 13.1 against the measured 12.7 [5].

The cleanest alpha decay of all makes the point sharply. ^{8}Be is two alphas, and it is barely *un*bound: two free alphas are more bound than ^{8}Be by only ≈ 92 keV, so ^{8}Be promptly dissociates, half-life $\sim 8 \times 10^{-17}$ s, into *two identical alphas*. This is a symmetric two-body decay driven purely by the mutual Coulomb repulsion of two charged clouds — no barrier to speak of, no daughter/emitter asymmetry, and no neutrino. In the RealNucleus picture ^{8}Be is a weakly bound "molecule" of two alpha "atoms," the charge conjugate of a covalent diatomic, and its anomalously weak bond and prompt decay are a feature of that picture [5]; the decay is simply the dissociation of the weak Coulomb bond.

The ladder then *stabilises* at carbon. ^{12}C is three alphas, and unlike ^{8}Be it is *bound* — by 7.27 MeV against breakup into 3α — so ^{12}C does not decay; it is stable, the endpoint of stellar burning and the basis of organic matter. The passage from the unbound two-alpha cluster to the bound three-alpha cluster is exactly the triple-alpha process ($\alpha + \alpha \rightleftharpoons {}^8\text{Be}$, then ${}^8\text{Be} + \alpha \to {}^{12}\text{C}$) that manufactures carbon, gated by the Hoyle state, an excited three-alpha cluster sitting just above the 3α threshold. Decay and stability are here two faces of one question — whether a Coulomb cluster of alphas holds — with ^{8}Be, ^{12}C, ^{16}O and beyond on a single alpha-cluster ladder that RealNucleus treats as charge-conjugate molecules of alphas. Alpha decay is what happens on the rungs where the molecule does not hold.

What is specifically RealQM here. The tunnelling calculation of §3 is standard Gamow physics and would read the same in any quantum mechanics; it fixes the *timing*. What is specific to RealQM is the *energetics* of the alpha and its clusters — the reason the alpha is the emitted unit and the ladder binds at all — obtained from *Coulomb alone, with no strong force*. With a single scale fixed on the deuteron and no further parameter, the RealNucleus computation reproduces the binding energy of the alpha (29.1 MeV computed against 28.3 measured, 103%) and the whole *alpha-conjugate binding-per-nucleon ladder* at a uniform $\sim 107\%$ (Table 1) [5], with the alpha-to-deuteron binding ratio 13.1 against a measured 12.7 as a scale-free prediction. In this picture the alphas are bound not by a strong force but by shared protons — the charge conjugate of the shared electrons that bond atoms into molecules — so "nucleus as alpha-cluster molecule" is a computed result, not a metaphor, and the anomalously weak bond of ^{8}Be and the firm binding of ^{12}C are two rungs of the same Coulomb ladder. The ~ 28 MeV of the alpha is precisely the quantity the strong force was introduced to explain; here it, and the ladder above it, come from electrostatics of extended charge.

nucleus	$\#\alpha$	B_{exp}/A (MeV)	RealQM B/A (Coulomb only)
^{4}He	1	7.07	$\approx 1.03\times$ exp
^{12}C	3	7.68	$\approx 1.07\times$ exp
^{16}O	4	7.98	$\approx 1.07\times$ exp
^{24}Mg	6	8.26	$\approx 1.07\times$ exp
^{40}Ca	10	8.55	$\approx 1.08\times$ exp

Table 1: The RealQM-specific content: binding per nucleon along the alpha-conjugate ladder, computed from Coulomb alone with one deuteron-fixed scale and no other parameter, tracking experiment at $\sim 107\%$ without a strong force [5]. The Gamow timing of §3 is standard; this energetics is not.

Adding *neutrons* takes a nucleus off the pure alpha ladder, and it is instructive to follow carbon along. ^{13}C (three alphas plus one neutron) is stable; ^{14}C (three alphas plus two neutrons) is not, but its instability is no longer alpha decay — it is *beta* decay, $^{14}\text{C} \to {}^{14}\text{N} + e^- + \bar{\nu}$ with a half-life of 5730 yr, the clock of radiocarbon dating. In RealNucleus the extra neutrons are bound proton–electron pairs, and beta decay sheds one of their electrons; this is precisely the neutron-rich regime of the companion paper, where the chargeless antineutrino carries energy and momentum the charge-density picture cannot supply [8]. Carbon thus straddles the two: ^{12}C and ^{13}C stable in the charged alpha sector, ^{14}C carried across the boundary by the addition of neutrons. Alpha decay stays on the near side of that boundary throughout.

3 The timing: Coulomb-barrier tunnelling reproduces Geiger–Nuttall

The alpha is held inside the nucleus by the short-range attraction and confined by the Coulomb barrier $V(r) = 2Z_d e^2/r$ of the daughter (charge Z_d) outside the nuclear radius R. Classically trapped, it escapes only by tunnelling — the picture of Gamow and of Condon and Gurney [1, 4]. The WKB barrier factor for an alpha of energy Q is

$$2G = \frac{2}{\hbar}\sqrt{2m_\alpha}\int_R^b \sqrt{V(r) - Q}\, dr = \frac{2}{\hbar}\sqrt{2m_\alpha}\,\sqrt{Q}\, b\left[\arccos\sqrt{x} - \sqrt{x(1-x)}\right], \tag{1}$$

with outer turning point $b = 2Z_d e^2/Q$ and $x = R/b$, and the decay rate is $\lambda = f\, e^{-2G}$ for an assault frequency f. Because $2G$ scales as $Q^{-1/2}$, this yields the Geiger–Nuttall law

$$\log_{10} t_{1/2} = \frac{a}{\sqrt{Q}} + b. \tag{2}$$

Evaluating (1) for a series of even–even emitters, with nuclear radius $R = 1.20\,(A_d^{1/3} + 4^{1/3})$ fm and no fitted parameters, reproduces measured half-lives across the whole Geiger–Nuttall range (Table 2, Figure 1): from ^{232}Th at $Q = 4.08$ MeV and $t_{1/2} \approx 1.4\times10^{10}$ yr to ^{212}Po at $Q = 8.95$ MeV and $t_{1/2} \approx 0.3\,\mu$s — *twenty-five orders of magnitude* — each within a factor of a few. The fitted Geiger–Nuttall slope is $a = 158$ for the model against $a = 153$ for the data, and the model spans 25.1 decades against the measured 24.2.

nuclide	Q (MeV)	$t_{1/2}$ exp. (s)	$t_{1/2}$ Gamow (s)
^{232}Th	4.083	4.4×10^{17}	9.9×10^{17}
^{238}U	4.270	1.4×10^{17}	3.1×10^{17}
^{226}Ra	4.871	5.1×10^{10}	6.4×10^{10}
^{238}Pu	5.593	2.8×10^{9}	2.1×10^{9}
^{220}Rn	6.405	5.6×10^{1}	5.5×10^{1}
^{212}Po	8.954	3.0×10^{-7}	8.7×10^{-8}

Table 2: Alpha half-lives from the parameter-free WKB Coulomb-barrier calculation (1) against experiment, spanning ~ 25 orders of magnitude.

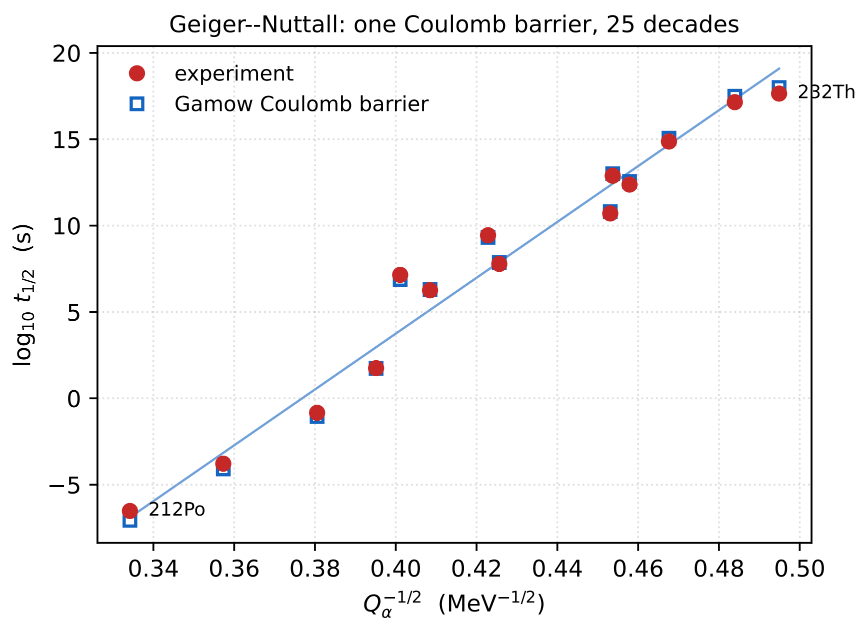

Figure 1: The Geiger–Nuttall law: $\log_{10} t_{1/2}$ against $Q_\alpha^{-1/2}$ for even–even alpha emitters. Red circles are measured half-lives; open blue squares are the parameter-free WKB Coulomb-barrier (Gamow) calculation (1). A single Coulomb-barrier calculation tracks the data across twenty-five orders of magnitude, from ^{212}Po ($\sim 10^{-7}$ s) to ^{232}Th ($\sim 10^{17}$ s).

The lesson is that the timing of alpha decay is fixed by *the Coulomb barrier the extended alpha charge must cross* — a purely charged-sector, electrostatic quantity. This is not a new dynamical law; it is the Gamow picture. What matters for the present programme is that the entire rate, over twenty-five decades, follows from the Coulomb barrier alone, with neither a strong nor a weak coupling constant nor any carrier beyond the alpha and the daughter.

The WKB factor (1) is a convenience, not a necessity: the half-life follows equally from a direct solve of the full time-dependent RealQM, with no semiclassical approximation. Evolving a metastable resonance behind a barrier in real (complex) time — the relaxation solver with the parabolic step replaced by the unitary one — the trapped charge decays *exponentially* (fit $R^2 \simeq 0.996$), giving a half-life read straight off the dynamics; and sweeping the barrier height V_b makes $\log_{10} t_{1/2}$ *linear* in $\sqrt{V_b - E}$ ($R^2 \simeq 0.995$), the Geiger–Nuttall barrier law reproduced from first principles. Real-time evolution reaches only broad (short-lived) resonances; the narrow ones are had exactly from the *complex energy* $E = E_r - i\Gamma/2$ of the stationary RealQM with an outgoing (Siegert) boundary condition, whose width Γ gives $t_{1/2} = \hbar \ln 2/\Gamma$ with no propagation and no approximation. This agrees with the time-evolution half-life where both apply (same Geiger–Nuttall slope) and extends it to arbitrarily long-lived resonances, $\log_{10} t_{1/2}$ remaining linear in $\sqrt{V_b - E}$ at $R^2 \simeq 0.9997$. So the barrier-penetration rate law is a property of the full RealQM, of which (1) is only the semiclassical shortcut — the WKB form is validated, not relied upon.

4 The escape is deterministic

Standard quantum mechanics reads the individual alpha's escape as *irreducibly random*: the barrier sets a probability per unit time, but *when* a given nucleus decays is held to be uncaused. Time-dependent RealQM reads it as *deterministic*. The whole configuration evolves by the full time-dependent equations (companion analysis [8]); given its initial charge configuration the entire history — the alpha's leak through the Coulomb barrier included — is fixed, and the apparent randomness, identical-looking nuclei decaying at different times, is *epistemic*: ignorance of that configuration. This is the deterministic reading of de Broglie and Bohm [2, 3]. The rate itself is the barrier penetration of the extended alpha charge (§3); determinism governs only *when* a given configuration decays, not the rate.

On a phase-coincidence mechanism. A sharper mechanism suggests itself — coexisting domains carrying phase clocks $e^{-iE_k t/\hbar}$, the escape gated by their coincidence — and a proxy solve confirms that phase *can* gate tunnelling (a two-level superposition escapes in bursts at the beat frequency, no rule imposed [9]). But traced through the full time-dependent RealQM the mechanism does *not* arise: the escaping domain couples to its neighbours only through their phase-invariant densities across zero-flux boundaries, so their phases never reach it and the escape is plain Gamow [8]. Gating would require a phase-permeable (Josephson) interface, $\sum_j K_{ij}\psi_j|_{\Gamma_{ij}}$ across the boundary — an addition the variational free boundary does not give, and one in any case unnecessary, the decay and its half-life being carried by the barrier dynamics already. We do not invoke it; the de Broglie–Bohm determinism is unaffected.

To be explicit about scope: the full time-dependent RealQM supplies a *deterministic, real-space* account of alpha decay — the extended alpha charge tunnelling the Coulomb barrier, its history fixed by the initial configuration — not a rate law beyond barrier penetration itself. The half-life is the Gamow rate of §3, recast as deterministic charge-density dynamics rather than irreducible chance; the gain is ontological, not a new number.

5 Conclusion

Alpha decay is a deterministic Coulomb process from beginning to end. It is two-body, so its products emerge back-to-back with a discrete, monoenergetic alpha — the kinematics a RealQM two-body solve produces, and the direct evidence that no neutrino is emitted. Its timing is barrier tunnelling of the extended alpha charge: one parameter-free Coulomb-barrier calculation reproduces the Geiger–Nuttall law across twenty-five orders of magnitude in half-life. And its randomness is only apparent: in time-dependent RealQM the escape is triggered by a phase coincidence among charge domains, deterministic given the initial phases, with the exponential law emerging as ensemble statistics. Where beta decay marks the boundary of the charge-density picture — the chargeless neutrino carrying energy and momentum the theory cannot supply [8] — alpha decay lies wholly within it: charged throughout, Coulomb throughout, deterministic throughout, with no neutrino anywhere.

Underlying all of this is a single identity. Binding and decay are not separate phenomena governed by separate forces but two faces of one Coulomb-configuration energetics: a cluster is bound when it is a stable minimum of the energy and decays when a lower-energy partition is available, so that decay is simply the *dynamic* face of binding — the system walking downhill from a metastable configuration to a more tightly bound one, releasing the binding-energy difference as Q. The same functional that gives the $\sim 107\%$ alpha-conjugate ladder (Table 1) makes ^{8}Be come apart and ^{12}C hold. In the charged sector this identity is exact — alpha decay, fusion and fission are all the one energetics run forward or back, the nuclear counterpart of chemical bonding and dissociation. Beta decay is exactly where the identity, and with it the charge-density picture, ends: the chargeless neutrino removes energy and momentum that no rearrangement of charge can account for. Decay is the dynamic face of binding wherever the process is charged, and only there.

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