Icarus Interstellar

International Interstellar Spacecraft Design Team

Spacecraft Propulsion Via Chiral Fermion Pair Production From Parallel Electric and Magnetic Fields

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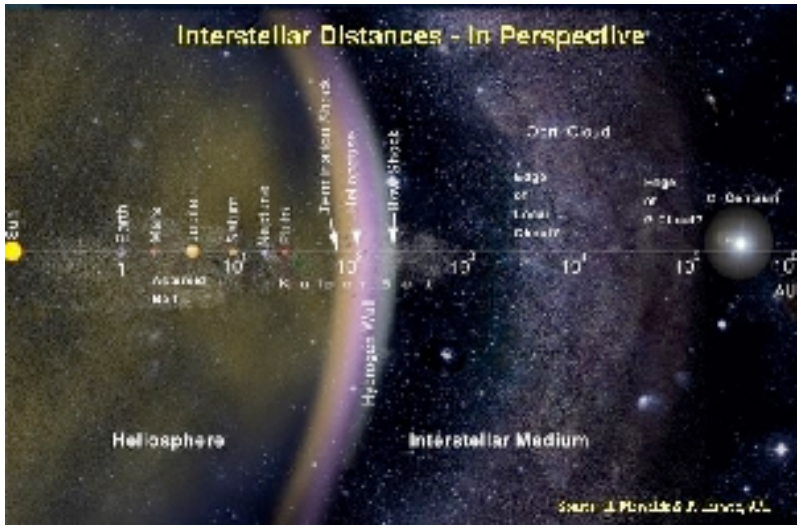
- For maximum probability of a successful (robotic or humaned) intrasolar/interstellar voyage, a spacecraft should have multiple redundancies and back-ups of all critical systems, including of its propulsion system(s).
  - Ideal matter/antimatter (MAM) propelled spacecraft should contain systems for both collecting and generating MAM, with creation especially as an emergency option if stored MAM leaks out of its magnetic containment chambers or is annihilated prematurely by matter leaking in.
  - More than one method of generating MAM on board:
    - Schwinger pair production via the vacuum through intense electric field quantum effects via lasers was has proposed (e.g. Icarus Interstellar' VARIES proposal.
    - Schwinger pair production via weak electric fields aligned in parallel with magnetic fields.

Chiral Fermion Pair Production From Parallel Electric and Magnetic Fields

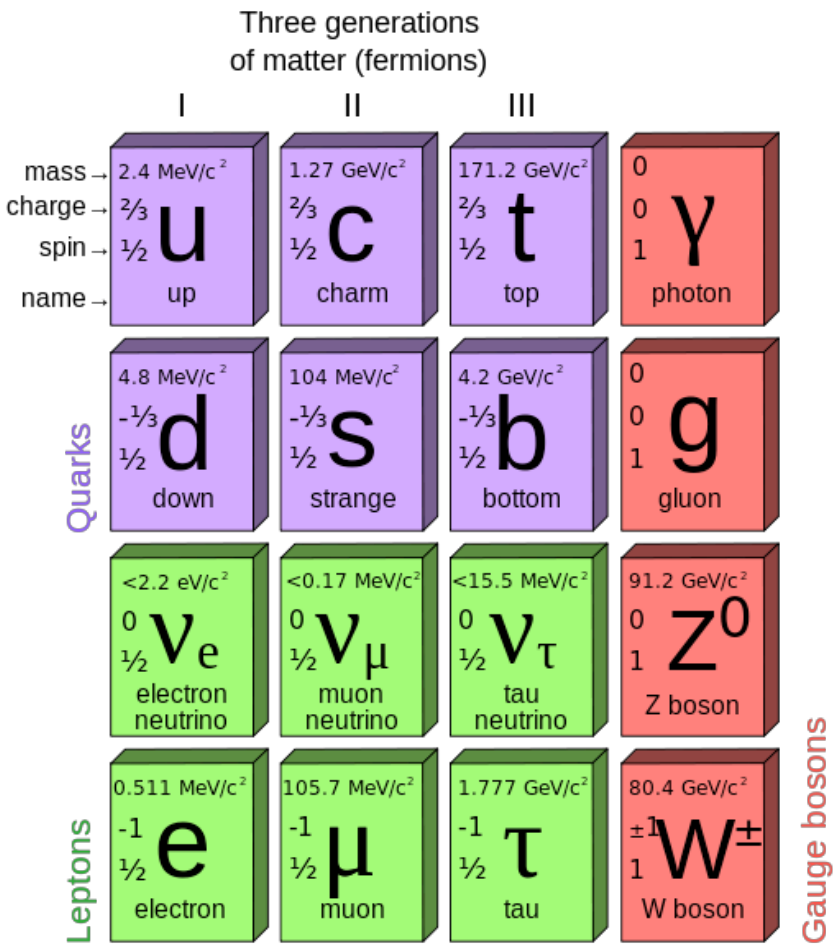
*While not envisioned as a propulsion source for spacecraft, this basic idea for MAM production via parallel fields was discussed by John Preskill at Caltech in the late 1980's.

- The underlying physics behind MAM production from parallel electric and magnetic fields will be presented and shown to be associated with chiral symmetry breaking (CSB).
- CSB is an effect that connects left- and right-handed elementary particles (specifically for quarks) in the strong coupling (low energy) limit of QCD.
- Why only the parallel components of the electric and magnetic fields are relevant to this effect will be worked out in the Hamiltonian (energy) formalism.

- The intriguing quantum physics of chiral pair production via parallel electric and magnetic fields, and its application to and feasibility for viable MAM propulsion systems for both intra solar and interstellar, will be developed.



Left-handed versions
(spin in direction opposite of its motion)



Right-handed versions
(spin in same direction of its motion)
=
Left-handed Anti-Particle

- Chirality = Handedness (Left-Handed and Right Handed)

- Chiral Symmetry = Left-Handed and Right-Handed versions of same particle (equivalently Left-Handed particle and anti-particle) are independent particles

  (Technically mean the phases of each are independent.)

- Chiral Symmetry Breaking (CSB) = L-H and R-H particles are not independent (phases are correlated & exactly opposite)

- At high energies (much above 100 GeV), when "strong force becomes weak", quarks have Chiral Symmetry

  At low energies (below 100 GeV), when "strong force is strong", quarks experience Chiral Symmetry Breaking

- CSB allows an interaction term $F_{\mu\nu}\widetilde{F}^{\mu\nu}$ between the field strength tensor F and its dual field strength tensor $\widetilde{F}^{\mu\nu} = \varepsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}$, where indices = 0, 1, 2, 3

For Electromagnetic force,

$$F_{01} = -F_{10} = E_x,\ F_{02} = -F_{20} = E_y,\ F_{03} = -F_{30} = E_z,$$

$$F_{12} = -F_{21} = -B_z,\ F_{13} = -F_{31} = B_x,\ F_{23} = -F_{32} = B_x,$$

- For electromagnetics, $F_{\mu\nu}\widetilde{F}^{\mu\nu} = E_xB_x + E_yB_y + E_zB_z = \mathbf{E}\bullet\mathbf{B}$.
(The dot product "•" indicates that only the parallel components of **E** and **B** interact).

- Why this term can result in particle/antiparticle pair production is interesting?

  Let's look at it from the hamiltonian (energy) approach. To start, consider spin $S = ½$ fermions of mass m and electric charge e in a constant magnetic field **B** aligned along the z-axis, $\mathbf{B} = B\hat{z}$.

  The electromagnetic gauge field producing the physical magnetic field **B** can be chosen as $A = Bx\hat{y}$. The square of the hamiltonian of a fermion in this field is

$$H^2 = (\mathbf{p} - e\mathbf{A})^2 + m^2 - g\, e\, \mathbf{B}\bullet\mathbf{S}$$
$$= p_x^2 + p_z^2 + (p_y - e\, B\, x)^2 + m^2 - geB\, S_z$$

  with **p** the fermion's momentum (operator), and g its gyromagnetic operator (which is very close to 2)

$$H^2 = p_x^2 + p_z^2 + (p_y - e\,B\,x)^2 + m^2 - 2\,eB\,S_z$$

p_y and p_z are constants of motion so can be ignored.

contributions

$$p_x^2 + (eB)^2(x - x_0)^2\,,$$

with $x_0 = -p_y/(eB)$ has the form of a simple harmonic oscillator which in quantum mechanics has the quantized energy states of

$(2\,n + 1)\,e\,B$, where n is an integer.

So, $H^2 = p_z^2 + p_y^2 + (2n + 1 - 2\,S_z)e\,B + m^2$

with $2\,S_z = +1$ or -1

So, consider a RH particle ($S_z = ½$) and the ground state mode ($n=0$) with no motion in the y direction

$$H^2 = p_z^2 + m^2$$

In the theoretical massless limit, this produces a "zero mode" which even very low energy parallel **E** (not on yet) and **B** fields can excite, resulting in pair production. In reality, for actual massive states (the quarks), the **E** field must be stronger.

Turn on an **E** field in the **B** direction, slowly (adiabatically) increasing its strength

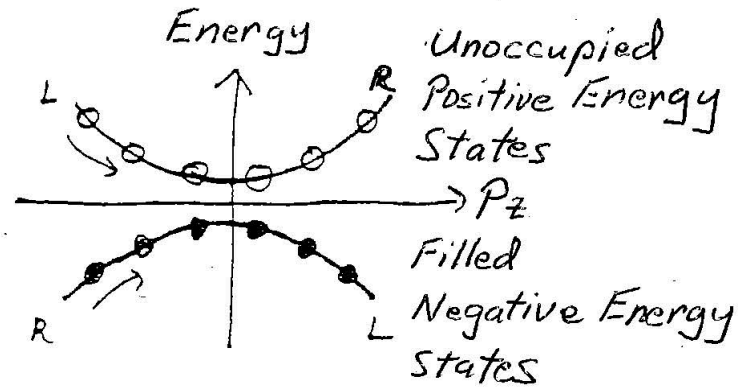
$\mathbf{E} = E\,\hat{z} = -d\mathbf{A}/dt$ with $A_z = E\,t$ (gauge choice $A_0 = 0$).

Then,

$$H^2 = (p_z - E\,t)^2 + m^2$$

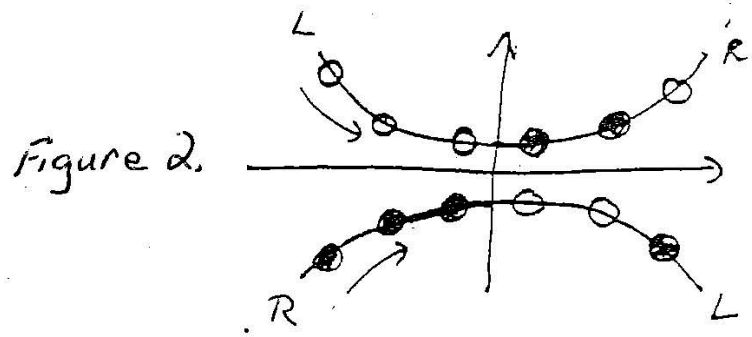
Energy levels are discrete and, with increasing t, move along a mass-shell hyperbola.

Figure 1.



Now we apply the famous "Dirac Sea" concept of both positive and negative energy states. In the ground state of the system, all negative energy modes are filled and all positive energy modes are empty.

Each mode can be assigned a helicity. Let all have $S_z = +1/2$. Then positive energy modes with positive (negative) momentum are right (left) handed. The opposite it true for filled negative energy modes.



For an electric field **E** with sufficient energy density, the negative energy quarks will "jump" across the 2m (~ 8 MeV for up quarks, ~14 MeV for down quarks) gaps separating the negative and positive energy states.

The physical realization of this is chiral particle pair production: a RH particle (filled energy state) and a LH antiparticle (negative energy state —that is, a hole).

The quark/anti-quark pair will either form an uncharged pion state or multiple charged or uncharged pions if the pair has sufficient kinetic energy to separate sufficiently far enough for the potential energy from strong force interaction of the quarks to be greater than the mass of another quark pair.

Thus, parallel electric and magnetic fields could be used as a MAM generator (a.k.a., chiral fermion pair production) via low energy effects allowed through chiral symmetry breaking.

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