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Latent Heat Could Solve Accelerated Nuclear Decay's Heat Problem—Part 1

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Abstract

A phase change for the condensed matter comprising large nuclei is proposed as a heat sink during an episode of accelerated nuclear decay, being particularly relevant to the formation of radiohalos. The proposed nuclear phase change would occur in ^{206}Pb nuclei, being the final stable progeny in the ^{238}U decay chain. With each cascade of decays, the latent heat for this presumed first order phase transition would be taken from (via heat transfer, generically invoked), and thereby continuously cool, the radio-center's immediate environment wherein the thermal energy is deposited. Arguing by analogy with atomic/molecular systems, the plausibility of providing sufficient cooling (absorbing enough energy) by a phase change is explored. The lower entropy phase for large, unstable nuclei during accelerated decay might consist of alpha clusters as compared with primarily nucleon pairings for the normal phase. The nuclear phase change would occur with/at the switch from unstable parent isotope to stable daughter in accordance with the dependence of a hypothetical nuclear phase diagram on the decreased strength of the nuclear force (a shallower nuclear potential) for unstable nuclei characterizing an episode of accelerated decay as compared with normalcy, as will be explained in Part 2.

Key Words: radiohalo, heat sink, latent heat, cooling, phase diagram, accelerated decay, uranium, polonium, nuclear decay, alpha cluster, condensed matter

Editorial Comment: Neither the reviewers, the physics editor, nor the author of this article were fully satisfied with the explanation of how heat could be transferred from the surroundings into the nucleus, but it was decided to leave that for future research.

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Introduction: A Change of Phase for the Nucleus

As a novel solution to the heat problem associated with accelerating nuclear decay, herein described in the context of radiohalo production during an episode of accelerated decay, a spontaneous endothermic process, occurring inside each new ^{206}Pb nucleus at the culmination of the ^{238}U decay chain,[1] is proposed. That is, an energy-absorbing phase change occurs in the newly formed lead nuclei at the radio-center thereby removing much of the heat just produced by the preceding chain of decays. The requisite latent heat for the phase change is taken[2] at Series' End from the adjacent rock where it is being deposited in rapid fire at a ring's radial distance away. This process is akin to an entropy-increasing first-order phase transition between two condensed states of matter in (nonnuclear) chemistry like the melting of an ice cube ($\Delta G < 0$, $\Delta H > 0$, $\Delta S > 0$), here due to an abrupt change in the nuclear force (the mean field describing the nuclear potential) when the nuclide switches (crosses over) from being unstable to being stable with the last alpha decay in the uranium series (^{210}Po $\rightarrow$ ^{206}Pb + α).[3] It is assumed (or asserted) that *only unstable nuclei are significantly affected by the change in the nuclear force* (residual strong force that holds the nucleus together) *responsible for accelerated decay*. That is, the phase of stable nuclei remains a condensed fluid, consistent with the Liquid Drop Model and current scientific consensus, regardless of accelerated nuclear decay, while the unstable nuclei undergoing accelerated decay find themselves in an unknown lower entropy state. This condition is necessary for the proposed solution to work, as will become apparent to the reader, and it is plausible that a change in the strong force would only affect a particular class of nuclides, like the unstable ones, given the inherent complications of few-body quantum physics. While every nuclide is its own system with significant dependence on size (neutron and proton counts) affecting various properties, classes of nuclides do share behaviors—like stability vs. instability against alpha or beta decay, low- vs. high-binding energy per nucleon, being symmetrical vs. deformed, etc.—all of which point to distinctions in how the strong force plays out in determining nucleon interactions and nuclear phase.

The Conundrum of Radiohalos

A radiohalo is a microscopic[4] heat scar commonly found in granitic rocks (within the black biotite specks, typically) that depicts the alpha decays in a radioactive decay series by a set of concentric spherical shells, or rings, in cross-section.[5] A hundred million to a billion parent isotopes in the halo's radio-center[6] have to decay to cause the discoloration that makes a fully developed radiohalo. On the low end of counts the outer rings are too faint to readily see while on the high end the inner rings are blurred from too much radiation damage. The only decay-series parent isotopes with high enough (and concentrated enough) natural abundances in Earth's rocks to make, or to have made, radiohalos appear to be uranium-238 and thorium-232. Yet polonium-218, polonium-214, and polonium-210 radiohalos are also found, and herein lies the conundrum because a fully naturalistic explanation for these halos and their radio-sources is lacking (Gentry, 1992, pp. 30–31).

What of polonium halos? All polonium being radiogenic and short-lived, if there were any primordial polonium, it would have decayed away within a few years of its creation. Among polonium's naturally occurring isotopes (decay progeny from ^{238}U, ^{237}Np, ^{235}U, and ^{232}Th), the ^{210}Po isotope is longest-lived by far with a half-life of 138 days, all the others having half-lives of 3 minutes or less.[7] Thus, polonium is mainly found as ^{210}Po dispersed in uranium ores[8] at about mg per metric ton (1 part in 10^{10}), uranium being 99.3% ^{238}U (0.7% ^{235}U) and the ^{210}Po isotope being ^{238}U's last unstable daughter in the uranium series.

At first take, this would seem to confine polonium halos to creation rock (Gentry, 1992, pp. 33–37), yet they are found spanning the geologic column chiefly in granitic plutons (melts or remelts) from Precambrian through Mesozoic (Snelling, 2005) and even Tertiary[9] but also in coalified wood from the Colorado Plateau (Gentry et al., 1976). Importantly, polonium

1 Or, occurring inside each new ^{208}Pb nucleus at the culmination of the ^{232}Th decay chain.

2 Just how the thermal energy gets into the nucleus to affect the phase change is unknown.

3 Or, with the last alpha decay in the thorium series (^{212}Po $\rightarrow$ ^{208}Pb + α).

4 Uranium radiohalos in granitic rocks are about 70 microns in diameter.

5 The leaves comprising biotite (mica) provide natural translucent thin sections for viewing radiohalos in cross-section under an ordinary optical microscope.

6 The radio-center approximates a point source, with rings differentiated, if it is smaller than the ring spacing.

7 Even the longest-lived of *all* polonium isotopes ^{209}Po (produced by proton bombardment of bismuth in a particle accelerator) has a half-life of only 125 years.

8 Ores include uraninite, UO_2, also known as pitchblende, as well as uranothorite (Th,U) SiO_4.

9 Radiohalos are ubiquitous in granitic rocks up through the Mesozoic while there is only one Tertiary halo-bearing sample in the *RATE* data set; however, the latter is from an index granite making its location in the geologic column relatively certain.

halos come in only three kinds: ^{218}Po, ^{214}Po, and ^{210}Po which are uranium-238's three polonium daughters. But any primordial ^{218}Po halos or primordial ^{214}Po halos—one of the latter being famously pictured on a book jacket (Gentry, 1992)—would not have survived their first ring's own heat production (6.0 MeV per decay and 7.7 MeV per decay, respectively, times ~500 million decays)[10] given the near-adiabatic heating due to their very short half-lives (3 min and 164 μs, respectively). Incidentally, the same goes if a radio-center's worth of ^{218}Po or ^{214}Po abruptly materialized in a host rock at any time (for any reason) in Earth's history: the halo would not survive its own heat. Radiohalos cannot survive high temperatures (≳150°C in biotite) because the rings of radiation damage, as assemblages of scorch marks, get annealed away (if not vaporized in production!). It is not enough only to explain the presence of polonium halo source isotopes.

Aside from the heat problem, the conundrum of the polonium halo finds resolution in the *RATE*[11] model (Snelling, 2005, pp. 152–174) in which polonium halos are really just partial uranium halos. That is, the U-halo's trailing rings—the rings due to emissions by polonium isotopes—are merely displaced from the origin U-halo(s). This one-atom-at-a-time displacement arguably occurred by the aqueous transport of the gaseous radon-222 daughter ($t_{½}$ = 3.8 d), some of which escapes the zircon (housing the uranium inclusion) into the surrounding biotite (mica) before decaying into polonium-218. The essential moving water (between flakes of mica and through microfractures) was chemically produced as the host granite crystallized with the flow slowing to a halt once the temperature dropped below ~75°C. This scenario presents a severely short time window of about five days[12] (at most) corresponding to a temperature window 150°C <T <75°C for radiohalos (uranium as well as polonium) to have formed.

This model presupposes (or requires) a Flood-Year episode of accelerated decay because *the U-halos and Po-halos necessarily formed simultaneously* despite their spectacularly disparate half-lives. During such episode, it is understood that the longest-lived, least-unstable isotopes like uranium-238 ($t_{½}$ = 4.5 Ga) experience the greatest increase in decay rate (by a billionfold) while the shortest-lived isotopes like polonium-214 ($t_{½}$ = 164 μs) are nominally affected, and the alpha particle energies (ring radii) remain essentially unchanged regardless of half-life. Being named for the longest half-life (primordial) isotope in the chain, alpha decay rates in a series tend to increase (half-lives decrease) until the chain culminates with the stable isotope[13] though there can be hiccups in this trend (preceding the grand one at Series' End) like there is at polonium-210 in the uranium series.[14] Regardless, the final alpha decays for the uranium series are the three poloniums (as are the two poloniums for the thorium series), all of which would experience negligibly small changes in their half-lives (while preserving ring order) when decay rates are accelerated.

Just as importantly though not generally put in such terms, this model implicitly presupposes (or requires) a commensurate and concurrent cooling (energy absorption) that allows each halo to survive its own heat, for each decay necessarily generates frictional heat as an alpha particle comes to a stop, scorching and discoloring the host rock (e.g., the mica in granitic rocks) along its track in the random direction it goes off (isotropically) but primarily at a stopping distance where the linear energy transfer peaks in accordance with its kinetic energy. In principle, the alpha particle's kinetic energy is determined from the almost-eigenstate of the quasi-bound alpha particle[15] inside the parent nuclide.

10 Not that rings form consecutively—rather, they develop simultaneously from multitudinous individual cascades—but by way of categorizing heat contributions.

11 *RATE* stands for *Radioisotopes and the Age of the Earth*, referencing the significant young-Earth creationist research initiative that published results in 2005.

12 Mean lifetime is ~1.4 times greater than half-life: $\tau = \frac{t_{½}}{\ln 2}$. So, 5 days is used instead of 4.

13 The stable isotope might be thought of as having infinite half-life as the limiting case.

14 Uranium series with its eight alpha decay half-lives:

$^{238}_{92}$U @ 4.5×10^9 y | $^{234}_{90}$Th, $^{234}_{91}$Pa | $^{234}_{92}$U @ 2.5×10^5 y |

$^{230}_{90}$Th @ 7.5×10^4 y | $^{226}_{88}$Ra @ 1600 y | $^{222}_{86}$Rn @ 3.8 d |

$^{218}_{84}$Po @ 3 m | $^{214}_{82}$Pb, $^{214}_{83}$Bi | $^{214}_{84}$Po @ 164 μs | $^{210}_{82}$Pb, $^{210}_{83}$Bi |

$^{210}_{84}$Po @ 138 d | $^{206}_{82}$Pb @ ∞ |.

Thorium series with its six alpha decay half-lives:

$^{232}_{90}$Th @ 1.4×10^{10} y | $^{228}_{88}$Ra, $^{228}_{89}$Ac | $^{228}_{90}$Th @ 1.9 y |

$^{224}_{88}$Ra @ 3.7 d | $^{220}_{86}$Rn @ 55.6 s | $^{216}_{84}$Po @ 144 ms |

$^{212}_{82}$Pb , $^{212}_{83}$Bi | $^{212}_{84}$Po @ 299 ns | $^{208}_{82}$Pb @ ∞ |.

Beta decay half-lives (not given here) are typically but not always intermediate in value between the sandwiching alpha decay half-lives. Alpha decay half-lives were found from the Decay Radiation Search at the National Nuclear Data Center https://www.nndc.bnl.gov/nudat3/indx_dec.jsp

15 An alpha particle is a helium nucleus consisting of two protons and two neutrons, denoted $^4_2$He or $^4_2\alpha$, where the preceding subscript is the atomic number Z (number of protons) and the preceding superscript is the mass number A (number of nucleons or protons plus neutrons), generically $^A_Z X$. A beta (minus) particle is an electron, denoted $^{-1}_{0}\beta$ or $^{-1}_{0}e$ or β^-, or simply β.

However, the very same heat that makes the halo by scarring the rock must necessarily prevent and/or undo the discoloration (scarring) unless it can dissipate into the surroundings faster than it is produced such that the host rock's temperature in the immediate vicinity of the halo remains below the annealing temperature ($T \lesssim 150$°C in biotite). During an episode of accelerated decay, per the transport-via-escaping-radon model for polonium (alongside uranium) halo formation, the vast majority of this heat cannot possibly get away in time given the time scales involved, with at least a hundred million decays occurring inside a 35-micron radius (^{214}Po's ring) in a matter of days. Thus, adiabatic heating gives the right order of magnitude, not just an upper limit, for the increase in temperature experienced by a halo *in the absence of any cooling*. Moreover, because natural annealing of radiohalos in samples taken from deep drill holes is found to be consistent with the temperature-depth profile for the drill holes (Laney and Laughlin, 1981), with the alpha particle tracks either surviving to the present or being erased accordingly, *as though no local heat surge from accelerated nuclear decay occurred*, the cooling (energy absorption) must be nearly commensurate with each halo's frictional heat generation. In other words, radiohalos act like there is no heat problem associated with accelerated decay.

Simply by energy conservation, such near-adiabatic heating requires a near-commensurate cooling of ~40–50 MeV per decay cascade;[16] otherwise, halos cannot have formed much less persist once formed. The adiabatic temperature rise is at least 1800°C for one U-halo or 180°C for one ^{210}Po halo where $\Delta T \sim Q/(\rho V c) \times 10^8$ for a sphere of biotite ($\rho = 2.9$ g/mL; $c = 0.88$ J/g°C; $V = \frac{4}{3}\pi r^3$) using polonium-214's ring radius ($r = 35$ μm) and heat $Q = 52$ MeV per decay cascade for a ^{238}U radio-center or $Q = 5.4$ MeV for a ^{210}Po radio-center (1 MeV ≈ 1.6 10^{-13}J; 1 μm^3 = 10^{-12} mL). Arguably the temperature increase could be 5–10 times greater, as much as 18,000°C for a fully developed U-halo. For comparison, the adiabatic temperature-rise for a typical pluton undergoing accelerated decay, encompassing *all* radioactive decay therein, has been estimated at 22,400 K (Snelling, 2005, p. 184). In other words, accelerating nuclear decay by upwards of 100 million-fold presents no small heat problem to solve (Worraker, 2018).

A Change of Phase for the Nucleus, Continued

Some kind of Liquid-Liquid Phase Transition for the lead nuclei, from a lower entropy (lower density?)[17] state where alpha particle clusters would dominate due to stronger many-body forces, to a higher entropy (higher density?) state mainly consisting of nucleon spin-antispin pairs, seems most likely. But the relative latent heat for atomic/molecular systems undergoing such phase transitions (like water) is too small to translate into the needed amount of cooling for radiohalos to have formed. Rather, the latent heat for the unknown phase transition in lead nuclei is compared to the latent heat of melting for a salt (e.g., *NaCl*), as justified later in this paper and continued in Part 2.

For a ^{238}U nuclide undergoing accelerated decay, it seems quite plausible that all eight departing alpha particles ($pnnp$ or $n_\beta nnn_\beta$)[18] are pre-formed, or pre-forming, as such in the nucleus, instead of just one at a time, with these clusters of nucleons—32 nucleons as 22 neutrons (n) and 10 protons (p) in order of decay as: $pnnp$, $n_\beta nnn_\beta$, $4 \times pnnp$, $n_\beta nnn_\beta$, $n_\beta nnn_\beta$—occupying quasi-bound alpha particle states above a stable ^{206}Pb-like core. In modeling alpha decay/tunnelling, half-life is often underpredicted, perhaps by about 2% to 20%, meaning that some hindrance factor is not accounted for in the basic formulation (Duarte and Siegel, 2010). Called the preformation factor, the discrepancy is interpreted as the *percentage of time* the outgoing alpha particle's composite quad of nucleons is an alpha particle versus not; but equivalently, the preformation factor could be seen as the percentage of the parent isotope's nucleon quads that are alpha particles *at any given time*.

Recent evidence for the tetraneutron as an extremely short-lived entity outside the nucleus makes a quad of sometimes-neutrons ($n_\beta nnn_\beta$) clustering in the nucleus seem not unreasonable (Kisamori et al., 2016; Duer et al., 2022). An excess of neutrons at the surface of neutron-heavy nuclei, termed the neutron skin, is also confirmed by experiment: the neutron skin thickness was recently measured for ^{208}Pb as 0.28 fm (Adhikari et al., 2021) which translates into about 20 of its 208 nucleons, 126 of which are neutrons ($A - Z = 208 - 82$).[19] Applying a comparable ratio of skin thickness to nuclear radius

16 The total energy released in the uranium series ($^{238}_{92}\mathrm{U} \rightarrow {}^{206}_{82}\mathrm{Pb} + 8\alpha + 6\beta^-$) is 51.7 MeV including the kinetic energies of the alphas and betas (with their neutrinos) as well as nuclear recoil; its alpha particle energies subtotal 43.7 MeV. For comparison, the thorium series ($^{232}_{90}\mathrm{Th} \rightarrow {}^{208}_{82}\mathrm{Pb} + 6\alpha + 4\beta^-$) is 42.6 MeV with an alpha subtotal of 37.5 MeV.

17 The low-density liquid (LDL) phase has lower entropy and the high-density liquid (HDL) phase higher entropy because the Liquid-Liquid Phase Transition (LLPT) is observed specifically for water-like liquids for which their solid phase floats in its own liquid; that is, water-ice floats.

18 n_β represents the *proton-plus-electron* that replaces a neutron (n) in beta decay ($n \rightarrow p + \beta^- + \bar{\nu}_e$), the idea being that the neutron is in some sense already a proton (p) plus electron (β^-) prior to decay.

19 Again, Z is the element's atomic number or proton count while A is the isotope's mass number or nucleon count.

to the slightly bigger ^{238}U translates into 22 of its 238 nucleons, 146 of which are neutrons ($A - Z = 238 - 92$).[20] Interestingly, this is precisely the number of neutrons lost in the chain of decays from ^{238}U to ^{206}Pb. Necessarily, there are no occupied positive energy (quasi-bound or resonant) states for lead's *stable* isotopes (including ^{206}Pb at the end of the uranium series, ^{207}Pb at the end of the actinium series, and ^{208}Pb at the end of the thorium series, besides primordial non-radiogenic ^{204}Pb)[21] while the 22 beta decay neutrons in ^{238}U (when acting like nucleons in spin-antispin pairs instead of alpha particles) would be resonances above the neutron well.[22] The existence of such surface neutrons in the energy sense is supported by the apparent existence of surface (skin) neutrons in the geometric sense based on scattering experiments.

So, like ice cubes cooling a beverage by heat transfer from the beverage (as the cube's surroundings) to the ice, thereby melting the cubes, *here the alpha clusters comprising an unstable nucleus undergoing accelerated decay would disassemble into nucleon pairs and sometimes dimers once they find themselves in a stable nucleus*. As a phase transition, presumed to be first-order,[23] this would absorb its latent entropic heat from the surroundings, both the local rock matrix and any connate water in microfractures, thereby making the radio-center (i.e., its radiation-source nuclides) also a heat sink (i.e., its end-product nuclides) *as a natural response to accelerated nuclear decay*. So, the radio-center's unstable nuclei are the source of the alpha particles, causing the surrounding rock matrix to heat up in stopping them, and the stable lead nuclei absorb the heat. Though radiohalos are the focus here, this energy absorption is not limited to radio-centers (concentrations of uranium or thorium in settings like a zircon which contain their progeny): each newly formed stable nucleus at Series' End (^{206}Pb for the uranium series and ^{208}Pb for the thorium series) would be a heat sink individually during an episode of accelerated decay whether the uranium or thorium is dispersed throughout the rock or concentrated as inclusions in zircons—though the energy balance argument would not necessarily apply.

Just how the transfer of heat to the nucleus, or absorption of energy by it, would occur is a subject for future research. While thermal conduction, per kinetic molecular theory, is understood to occur by momentum transfer between atoms/molecules, and absolute temperature describes this motion statistically as a mean kinetic energy,[24] how the nucleons that comprise an atom's nucleus might couple to this molecular motion to effect the heat transfer is unknown. But the thermal energy (as blackbody radiation?)[25] must be able to get back into the nucleus. For one, it must be in the right energy range to be absorbed by lead nuclei (such as occurs with vibrational levels of small spacing) and the resulting nuclear excitation effects the phase change (Chaffin, 2022). But for the present, heat transfer is invoked without a specific mechanism offered for consideration, though the author welcomes ideas in this regard. This important issue aside, to further explain and justify the idea of a phase change for lead nuclei being a heat sink during an episode of accelerated nuclear decay—where an unknown phase comprised of alpha clusters reverts to the normal state as a condensed fluid of nucleon pairs and sometimes dimers—requires reviewing some basic nuclear chemistry and noting which model(s) of the nucleus make successful predictions for stable vs. unstable nuclides.

Nuclear Chemistry: Quantum Shells or Liquid Drop?

The success of the quantum *nuclear shell model*, as a mean field approximation, is highly surprising: how can one member (proton or neutron) of a *few-body* system of nucleons act like an independent particle moving in the field made by the remaining particles; that is, by the one-fewer few-body system? Yet the nuclear shell model rightly predicts the nuclear magic numbers

20 While neutron-heavy nuclei are deformed (prolate) spheroids and the skin might be tougher (denser) than the interior, uniform density and spherical symmetry are assumed for simplicity, the quoted value of 0.28 fm for ^{208}Pb being, in effect, an average. Thus, $\frac{\Delta V}{V} \approx 3\frac{\Delta R}{R}\left(1 - 2\frac{\Delta R}{R}\right) = 9.4\%$ with radius $R \approx 1.3\,A^{1/3}$ fm $= 1.3(208)^{1/3}$ fm $= 7.7$ fm.

21 Interestingly, lead is the last element in the Periodic Table with stable isotopes, though the very nearly stable $^{209}_{83}Bi$ with its magic number of 126 neutrons lies between lead ($Z = 82$) and polonium ($Z = 84$).

22 The nuclear shell model is depicted as side-by-side neutron and proton potentials yielding the magic numbers separately when counting neutrons vs. protons. The neutron well is deeper than the proton well for neutron-heavy nuclides, and there is a Coulomb barrier for the proton well but not for neutron (neutrons being neutral). As such, positive energy solutions for the neutron well are called resonances (unbound but not free) while they are quasi-bound states for the proton well (depicted schematically in Part 2 in the context of describing uranium-238 during accelerated nuclear decay, hypothetically).

23 There is a latent heat only for first-order phase transitions for which the first derivative of the free energy with respect to one of its dependent thermodynamic variables is discontinuous.

24 That is, $k_BT \propto (\frac{1}{2}\, mv^2)$ where m is particle mass, v particle velocity and k_B Boltzmann's constant.

25 This being the relevant form for accelerated decay's thermal energy per another paper that addresses the heat problem (Humphreys, 2018, p. 735), though it takes a very different approach.

for neutrons and protons[26] corresponding to high nuclear stability (as long as the model includes energy-level splitting due to spin-orbit coupling). This success is akin to how the single electron model of the atom rightly predicts the atomic magic numbers corresponding to the noble gases (Group XVIII elements) as well as inter-atomic bonds giving rise to molecules and compounds and the residual intermolecular forces giving rise to the various phases of matter. In both systems, spin-antispin pairing means that otherwise identical quanta can occupy the same level (like pairs of shared electrons comprise an atomic bond) *making these pairs rather particle-like* by virtue of their having the same energy and locale (orbital). The quantum parallel between atomic and nuclear systems holds despite the atom being mostly empty space and electrons planet-like in a quantum solar system, while the nucleus is densely packed with no empty space for its nucleons to move around in any classical sense so its orbitals would not seem at all orbit-like.[27]

While predicting magic numbers validates the nuclear shell model, especially for nuclides with $Z \le 82$ and $N \le 126$, it is a (semi-classical) *alpha particle model* that predicts the logarithmic relationship between the escaping alpha particle's energy and parent isotope's half-life, whether it is very short-lived polonium-214 or very long-lived uranium-238. That is, the nucleus acts like an assemblage of alpha particles (*alpha particles being the quanta* instead of nucleons) where the outermost shell is quasi-bound with positive energy (instead of a bound state with negative energy) so that the alpha particle can escape (tunnel out)—even when far from being a so-called $4n$ nucleus (i.e., $A = Z + N = 2Z = 4n$) meaning its set of A nucleons does not translate into an integer number of alpha particles. Surprisingly, a simple square well potential and semi-classical approach gives Gamow's analytical formula[28] for the half-life of even-even nuclei as well as the Geiger-Nuttall Law.[29] For polonium-214 ($E_\alpha = 7.7$ MeV), Gamow's model predicts a 370 μs half-life while experiment gives 164 μs, and for uranium-238 ($E_\alpha = 4.27$ MeV), it predicts a 40.6 Ga half-life while experiment gives 4.5 Ga. In the first case the model's decay rate is quite close (half-life too long by a factor of two) while in the second the model's rate is too low (half-life too long by a factor of ten). Nonetheless, it is truly remarkable that the huge disparity (microseconds vs. giga-anna) in half-lives for ^{214}Po vs. ^{238}U is rightly predicted with

$$t_{½} \sim \left(10^{\,1/\sqrt{E_\alpha}}\right)^{aZ}$$

for alpha decays from even-even nuclei with Z = 78–118 (Qi et al., 2012).

A quantized alpha particle model with a Lennard-Jones shaped potential[30] plus a Coulomb barrier has been used to model light $4n$ nuclei including ^{8}Be, ^{12}C, and ^{16}O with limited success (Blatt and Weisskopf, 1952, pp. 292–293). Modeled thus, such nuclei are geometric structures (^{16}O being a tetrahedron of alpha particles, for example) possibly contradicting

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26 The shells for protons and for neutrons are independent of each other meaning each has its own Woods-Saxon potential $V(r) = \frac{-V_0}{1+e^{(r-R)/a}}$ which differ when $N \neq Z$; for example, $V_0 = 51 \pm 33\left(\frac{N-Z}{A}\right)$ giving $V_0 = 58.5$ MeV for the deeper neutron well and $V_0 = 43.5$ MeV for the proton well, for $^{238}_{92}$U. This presents like a broken degeneracy due to a lost symmetry where the pairs of pairs (nn & pp) no longer have the same energies.

27 The fact that the single-electron model of the atom works as well as it does is itself rather surprising (why should the Z – 1 electrons occupy shells as determined for the two-body problem?), but less so than the nuclear shell model's success.

28 For potential $V(r) = -V_0$ for $r < R$ and $V(r) = \frac{zZ_De^2}{r}$ for $r < R$ where $R = R_0A^{⅓}$, the decay constant becomes $\lambda \approx \frac{v_{in}}{R}e^{-\gamma}$ with $\gamma = \frac{2}{\hbar}\int_R^{R'}\sqrt{2M_0\left(\frac{zZ_De^2}{r} - Q_\alpha\right)}dr$ where $z = 2$ for alpha decay while $M_0 = \frac{M_\alpha M_D}{M_\alpha + M_D}$ is the reduced mass with $M_\alpha = 2u$. If the parent nuclide is ^{238}U then $Z_D = 234$, $M_D = 234u$; $Q_\alpha = \frac{1}{2}M_0v_{in}^2 = \frac{zZ_De^2}{R'} = 4.27$ MeV is the alpha particle's energy (purely kinetic inside the well and purely potential upon emerging from the tunnel). Integrating gives $\gamma = \frac{zZ_De^2}{\hbar v_{in}}\left(\cos^{-1}\sqrt{\frac{Q_\alpha}{V(R)}} - \sqrt{\frac{Q_\alpha}{V(R)}}\sqrt{1-\frac{Q_\alpha}{V(R)}}\right)$ but for thick barriers with $\frac{R}{R'} \ll 1$, $\gamma \approx \frac{2\pi zZ_De^2}{\hbar v_{in}} - \frac{4}{\hbar}\sqrt{2zZ_De^2M_0R}$. The quoted numbers use $R_0 = 1.4$ fm but 1.3 fm is also common.

29 Either: $\log_{10}t_{½} = aZ / \sqrt{Q_\alpha} + b$ where $t_{½}$ is the half-life for the alpha decay, Q_α is the total alpha decay energy ($Q_\alpha \approx E_\alpha$ for large nuclei), Z is the parent isotope's proton number, and a, b are constants for a given Z though $a \approx 1.5$ is very nearly constant across Z for even-even isotopes with $Z \ge 84$, $N \ge 128$. Or: $\log_{10}\lambda = c\log r + d$ when given in terms of the decay constant λ (instead of the half-life) and the alpha particle's range r (instead of the alpha particle's energy E_α) with constants c, d. Note that range corresponds to ring radius for a radiohalo though the medium is generally air or water for range measurements.

30 The Lennard-Jones "12–6" potential $V(r) = 4\varepsilon\left[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^{6}\right]$ with well depth ε and particle size σ (measured center-to-center making it a diameter) is used to model intermolecular (Van der Waals) forces *classically* and has a corresponding phase diagram for the so-called *Lennard-Jonesium* substance with temperature scaled as k_BT / ε. Nuclear wells describing the α–α interaction have ε~50 MeV compared to ε~10 *MeV* for molecular wells describing the *Ar*–*Ar* interaction (for example); this means that any terrestrial temperature lies at the bottom of such a phase diagram for nuclear condensed matter (where $k_BT = 26$ meV at 25°C or 36 meV *at* 150°C). In this region ($k_BT / \varepsilon < 0.687$) with appropriate density ($\rho\sigma^3 \lesssim 1$), the phase is solid, same as for real argon.

the liquid-like saturation that motivates and justifies the Liquid Drop Model (Blatt and Weisskopf, 1952, pp. 300–305). The saturation or flat topping exhibited by the binding energy per nucleon BE/A vs. the number of nucleons A (Figure 1) is fluid-like with a constant latent heat of evaporation as the binding energy per fluid molecule, while the nuclear density $A/R^3 \sim 1/r_0^3$, where A is the nucleon count and R and r_0 are nuclear and nucleon radii respectively, argues for a condensed state like an incompressible fluid (i.e., liquid).

Interestingly, the (quantum) alpha particle model with its finite structures does show saturation on a per-bond basis at about 2.4 MeV (or 4.1 MeV once corrected for Coulomb repulsion between alpha particles) as compared to the per-nucleon value of 8.8 MeV where the binding energy curve tops out for ^{56}Fe and/or ^{62}Ni. In any case, "they [the modelers] were aware of the shortcomings of a naïve alpha particle model [like the exclusion of all not-4n nuclides] and suggested that the alpha particles, rather than being stable structures inside a nucleus, be considered to have only a short-lived identity. After a certain time…the alpha particle dissolves into its constituents, and the remains of this and other dissolved alpha particles rearrange themselves into a new alpha particle structure, etc." (Blatt and Weisskopf, 1952, p. 293). Since then, the nucleus as a superfluid condensate of alpha particles has also been studied (Ring et al., 1983). Now, alpha particles have been seen experimentally in nuclei (Tanaka et al., 2021), and there is evidence suggesting if not confirming an alpha particle condensate for carbon-12 nuclei (Funaki et al., 2003) and oxygen-16 nuclei (Funaki et al., 2008). It would seem that alpha particles really do exist pre-formed in the nucleus (or forming, disintegrating, and re-forming), *and the nucleus is apparently subject to changing phase* (Chaffin, 2008).

Moreover, the success of modeling beta decay as an electron tunnelling out of the nucleus for the case of bound-state beta decay[31] (Woodmorappe, 2001) implies that the neutron acts like a proton-plus-electron inside the nucleus ($n \leftrightarrow p + \beta^- + \bar{\upsilon}_e$) prior to the beta decay event in the same sense that a pair of nucleon pairs makes an alpha particle in the nucleus ($n_\uparrow n_\downarrow + p_\uparrow p_\downarrow \leftrightarrow \alpha$)[32] prior to the alpha decay event (Subedi et al., 2008). An either/or model (shell nucleons sometimes organizing into alpha particles) with various adjustable parameters (making it semi-empirical) is commonly studied computationally where a typical model potential generally includes adjustable well-bottom V_0 and surface thickness a for a standard Woods-Saxon potential $V(r) = \frac{-V_0}{1+e^{(r-R)/a}}$ with nuclear radius $R = 1.3A^{⅓}$ fm plus a Coulomb barrier outside the nucleus ($r > R$). An escaping pair of pairs (neutron pair plus proton pair) is thought to assemble into an alpha particle "near the surface" occupying the first (lowest positive) quasi-bound alpha particle state, which must correspond with paired states above the neutron and proton wells respectively per the nuclear shell model.[33] In the end, getting an accurate half-life (better than within a decade) requires correcting for systematically under-predicting the true half-life. In other words, the calculated barrier potential decay rate is multiplied by whatever "preformation factor" P is needed to get the decay rate λ that is found experimentally: $\lambda_{expt} = P\lambda_{calc}$ or $t_{½expt} = \ln 2/\lambda_{expt} = P^{-1}t_{½calc}$ where $t_{½}$ is half-life. For uranium-238 ($^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\alpha$), the value of P is perhaps about 20% (Duarte and Siegel, 2010) and understood to be the percentage of time the four nucleons act like an alpha particle. Though it seems like merely a fudge factor, the variation in P from isotope to isotope within the scope of a particular model is measuring or reflecting something that is hindering decay.

All this is to say that nuclei generally act like assemblages of nucleons (spin-antispin pairs filling energy levels in separate neutron- and proton-potential wells) per the nuclear shell model's rightly predicting nuclear magic numbers, while large, unstable nuclei also act like assemblages of alpha particles per the alpha/tunnelling model's rightly describing alpha decay half-lives.[34] While four nucleon clusters can occur within the normal nuclear "liquid drop" phase whether a nucleus is stable or unstable (forming and breaking up on the surface of large nuclei, and tunnelling out as alpha particles if unstable), it is assumed that all the nucleon pairings would be paired up into alpha clusters in the unknown lower entropy phase describing unstable nuclei undergoing accelerated decay. All along the chain, the rapidly decaying nucleus would be characterized by this unknown phase comprised of alpha clusters but then would revert to the normal, higher entropy phase with a presumed first-order phase transition occurring for stable lead at Chain's End.

31 If a nucleus is stripped of atomic electrons, the beta decay electron can tunnel out more easily to occupy an atomic bound state (e.g., the ground state) rather than having to reach the continuum. The dramatic decay-rate acceleration (half-life shortening) observed for plasmas is explained thereby.

32 Or possibly $np + pn \leftrightarrow \alpha$ as the deuteron (np) has also been seen in the nucleus.

33 Exactly what quanta should be said to be filling the well, whether nucleons or alpha particles, is unclear. It is also unclear whether all underlying (negative) bound states are filled though it would seem they must be for spontaneous decay because the nucleus is not in an excited state.

34 An alpha particle's escape by tunnelling translates into the Geiger-Nuttall Law.

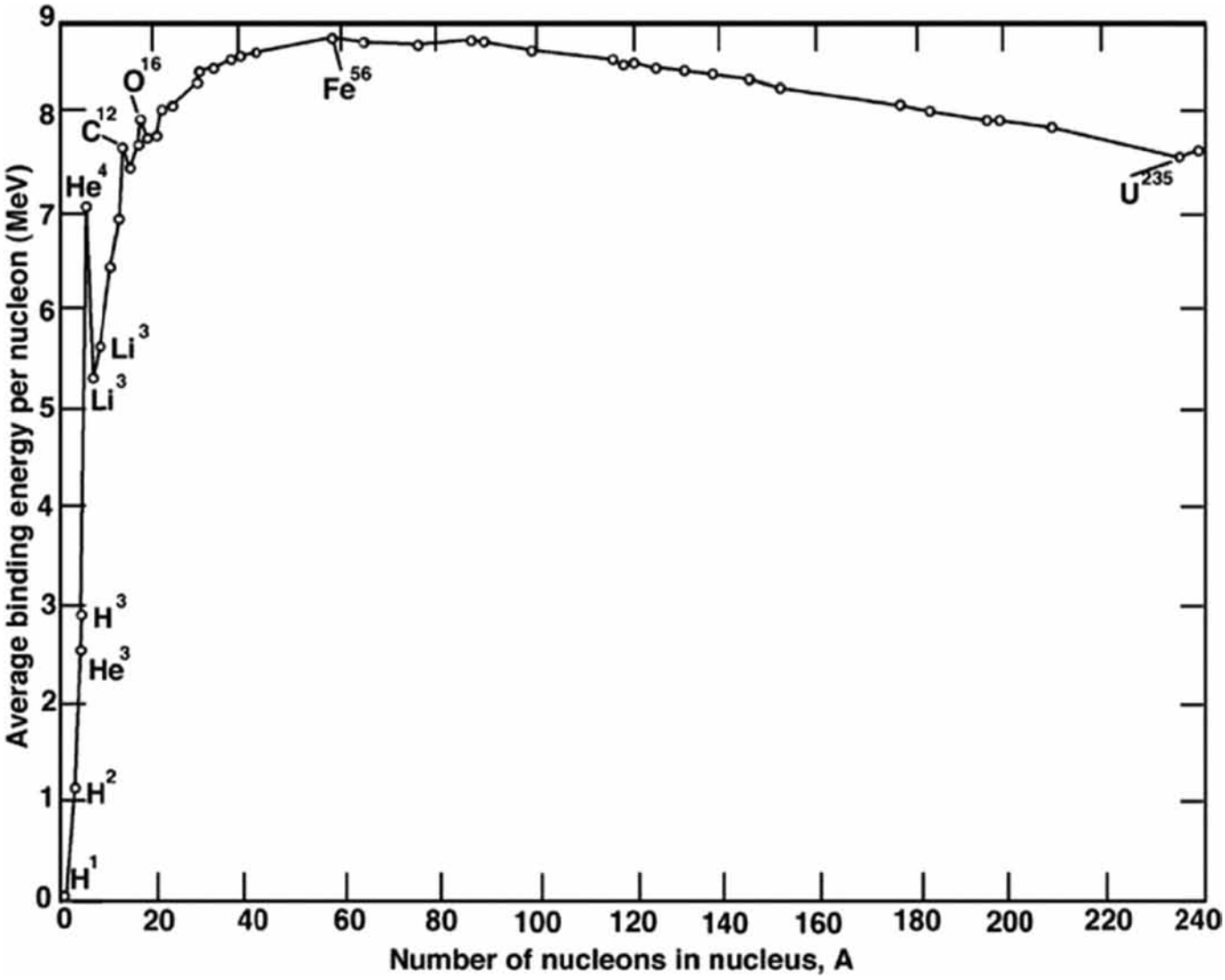

Figure 1. The saturation or flat-topping exhibited by the curve for the binding energy per nucleon vs. the number of nucleons (BE/A vs. A) is fluid-like with a constant latent heat of evaporation as the binding energy per fluid molecule, thus supporting the Liquid Drop Model of the nucleus.

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Nuclear Phase by Analogy

Since the nuclear force between hadrons is *residual*, "leftover" from the strong force that holds quarks as hadrons together, it follows that *inter-nucleon* forces are more like the *intermolecular* forces that determine a material's phase than they are like the intramolecular forces (i.e., covalent bonds) that determine a material's chemical composition. In this sense, bonds between ions as charged molecules (i.e., ionic bonds) can be understood as very strong intermolecular forces. Thus an ionic melt is perhaps the best analogy for the normal nuclear phase: the alpha particle's total binding energy of 28.3 MeV translates into ~4 MeV for the nuclear "ionic" bond[35] (that is, the bond *between*

35 Here, the coordination number counts nearest anions around a cation or vice versa. Six corresponds to simple cubic (sc), like the structure for Na^+Cl^-: ⅙([28.3 MeV – 2(2.225 MeV)] = 3.975 MeV > 2.225 MeV.

$n_\uparrow n_\downarrow$ and $p_\uparrow p_\downarrow$ by analogy) which is significantly *greater than* (certainly not weaker than) the bond in each diatomic ion (that is, *within* $n_\uparrow n_\downarrow$ or $p_\uparrow p_\downarrow$ by analogy) as approximated by the binding energy of the deuteron *np* (2.225 MeV).[36] It is therefore not unreasonable to treat the nucleon spin-antispin pair as a mono-atomic ion by analogy. Treating nucleon spin-antispin pairs as interacting entities is not new to nuclear physics (Chaffin, 2008). Nor is such pairing a stranger to atomic/molecular physics: the electron spin-antispin pair is treated as an entity (a bond) with repulsion between bonds explaining molecular geometry via Valence Shell Electron Pair Repulsion (*VSEPR*). The Cooper Pair of superconductivity is yet another example.

Consider a molten salt like NaCl. This ionic melt is a fluid consisting of its cations and anions, Na^+ and Cl^-, not really free from each other yet also not really bound (having no fixed crystalline array). Vaporized sodium chloride is not merely a gas of its ions but exhibits neutral polar-molecule-like pairings NaCl and Na_2Cl_2 (McCaffrey et al., 2007; Galamba, 2010) so its liquid phase surely exhibits such pairings too. Interestingly, liquid water's polar molecules occasionally morph back into cation plus anion $2HOH \rightleftharpoons H_3O^+ + OH^-$ where water's *pH* (or *pOH*) measures hydronium (or hydroxide) concentration. Or, consider that the liquid phase of nonpolar beryllium dichloride, Cl·Be·Cl (nonpolar as a molecule though its bonds are polar), includes both monomers $BeCl_2$ and dimers Be_2Cl_4, while its lower-entropy phase is a polymer (Pavlatou and Papatheodorou, 2000). Point being fluids are known to have "structure" (clustering tendencies) given their X-ray diffraction patterns and corresponding radial distribution functions.

Thus one might envision the unknown higher-entropy liquid phase of lead nuclei as consisting of the monomers $n_\uparrow n_\downarrow$ and $p_\uparrow p_\downarrow$ (analogous to cation and anion for an ionic melt) as well as sometimes-dimers, the paired pairings (or alpha clusters) *nppn* or *pnnp*, in contrast to a lower-entropy unknown phase consisting of all alpha clusters, possibly a distinct fluid with its own "structure" (rings or chains of alpha clusters: … *pnnppnnppnnppn*…). This would explain the preformation of alpha particles in nuclei, by this analogy with atomic/molecular systems, as dimers within the higher-entropy phase. In the present context the unknown lower-entropy phase is purely hypothetical, imagined as existing only in unstable nuclei during an episode of accelerated decay as a result of a change in the strong force miraculously wrought by God.

36 There is also an *np* pairing in the nucleus important for nuclides with the same number of neutrons as protons (Chaffin, 2021, p. 193) for which the nucleons are farther apart than for the deuteron ^2H (Isaule et al., 2016) possibly suggesting a weaker attraction for nucleon pairings inside the nucleus and thus a somewhat lower number than the deuteron's 2.225 MeV.

Summary

To reiterate, a phase change for the condensed matter comprising large nuclei is proposed as a heat sink during an episode of accelerated nuclear decay, being particularly relevant to the formation of radiohalos. The proposed nuclear phase change would occur in ^{206}Pb nuclei, being the final stable progeny in the ^{238}U decay chain. With each cascade of decays, the latent heat for this presumed first-order phase transition would be taken from (via heat transfer, generically invoked), and thereby continuously cool, the radio-center's immediate environment wherein the thermal energy is deposited. Arguing by analogy with atomic/molecular systems, the plausibility of providing sufficient cooling (absorbing enough energy) by a phase change is explored. The lower-entropy phase for large, unstable nuclei during accelerated decay might consist of alpha clusters as compared with primarily nucleon pairings for the normal phase. The nuclear phase change would occur with/at the switch from unstable parent isotope to stable daughter in accordance with the dependence of a hypothetical nuclear phase diagram on the decreased strength of the nuclear force (a shallower nuclear potential) for unstable nuclei characterizing an episode of accelerated decay as compared with normalcy, as will be explained in Part 2.

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