A Coulomb Route to Solar Fusion: $p + e + p \to d$ and $d + d \to {}^4\mathrm{He}$

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Physical argument by the author; numerical implementation with AI assistance (Claude, Anthropic).

Abstract

In the standard proton–proton chain, solar hydrogen burning begins with $p + p \to d + e^+ + \nu_e$, a *weak*-force reaction that converts a proton into a neutron with emission of a positron and a neutrino, and is the slow, rate-limiting step of the whole chain. In the RealNucleus picture — in which the neutron is a bound proton–electron pair and the deuteron is $2p + 1e$ — the same first step is purely *electromagnetic*: $p + e + p \to d$, an electron from the plasma captured as the deuteron's glue, with no flavour change, no positron, and no neutrino. Two deuterons then fuse to the alpha, $d + d \to {}^4\mathrm{He}$, a reaction computed directly in RealQM. The net process $4p + 2e \to {}^4\mathrm{He}$ releases the same $\sim$26.7 MeV as the standard chain but retains the $\sim$0.5 MeV per alpha ($\sim$2%) that the standard chain loses to neutrinos. The decisive difference is a lepton one: in RealNucleus no lepton is created or destroyed — the electron persists as the deuteron's constituent — so lepton-number conservation requires *no* neutrino, whereas the standard neutrino is the signature of the flavour-changing weak vertex $p \to n$. We set the two schemes side by side and identify the experimentum crucis: the solar neutrino flux, directly measured, which the standard weak picture predicts and which the Coulomb picture must account for. The comparison is thus sharp and falsifiable.

Keywords: solar fusion; proton–proton chain; deuteron formation; electron capture; RealNucleus; weak force; solar neutrinos; hydrogen burning.

1 Introduction

The Sun shines by fusing hydrogen to helium, $4p \to {}^4\mathrm{He}$, releasing 26.73 MeV per helium nucleus. In the standard account [2, 5] this proceeds through the proton–proton (pp) chain, whose first and rate-limiting step,

$$p + p \;\longrightarrow\; d + e^+ + \nu_e, \tag{1}$$

is a *weak*-interaction process: two protons collide, one is converted to a neutron ($p \to n + e^+ + \nu_e$), and the resulting proton and neutron bind as a deuteron. Because it requires the weak force acting during the brief instant two protons are within nuclear range, this step is extraordinarily slow — it is what makes the Sun's hydrogen last billions of years — and it emits a neutrino that escapes the Sun directly.

RealNucleus [8, 9] offers a different account of the same burning. There the neutron is not elementary but a bound proton–electron pair, $n = (p\,e^-)$, and the deuteron is accordingly $2p + 1e$: two protons glued by a single shared electron, the charge-conjugate of the one-electron molecular ion H_2^+. In this picture the first step of hydrogen burning is not weak but electromagnetic,

$$p + e + p \;\longrightarrow\; d, \tag{2}$$

an electron drawn from the surrounding plasma and captured as the deuteron's glue — no proton is converted, no positron is created, and no neutrino is required. The chain then closes with the direct fusion of two deuterons,

$$d + d \;\longrightarrow\; {}^4\mathrm{He}, \tag{3}$$

a reaction we have computed directly in RealQM [8]. This paper places the two accounts side by side, compares their energetics and their lepton content, and identifies the single measurement that decides between them.

2 The standard proton–proton chain

The dominant (ppI) branch of the standard chain is

$$\begin{aligned}
p + p &\to d + e^+ + \nu_e && (Q = 0.42\ \text{MeV};\ \text{weak, rate-limiting}), && (4)\\
d + p &\to {}^3\mathrm{He} + \gamma && (Q = 5.49\ \text{MeV}), && (5)\\
{}^3\mathrm{He} + {}^3\mathrm{He} &\to {}^4\mathrm{He} + 2p && (Q = 12.86\ \text{MeV}), && (6)
\end{aligned}$$

with the two positrons annihilating on plasma electrons. Summing the branch and the annihilations, the net is

$$4p + 2e^- \;\longrightarrow\; {}^4\mathrm{He} + 2\nu_e + 26.73\ \text{MeV}, \tag{7}$$

of which the two neutrinos carry away, on average, $\sim$0.5 MeV, so that $\sim$26.2 MeV is deposited as heat. The rate is set by two factors in series: the Coulomb barrier the two protons must tunnel (the Gamow factor, steeply temperature-dependent), *and* the weak matrix element for $p \to n$ conversion during the collision. The second factor is tiny, and it is the weak bottleneck — not the Coulomb barrier alone — that fixes the Sun's luminosity and lifetime. A minor variant, the *pep* reaction $p + e^- + p \to d + \nu_e$ (about 0.4% of pp), captures a plasma electron instead of emitting a positron, but is still weak and still emits a neutrino.

3 The Coulomb route

In RealNucleus the ground state of a nucleus is a set of proton and electron charge clouds on non-overlapping domains with free boundaries, minimising the Coulomb (electrostatic) energy alone,

$$E \;=\; \sum_i \tfrac{1}{2}\int |\nabla\psi_i|^2 \;+\; \tfrac{1}{2}\iint \frac{\rho(x)\rho(y)}{|x-y|}\,dx\,dy, \qquad \rho = \sum_i q_i\psi_i^2, \tag{8}$$

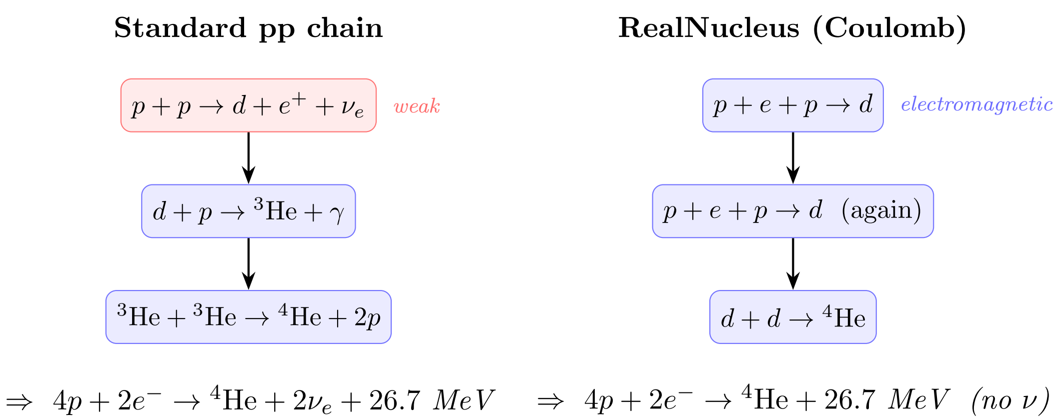

Figure 1: The two accounts of solar hydrogen burning. *Left:* the standard pp chain opens with the weak reaction $p+p \to d+e^+ +\nu_e$ (red), which converts a proton to a neutron and emits a neutrino. *Right:* the RealNucleus chain opens with the electromagnetic capture $p + e + p \to d$ (blue), the electron becoming the deuteron's glue, and closes with the directly-computed $d + d \to {}^4\mathrm{He}$. Both net to $4p + 2e^- \to {}^4\mathrm{He}$ at 26.7 MeV; only the standard chain emits neutrinos.

with $q_i = \pm 1$ [9, 8]. A free proton and a free electron form the model neutron $1p + 1e$, which does *not* bind on its own (matching the instability of the free neutron); but a *second* proton produces the deuteron $2p + 1e$, which does. The single electron cannot glue one proton into a bound unit yet glues two — the charge-conjugate H^-/ H_2^+ configuration, the two protons splitting into halfspaces around the central electron core. This is the reaction (2): it needs only an electron, always abundant in the solar plasma, and the Coulomb attraction that binds it; no proton is transmuted.

The second step (3), $d + d \to {}^4\mathrm{He}$, is the fusion of two such units into the alpha $4p + 2e$ — the closed, dual-confined structure in which a -2 electron core is caged by four protons. In RealQM this reaction is computed directly: two deuterons, each a central electron core with its two protons split into halfspaces, are brought together and relaxed, and the energy falls monotonically onto the deeply bound alpha as the separation decreases [8]. The overall balance is

$$4p + 2e^- \longrightarrow {}^4\mathrm{He} + 26.73\ \mathrm{MeV}, \tag{9}$$

identical in energy to the standard net (7) except that no energy is carried off by neutrinos.

Which second step? A caveat on abundances is in order. In the solar core protons outnumber deuterons enormously: a deuteron, once formed, is consumed almost at once, so its equilibrium abundance is only $[d]/[p] \sim 10^{-18}$. In the standard chain this is precisely why deuterium burns by $d + p \to {}^3\mathrm{He}$ and not by $d + d$, which is utterly negligible. The same abundance argument applies to the Coulomb route: the dominant second step in a proton-rich plasma is likewise $d + p \to {}^3\mathrm{He}$ — in RealNucleus simply $3p + 1e$, again electromagnetic — followed by ${}^3\mathrm{He} + {}^3\mathrm{He} \to {}^4\mathrm{He} + 2p$, exactly the ppI topology but with every step Coulombic and neutrino-free. We write the chain as $d + d \to {}^4\mathrm{He}$ in (3) because that reaction is the one computed directly in RealQM [8] and the cleanest picture of two dual-confined units merging into the closed alpha; the abundance-weighted path through ${}^3\mathrm{He}$ tells the same electromagnetic story, $4p + 2e^- \to {}^4\mathrm{He}$, and is equally free of the weak vertex. The essential contrast with the standard chain therefore lies entirely in the *first* step, the formation of the deuteron: whether it is the weak $p + p \to d + e^+ + \nu_e$ or the electromagnetic $p + e + p \to d$. Every step thereafter is Coulombic in both accounts; only the entry point carries — or does not carry — the neutrino.

4 Comparison

Table 1 sets the two accounts against each other. They agree on the overall transmutation and on its energy release; they differ on the *mechanism* of the first step, and hence on the leptons and the neutrinos.

	Standard pp chain	**RealNucleus (Coulomb)**
first step	$p + p \to d + e^+ + \nu_e$	$p + e + p \to d$
force	weak (flavour-changing $p \to n$)	electromagnetic (Coulomb)
what the deuteron is	$p + n$, n elementary	$2p + 1e$, $n = (p\,e^-)$ bound
second step	$d + p \to {}^3\text{He}$, then ${}^3\text{He}+{}^3\text{He}$	$d + d \to {}^4\text{He}$ (computed)
leptons	e^+ and ν_e created	electron retained; none created
neutrinos	yes ($2\,\nu_e$ per ${}^4\text{He}$)	none
net	$4p + 2e^- \to {}^4\text{He}+2\nu_e$	$4p + 2e^- \to {}^4\text{He}$
energy	26.73 MeV (~ 0.5 to ν)	26.73 MeV (all retained)
rate limiter	weak vertex $\times$ Coulomb barrier	Coulomb barrier (three-body *pep*)

Table 1: The standard proton–proton chain and the RealNucleus Coulomb route to solar hydrogen burning, step by step.

The lepton argument. The cleanest distinction is one of lepton bookkeeping. In the standard first step a proton is turned into a neutron, a flavour-changing weak transition that must create a positron and a neutrino to conserve charge and lepton number: the neutrino is the *signature of the weak vertex*. In the Coulomb route no proton is transmuted and no lepton is created or destroyed — the plasma electron simply becomes the deuteron's glue and remains as the constituent electron of the $n = (p\,e^-)$ pair. Lepton number is then conserved trivially, with no neutrino. The presence or absence of the solar neutrino is thus a direct readout of which mechanism operates.

5 Energetics and the neutrino budget

Both routes conserve energy at the same value because both effect the same net transmutation $4p + 2e^- \to {}^4\text{He}$, whose Q-value is fixed by the masses,

$$Q = \big(4m_p + 2m_e - m_{{}^4\text{He}}\big)c^2 = (3753.09 + 1.02 - 3727.38)\ \text{MeV} = 26.73\ \text{MeV}. \tag{10}$$

It is worth seeing where this energy is actually generated, because in the Coulomb route the two steps are very unequal. Forming the two deuterons releases little: each deuteron sits only 1.44 MeV below $2p + e$ (the familiar 2.22 MeV binding measured against $p + n$ becomes 1.44 MeV against protons and electrons, since the neutron itself lies 0.78 MeV above $p + e$), so the two formations contribute $2 \times 1.44 \approx 2.9$ MeV, about 11% of the total. The overwhelming balance comes from the fusion of the two deuterons into the alpha,

$$d + d \to {}^4\mathrm{He}: \qquad 2m_d - m_{^4\mathrm{He}} = 23.8 \text{ MeV} \ \ (\approx 89\%), \tag{11}$$

where the two loosely-bound $2p + 1e$ units merge into the deeply-bound $2e + 4p$ alpha — the two electron cores settling into a single -2 glue now caged by *four* protons instead of two. The Sun's luminosity is therefore, to $\sim 89\%$, the *alpha-binding energy*: deuteron formation is only the small doorway, and $d + d \to {}^4\mathrm{He}$ is the powerhouse. (In the Sun the abundance-weighted path reaches the alpha through $d + p \to {}^3\mathrm{He}$ and ${}^3\mathrm{He} + {}^3\mathrm{He}$ rather than $d + d$, since deuterium is consumed by protons far faster; the total is the same state-function 26.73 MeV, only distributed differently.)

The standard chain gives up about 0.5 MeV of this to its two neutrinos (mean pp-neutrino energy ≈ 0.27 MeV each), so ≈ 26.2 MeV becomes solar heat and light; the Coulomb route retains the full 26.73 MeV. Equivalently, the standard model predicts a solar *neutrino luminosity* of about 2% of the total, while the Coulomb route predicts essentially none. This few-percent split is small in the energy budget but it is the whole of the observable neutrino signal.

6 The decisive test: solar neutrinos

Here the comparison becomes an experiment, and honesty requires stating the current evidence plainly. The standard chain predicts a pp-neutrino flux at Earth of about $6 \times 10^{10}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, tied directly to the solar luminosity, and solar neutrinos are *observed*: the chlorine and gallium radiochemical experiments, Super-Kamiokande and SNO (which established flavour oscillation and measured the total ${}^8\mathrm{B}$ flux), and above all Borexino, which has directly measured the low-energy pp, ${}^7\mathrm{Be}$ and pep neutrinos in real time at fluxes consistent with the standard solar model [7, 6, 5]. Detection is by neutrino–electron scattering and inverse beta decay, which count arriving neutrinos in a largely production-model-independent way. Taken at face value, this flux is strong evidence for a neutrino-emitting — hence weak — first step, and it is the principal challenge the Coulomb route must meet: a strictly neutrino-free burning is disfavoured by the measured flux unless that flux can be attributed to another source.

We therefore state the position without overreach. The Coulomb route is a well-defined, computable, and energetically exact account of $4p + 2e^- \to {}^4\mathrm{He}$ that removes the awkward features of the weak first step — the unbound diproton, the improbable in-flight $p \to n$ conversion — and predicts a specific, falsifiable consequence: little or no solar neutrino emission from the initial deuteron formation. The measured pp-neutrino flux is the experimentum crucis. If that flux is genuinely of primary solar origin at the standard-model value, the strictly neutrino-free version is excluded and any Coulomb account must incorporate a neutrino-producing channel; if some part of the inferred flux rests on assumptions about the production mechanism, that part is open to reexamination. Either way the question is settled by measurement, not by preference — which is the proper standing of a physical proposal.

7 The original need for the neutrino, and whether it disappears

Pauli's neutrino of 1930 was a *desperate remedy* [1]: a particle postulated solely to rescue two conservation laws that beta decay appeared to violate. First, *energy and momentum* — the beta electron emerges with a *continuous* spectrum, whereas a two-body decay $n \to p + e$ would make it monoenergetic, so a third, unseen body must carry the balance. Second, *angular momentum and statistics* — the neutron is spin-$\frac{1}{2}$, but $n \to p + e$ yields spin 0 or 1 (two fermions make a boson), so a third spin-$\frac{1}{2}$ fermion is needed to restore both the half-integer spin and the fermionic statistics. Pauli's neutrino supplied both at a stroke, and went undetected for a generation. Two questions then separate: whether the present picture *needs* the neutrino, and whether the *original* need is still what makes it compelling.

For the first step of solar burning *according to RealNucleus* the energy–momentum half of the need does not even arise, because that step is then a *capture*, not a decay. Deuteron formation $p + e + p \to d + \gamma$ proceeds to a *bound* state and emits a definite energy — the 2.22 MeV deuteron line, exactly the gamma of the observed radiative capture $n + p \to d + \gamma$. There is no continuous spectrum and no missing energy; a photon carries the balance. The continuous-spectrum argument that half-created the neutrino is specific to decays, and in this capture it is silent.

The statistics half, by contrast, does *not* lapse, and we state it plainly as the open problem of the electron-in-nucleus picture. The neutron is spin-$\frac{1}{2}$ (a fermion) and the deuteron spin-1 (a boson); yet a composite $n = (p\,e)$ of two spin-$\frac{1}{2}$ constituents is a boson, and $d = (2p, 1e)$ of three is a fermion — the reverse of measurement. This is the "nitrogen anomaly" that drove the abandonment of nuclear electrons in 1932. Whether the RealQM charge-density description, which represents constituents as continuous clouds rather than point fermions, escapes this bookkeeping is a foundational question we do not settle here; we flag it as the principal open issue, distinct from the binding and energetic results.

Is the neutrino, then, still indispensable? Within the Standard Model, unquestionably: it is a fundamental lepton woven into the electroweak theory — the charged weak current couples (ν, e) doublets, and beta decay is W-boson exchange — so the Standard Model cannot function without it. Its support is also *broader* than the original beta-spectrum need, resting now on distinct phenomena in distant domains: the reactor detection of Reines and Cowan [3] in 1956, the invisible width of the Z boson at LEP counting exactly three light species, $N_\nu = 2.984 \pm 0.008$ [4], and established neutrino oscillations. One should not overstate this, however. These are logically distinct *observations*, not the beta spectrum re-read; but each is still interpreted within the very electroweak theory built to house the neutrino. And, crucially, the neutrino does not stand on the same footing as the electron and the proton. Those can be isolated, held one at a time in a trap for months, counted, and steered as beams, their charge, mass and magnetic moment measured to many digits (the electron moment to roughly twelve); they interact electromagnetically and leave continuous, reproducible, manipulable traces. The neutrino has never been isolated, held, or counted singly; it registers only as rare statistical events through its feeble weak coupling, $\sigma \sim 10^{-44}\,\mathrm{cm}^2$, and its absolute mass remains unknown. Its epistemic standing is thus genuinely weaker and more provisional —

which is precisely what makes it legitimate to ask whether a given process truly requires it. This weakness does not make the neutrino a fiction: the directional and luminosity-locked solar flux (§6) must still be accounted for. But it does mean the honest position is unequal — the neutrino is more questionable than the charges this model is built from — and that the challenge is best made bounded and empirical. The comparison of this paper is accordingly narrow by design: RealNucleus does not claim to remove the neutrino from physics, but only to challenge the *weak framework in one bounded place* — the electromagnetic capture that forms the deuteron, where a photon suffices — and to let the solar-neutrino flux (§6) decide.

8 Rates and the Coulomb barrier

Both routes share the Coulomb barrier: two protons must tunnel through their mutual repulsion to reach the range at which an electron can glue them, so both inherit the steep Gamow temperature dependence that localises hydrogen burning to the solar core. The routes differ in what multiplies that barrier. The standard rate carries the additional tiny weak matrix element, which is the dominant suppression. The Coulomb route replaces it with the phase-space factor for a *three-body* encounter $p + e + p$ — the requirement that an electron be present in the small volume where two protons briefly meet — which in a dense plasma is far less suppressed than the weak vertex. The two pictures thus make *different rate predictions* for a given core temperature and density: whether the observed solar burning rate is better matched by the weak bottleneck or by the three-body Coulomb capture is a second, quantitative discriminator, to be developed with a proper plasma phase-space calculation alongside the neutrino test.

9 Conclusion

Solar hydrogen burning can be told two ways. In the standard proton–proton chain the first step $p + p \to d + e^+ + \nu_e$ is a weak, neutrino-emitting conversion of a proton into a neutron. In the RealNucleus picture the neutron is a bound proton–electron pair, so the same step is the electromagnetic capture $p + e + p \to d$, followed by the directly computed fusion $d + d \to {}^4\mathrm{He}$; no proton is transmuted, no lepton is created, and no neutrino is required. Both net to $4p + 2e^- \to {}^4\mathrm{He}$ at 26.73 MeV, differing only in the $\sim$2% the standard chain gives to neutrinos. The accounts are therefore not vague alternatives but sharply opposed at one observable: the solar neutrino flux. The standard chain predicts it and it is measured; the Coulomb route predicts its absence from the primary step. We put the two side by side precisely so that the measurement can decide.

Code and simulations

The $d + d \to {}^4\mathrm{He}$ fusion and the deuteron and alpha structures are computed with an open-source WebGPU RealQM solver, runnable from the interactive gallery [10] at `https://claes542.github.io/RealMolecule/gallery.html`; see in particular the deuteron (`nucleus_2h.html`), the alpha (`nucleus_he4_2plus2.html`), and the D + D fusion sweep (`nucleus_DD_fusion_Rsweep.html`).

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