

Alpha-Decay Alpha-Particle Propulsion for Deep-Space Missions: A First-Order Feasibility Study

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ABSTRACT

Alpha decay ejects MeV-scale alpha particles at $\sim 10^7$ m/s, implying an extremely high effective exhaust velocity and specific impulse. This paper studies whether that exhaust can be used as a practical thrust source for deep-space missions **without external electrical power** by directly allowing decay products to leave a spacecraft in a preferred direction. The key obstacle is not exhaust velocity but **momentum directionality and energy deposition**: alpha emission is nearly isotropic and alpha particles have very short ranges in solids, so most decay energy becomes heat unless the radioactive material is structured as ultra-thin films.

We develop a thin-film “decay sail” model, implement a reproducible Monte Carlo simulation (no external dependencies) to estimate an effective momentum coupling coefficient $\eta(d/R)$, and perform isotope scaling studies for Po-210, Th-228, Pu-238, and Am-241. For a representative geometry $d/R \approx 0.5$ and an areal mass of 10 mg/cm², our model predicts an initial thrust density of $\sim 3.2 \times 10^{-4}$ N/m² for Po-210 (tens of nN/cm²), consistent with published MCNP-based estimates for similar configurations. The same geometry implies **kilowatt-to-tens-of-kilowatt per m² heat fluxes** for short-half-life isotopes and **mA/m²-scale charging currents** unless charge neutralization is provided. We conclude that alpha-decay propulsion is generally **thrust-poor but power-rich**, best suited to niche missions that can tolerate extremely low thrust, very large emitter area, and significant thermal/charging engineering.

Introduction

Alpha emitters continuously produce helium nuclei (“alpha particles”) with MeV-scale kinetic energy. In vacuum, those particles can traverse centimeters to meters without collision, so their momentum could in principle be used as exhaust. The appealing feature is that the kinetic energy comes from **nuclear binding energy**, requiring no spacecraft electrical power to accelerate propellant.

However, three facts dominate feasibility:

1. **Directionality**: alpha emission is approximately isotropic in the rest frame of the nucleus; a usable thruster must break symmetry so more momentum leaves in one direction than the other.
2. **Escape from matter**: alpha particles lose energy extremely rapidly in condensed matter and typically stop within very short distances; thick sources behave primarily as heaters rather than thrusters. Stopping-power and range tables (e.g., NIST ASTAR/ICRU methods) quantify this behavior. [5–6]
3. **Systems closure**: even if thrust is produced, the resulting heat flux, spacecraft charging, contamination, and safety/regulatory constraints can dominate the design. [10–12]

Recent work has revisited “alpha-decay sails” and thin-film micropropulsion using MCNP/Geant4 and simplified analytic models, including Po-210 and Pu-238 thin-film studies and NASA NIAC concept work (TFINER). [1–4]

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He et al. used MCNP to model thin Po-210 films on aluminum substrates and reported thrust densities on the order of tens of nN/cm² for micron-scale films, and compared Monte Carlo results

against an analytic constant-stopping-power model. [1] Fang et al. presented a conceptual alpha micro-propulsion device design using Geant4 for particle transport and CFD for thermal analysis, reporting that thinner films increase escape rate and specific impulse and identifying a ~ 10 μ m Pu-238 film as an “optimal configuration” in their study setup. [2]

NASA NIAC’s TFINER concept proposes large-area, staged thin films (baseline Th-228) and argues that cascade decay chains can increase performance substantially, while also noting charging and possible charge neutralization strategies. [3–4]

1. Physics and Scaling Laws

1.1 Alpha exhaust velocity and specific impulse

For an alpha particle of kinetic energy E_α and mass m_α , the non-relativistic relations are given by Eq. (1):

$$p = \sqrt{2m_\alpha E_\alpha}, \quad v = \sqrt{\frac{2E_\alpha}{m_\alpha}}.$$

where:

- p is alpha particle momentum (kg·m/s)
- v is alpha particle speed (m/s)
- m_α is alpha particle mass (kg)
- E_α is alpha particle kinetic energy (J or MeV)

For typical alpha energies in the 4–8 MeV range, $v \sim 10^7$ m/s, implying $I_{sp} = v/g_0 \sim 10^6$ s. [8]

1.2 Thrust from activity: why high I_{sp} does not mean high thrust

Let N be the decay rate (activity, in decays/s). If a fraction of emitted particles escape the spacecraft and the average directed momentum per decay (normalized by the initial alpha momentum) is η , the thrust magnitude can be modeled as Eq. (2):

$$F(t) \approx \eta(d/R) p_0 N(t),$$

where:

- $F(t)$ is thrust (N)
- $\eta(d/R)$ is a dimensionless momentum-coupling coefficient

capturing directionality and escape statistics for a film of thickness d and alpha range R

- p_0 is the initial alpha momentum at emission (kg·m/s)
- $N(t)$ is activity / decay rate (decays/s)

with $N(t) = N_0 e^{-\lambda t}$ for a single isolated isotope. The key point is that F scales linearly with activity and η , not with I_{sp} .

1.3 Thrust-to-power penalty for very high exhaust velocity

If each decay releases alpha kinetic energy E_α and produces directed momentum p , then the idealized thrust-to-kinetic-power ratio for directed escaping alphas is given by Eq. (3):

$$\frac{F}{P} = \frac{p}{E_\alpha} \approx \frac{1}{v}.$$

where:

- F is thrust (N)
- P is escaping alpha kinetic power (W)
- p is directed momentum per escaping alpha (kg·m/s)
- E_α is alpha kinetic energy (J)
- v is alpha speed (m/s)

Thus, high v implies intrinsically low thrust per unit decay power. Practically, additional losses reduce F/P further (only a subset of alphas escape; many deposit energy as heat).

2. Thin-Film Decay Sail Concept

2.1 One-sided escape geometry

A minimal symmetry-breaking geometry is a thin alpha-emitting film deposited on a backing substrate. Particles emitted toward the free surface can escape; particles emitted toward the backing are stopped and do not contribute to net external thrust because they remain onboard.

This “one-sided escape” viewpoint is consistent with thin-film micropropulsion models that treat thrust as a statistical result of many escaping decay products from the upper surface. [1–3]

2.2 Key dimensionless design parameter: d/R

Let d be film thickness and R the alpha range in the film material at relevant energies. When $d/R \ll 1$, roughly half the emitted alpha particles head toward the free surface and many can escape with near-full energy. When $d/R \gtrsim 1$, most particles stop inside the film and thrust falls.

3. Methods and Reproducible Simulation Setup

3.1 Thin-film Monte Carlo model

We simulate decays uniformly distributed across film thickness and isotropic emission directions. For each decay we compute whether the alpha reaches the free surface before exhausting its range. We use a constant stopping-power approximation so that the exit energy decreases linearly with path length in the film, producing a reduced exit momentum.

We report:

- Escape fraction $f_{esc}(d/R)$
- Momentum coefficient $\eta(d/R) = \langle p_{z,exit}/p_0 \rangle$ averaged over *all*

decays

This is intentionally a simplified model meant to (a) produce correct scaling trends and (b) be easily reproducible without external particle-transport codes. Published work shows that constant-stopping-power analytic models can match MCNP results at the few-percent level for some thrust metrics under stated assumptions, while detailed scattering/straggling effects matter for higher fidelity. [1]

3.2 Isotope scaling and thermal/charging “closure checks”

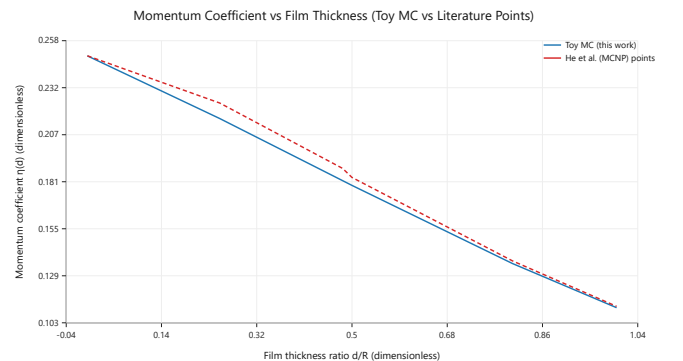
Using nuclear half-life and mean alpha energy data from tabulated sources, we compute specific activity and thrust density over time for fixed areal mass. [7] We also compute order-of-magnitude heat flux (from non-escaping alpha energy) and charging current density (from escaping alpha charge) for a representative geometry.

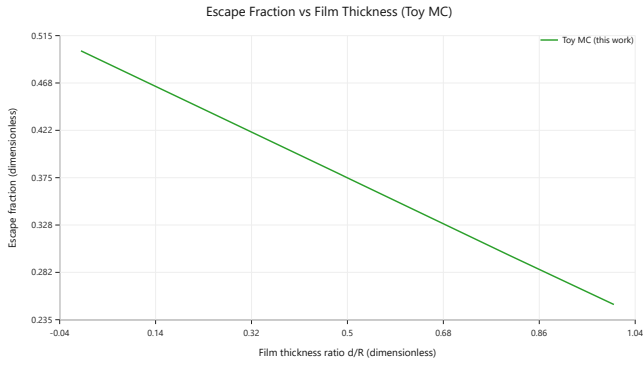
4. Results

4.1 Momentum coefficient and escape fraction vs thickness

Our toy Monte Carlo reproduces the expected limiting behavior $\eta \rightarrow 0.25$ as $d/R \rightarrow 0$ (half-space emission; mean $\cos\theta$ over a hemisphere). For thicker films, both escape fraction and η drop.

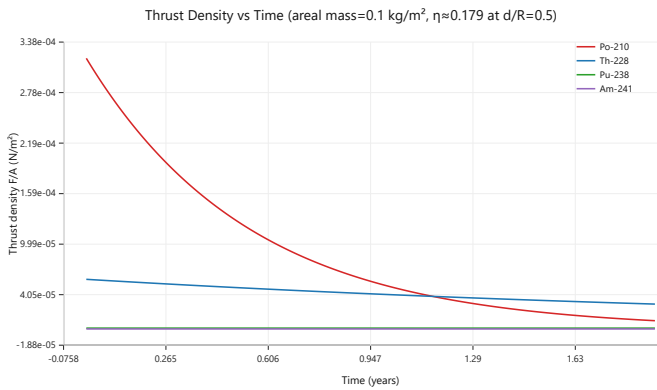
The plot below overlays our toy Monte Carlo with published reference points from a Po-210 thin-film study for comparable thickness ratios, showing close agreement for this simplified geometry factor. [1]





4.2 Isotope scaling: thrust density vs time at fixed areal mass

At fixed areal mass (10 mg/cm^2) and fixed geometry coefficient η (taken at $d/R = 0.5$ in our toy model), the initial thrust density scales primarily with specific activity (shorter half-life $\Rightarrow$ higher activity $\Rightarrow$ higher thrust).



The constants used to generate this plot (half-life, mean alpha energy, computed specific activity, and I_{sp}) are exported to `sim/out/isotope_trade_study_constants.csv`. Nuclear data for the isotopes were taken from MIRDspecs online tables (half-life and mean alpha energy). [7]

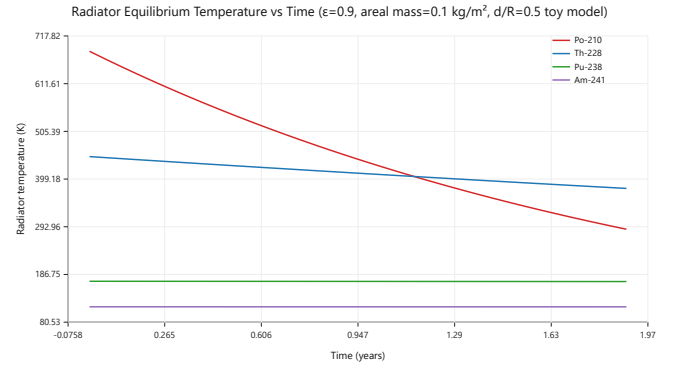
4.3 Thermal and charging implications

Because a large fraction of decay energy is deposited in the film/backing rather than leaving as escaping alpha kinetic energy, thin-film alpha thrusters can impose significant heat-rejection requirements. Alpha exhaust also removes $+2e$ charge per escaped alpha, creating a net current that would charge a spacecraft to extreme potentials unless neutralized.

For the same representative geometry used above ($d/R = 0.5$, escape fraction ≈ 0.37) and areal mass 10 mg/cm^2 , we compute:

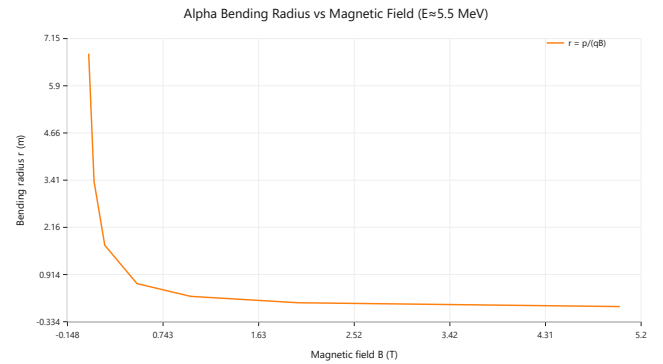
- Total alpha kinetic power density P_{total}/A
- Escaping alpha kinetic power density P_{esc}/A
- Residual heat to reject $P_{\text{heat}}/A = P_{\text{total}}/A - P_{\text{esc}}/A$
- Alpha charging current density $I/A \approx (2e) f_{\text{esc}} N/A$

The radiator-equilibrium temperature below assumes purely radiative rejection $P = \epsilon \sigma T^4$ with emissivity $\epsilon = 0.9$ (a simplifying bound; real systems must conduct heat from the film and may have temperature non-uniformity).



4.4 Magnetic steering (order of magnitude)

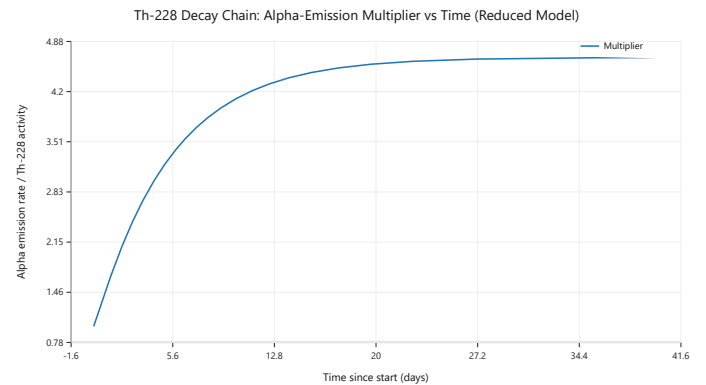
Electromagnetic steering of MeV alpha particles is possible but may require non-trivial field strengths and bending radii. Using the cyclotron radius $r = p/(qB)$ for $+2e$ charge:



This plot is intended only as a scale estimate; real steering would require field shaping and must account for energy spread and interactions with the spacecraft environment.

4.5 Th-228 decay-chain alpha multiplier (reduced dynamics)

NIAC concept descriptions emphasize that decay chains can increase performance by producing multiple additional alpha emissions after the initial parent decay. [3-4] Using the ICRP 107 chain table for Th-228 (half-lives and Bi-212 branching) [9] we simulate a reduced, non-stiff chain model that captures the multi-day buildup of daughter activities. The resulting alpha-emission multiplier approaches $\approx 4.6 \times$ the parent Th-228 activity after daughters accumulate (near secular equilibrium), consistent with the “several additional alphas per parent” interpretation.



5. Systems Engineering Considerations

5.1 Thermal management and material limits

Short-half-life alpha emitters produce very high specific activity and therefore high thrust density—but also high heat flux unless most alpha energy escapes. In our representative case, Po-210 at 10 mg/cm² produces $\mathcal{O}(10 \text{ kW/m}^2)$ heat loads from non-escaping alpha energy (see `sim/out/thermal_charge_trade.csv`), driving high radiator temperatures and/or large radiator area.

5.2 Charging and neutralization

Escaping alpha exhaust removes positive charge. Without neutralization, the spacecraft quickly charges to very large negative potentials, which will:

- electrostatically deflect/recapture outgoing alphas (reducing thrust)
- create arcing/field-emission risks and interfere with instruments

Charge neutralization can be provided by an electron source; NIAC concept work explicitly mentions beta emitters for neutralization and/or voltage biasing. ^[3-4]

5.3 Contamination, implantation, and sputtering

MeV ions impacting nearby structures can cause sputtering and helium implantation, potentially degrading surfaces and changing optical/thermal properties. A credible design must bound sputter yields and consider long-duration material evolution.

5.4 Thrust vectoring and “throttling”

Pure radioactive decay cannot be throttled in the usual sense; the decay rate is set by nuclear physics. Practical thrust modulation may rely on geometry: shutters, rotation, panel articulation, or reconfiguration of “thrust sheets” (vectoring) as described in concept studies. ^[3-4]

6. Mission-Level Implications (Deep-Space)

6.1 Velocity increment for exponentially decaying thrust

If the spacecraft mass m is approximately constant and thrust decays as $F(t) = F_0 e^{-\lambda t}$, then the asymptotic total velocity increment is given by Eq. (4):

$$\Delta v_\infty \approx \frac{F_0}{m \lambda}.$$

where:

- Δv_∞ is the asymptotic total velocity increment as $t \rightarrow \infty$ (m/s)
- F_0 is initial thrust at $t = 0$ (N)
- m is spacecraft mass (kg)
- λ is decay constant (1/s), with $\lambda = \ln 2 / T_{1/2}$

- $T_{1/2}$ is half-life (s)

This highlights a design tension: short half-life increases thrust (via higher activity) but reduces operating time (larger λ).

6.2 Worked scaling example (Th-228 thin-film sheet)

NASA’s TFINER concept uses a baseline $\sim 10 \mu\text{m}$ Th-228 film with a half-life of ~ 1.9 years and notes that the subsequent decay chain produces multiple additional alpha emissions over short daughter half-lives. ^[3-4] Independent nuclear decay chain tables (ICRP 107-based) show that Th-228 decays through a sequence that includes several alpha decays (with a branching at Bi-212). ^[9] In this workspace, a reduced chain simulation (`sim/out/th228_chain_multiplier.svg`) shows that the alpha emission rate can build up to $\sim 4.6 \times$ the parent activity once daughters accumulate.

Using our single-alpha, single-isotope toy model with areal mass $\sigma_m \approx 30 \text{ kg}/250 \text{ m}^2 = 0.12 \text{ kg/m}^2$ and $\eta(d/R = 0.5) \approx 0.18$, we estimate an initial total thrust of order 10^{-2} N for a 250 m^2 sheet. For a 60 kg combined system mass (30 kg payload + 30 kg isotope, ignoring additional structure), this yields a single-isotope Δv on the order of a few $\times 10 \text{ km/s}$. If the decay chain effectively contributes multiple additional alpha emissions that also escape with similar η , the effective thrust and impulse can increase by several-fold, bringing Δv toward the $\sim 10^2 \text{ km/s}$ regime claimed in NIAC concept summaries. ^[3-4,9]

This comparison is illustrative only: a realistic model must include daughter implantation and redistribution (recoil), energy-dependent ranges, backing geometry, and thermal/charging limits.

7. Limitations and Future Work

This paper intentionally starts from a minimal physics model. Next simulation steps that would materially increase fidelity:

1. Replace constant stopping-power with energy-dependent stopping power/range from SRIM/ICRU/NIST tables for the specific film and backing materials. ^[5-6]
2. Include angular scattering, straggling, and surface roughness (particle transport via Geant4/MCNP). ^[1-2]
3. Couple energy deposition to a thermal model (conduction + radiation + temperature-dependent material properties). ^[2]
4. Add spacecraft charging and plasma interaction modeling; include explicit neutralizer design. ^[3-4]
5. Mission-level optimization: stage mixing, decay-chain dynamics, thrust vectoring schedules, and trajectory integration. ^[3-4,9]

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During the preparation of this work the author used Chat GPT and Codex in order to learn and apply the appropriate formulas, code and run simulations, and correct any formatting errors in the paper. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.