Two ideas for relativistic spaceprobes capable of interstellar travel

Warren D. Smith, `warren.wds@gmail.com`, July 2024.

ABSTRACT. We explore two crazy ideas for pushing spaceprobes to the relativistic speeds needed to reach other stars: (§1) "Graphene lightsail" accelerated by a laser on the Moon. (§2) "Magnetic superconductor loop" accelerated by charged particle beams emitted from a linac, betratron, Van de Graaff, and/or synchrotron on the moon. Although the first idea seems to be quite technologically infeasible, my initial analysis of the second idea made it look feasible, or at least not very infeasible, with technology plausibly attainable within 10-100 years! (Both analyses are mostly freshman-level physics.) This is not claimed to be a super-detailed very-complete analysis, but rather, only the beginning. Unfortunately §3 finds serious objections to our initially-rosy analysis of idea 2: (a) beam-aim precision requirements likely are too difficult to achieve in practice, (b) high-current betatrons only produce high *electron* not positron, currents – the latter might be impractical. One could counter that we don't know any fundamental physical obstacles preventing a and b in principle. But today's technology cannot do it. We conclude (§4) by suggesting future investigation of CEPP – cold electron positron plasma – since idea #2 indicates it is a potentially useful substance, and it likely has amazing properties.

Preface

To be clear: In my view the human species is *not* going to go to other stars, nor even migrate onto any other bodies within our own solar system, and should *not* try, because that is extremely stupid. Only robots should try to do anything like that. I say this because numerous leaders in e.g. Washington, are perpetually too stupid to recognize that.

But it nevertheless is interesting to examine "science fiction" schemes for interstellar travel and attaining relativistic speeds. And for a brief shining moment of delusion, I thought I'd shown idea #2 analysed below actually was a lot closer to being practical than most or all other interstellar-travel schemes. Unfortunately section 3 has good arguments that *is* delusory and the idea still will remain impractical unless and until far better beam-aiming and far better positron-beam sources can be invented – which might never happen.

Nevertheless, this exercise has had the possibly-useful effect of focusing our attention on an interesting and little-before-studied kind of matter: "cold electron positron plasma" (CEPP). Idea #2, to the extent it is a good idea, depends heavily on CEPP, showing for the first time an actual use, arguably even "very impressive use," for the stuff. It conjecturally has highly interesting properties, including superfluidity and superconductivity – if so, the first substance to be both simultaneously! It also might exhibit ferro- or antiferromagnetism, which I think would make it the first non-solid to do so! Can it crystallize? Form a liquid? I'd like to see theoretical and/or experimental work on CEPP to try to determine its equation of state and properties, and enquire what implications they will have for space-travel schemes like ours.

1. Graphene lightsail powered by moon-based laser

By "graphene" we mean N≥1 planar layers of graphite (carbon). This is a 2-dimensional macromolecular sheet, N atoms thick. It has been shown feasible to create millimeter-size pieces of graphene. Perhaps there is some way to create square-kilometer graphene sheets, but present-day humanity cannot. The interlayer distance in graphite normally is 335pm. Graphene nanoribbon strength (monolayer) has been measured at 99 GPa, making it, or one of its cylindrically wrapped forms ("nanotubes") probably the strongest known substance, especially on a per-unit-weight basis. Equivalently, the tensile strength of an N-layer graphene ribbon of width L meters is 33NL newtons. The (two-dimensional) density of (monolayer) graphene is 0.763 milligrams per square meter. Flat graphene monolayer sheets are unstable with respect to scrolling, i.e. bending into a cylindrical shape, which is a lower-energy state.

The optical transmittance of CVD (chemical-vapor depositied) graphene is a decreasing function of N, but an increasing function of wavelength λ, throughout the visible range 380≤λ≤800 nm, then continues increasing (slowly) for infra-red wavelengths 1-2.5μm. For 400nm light and N=11.2, measured transmittance is 23%, and for a monolayer 96.7 to 97.7%. There is a strong transmittance valley, i.e. absorption peak, at λ≈290nm. The transmission coefficient is only 77% for a trilayer at that wavelength. I think the majority of the nontransmission is due to absorption (which is why graphite is black) with only a minority due to reflection.

So for initial examination, consider a **circular disk of 11-layer graphene with diameter=3km**, spinning about its axis to keep it flat. I do not claim to know how to manufacture this, but suppose it somehow has been manufactured. (Total mass = 59 kg.) Aim a **soft-UV laser beam (λ≈290nm)** at its back side. (Since aluminum is over 90% reflective for all λ with 100≤λ≤700nm and over 96% for 1100≤λ≤2000nm, it is feasible to build aiming mirrors. Excimer lasers such as KrF with λ=248nm and XeCl with λ=208nm are currently operated pulsed and the feasibility of continuous-wave excimer lasers is unclear. Ion lasers can generate continuous-wave UV light but much less efficiently. Solid state UV laser diodes are commercially available with λ=375nm, and another, by means of a integral frequency-doubler, at λ=266nm.) The intensity of the laser beam being absorbed by the graphene presumably could safely be as great as "**100 suns**," i.e. 136 kilowatts/meter^2, because if we model the graphene as a 2-sided blackbody reradiating that amount of power, then its steady state temperature would be 1046°K, far below the melting point of carbon at 3823°K. A 3-km-diameter beam with that intensity would have power=961 gigawatts, although greater power would be needed if the graphene is less than 100% light-absorbing and/or the beam spreads. (For simplicity I am pretending it is 100% absorbing despite measurement of 23.6% transmission, because there also is some reflectivity.) Compare: Averaged over the year 2023, the entire world's electricity generation amounted to about 3.4 terawatts.

The light-pressure exerted by absorbing 136 kilowatts/meter^2 then would be (136 kilowatt/meter^2)/c=0.45 millipascals. (That would be doubled if we somehow could cause the graphene to reflect the light instead of absorb it, but I do not know how to make that happen.) That would be enough to accelerate our graphene sheet at 54 meters/second^2, i.e. 5.5 "gees." Assume the beam spread is diffraction limited with aperture diameter D=3 km and wavelength λ=290nm. (I do not know how to build a 3-km-diameter mirror and/or laser that powerful and precise on the moon, but assume it somehow has been built.) Then we get beam spread angle $1.22\lambda/D=1.18\times10^{-}$

^{10} radians. So it would be reasonable to switch on the laser for the first 1.5km/(1.18×10^{-10}) = 1.27×10^{10} kilometers of flight, whereupon the beam would be getting too spread out to produce much acceleration anymore, so we switch it off. The net effect then would be 5.5 gees acceleration for a total fall-distance of 1.3×10^{10} km. This distance is 85 AU (where one astronomical unit, AU, equals the earth-sun distance) or 12 light-hours. This would yield final speed of about 37000km/sec=0.12c, good enough to reach Alpha Centauri in about 37 years, and also exceeding the solar-neighborhood's galactic escape velocity (≈310 km/sec) by a factor >100 in case you wanted to reach other galaxies. For contrast, according to Guinness book of world records, the fastest spacecraft speed yet achieved is 163 km/sec by the Parker Solar Probe at 21:25 UTC on 20 November 2021. The total laser switch-on time would be about 8 days. Note this whole calculation has assumed a bare graphene sheet with no payload – completely useless. The total energy radiated by the laser would be about 1.3×10^{18} joules, and the final kinetic energy of the graphene disk about 3.8×10^{16} joules, for about 3% efficiency. However, if we also counted the efficiency of the laser, the mirror, and whatever powers the laser, then reduce that.

If we instead had *four* launch lasers, say one on the Moon, one on the planet Mercury, one on some moon of Jupiter, and another on some moon of Neptune, and arranged a flight-path with 4 close-flybys enabling using all four successively, then we (in the nonrelativistic limit) could achieve 4× spaceprobe momentum via 4× laser energy expenditure via 4× the total laser switch-on time (versus same parameters for a single laser with short switch-on time) while also enhancing efficiency. However, that would only permit a small choice of launch-directions out of the solar system, with many forbidden.

This whole graphene-lightsail scheme is certainly absurdly infeasible with today's technology, and it is unclear to me that it ever could be feasible. That would depend on hypothetical future development of vastly larger lasers, huge but precise mirrors, and the ability to makes huge graphene sheets.

2. Superconducting magnetized loop accelerated by charged-particle beam from moon

An eternal supercurrent in a superconducting loop (or multiturn coil) of wire creates a local magnetic field. Present-day superconductors can operate at liquid nitrogen temperatures (77°K) and hence should work throughout the outer solar system (Saturn and outward), where it is that cold, and perhaps also 5× nearer to the sun if the wire were, e.g, reflective or white on its sunward side but black on the other side. If one or more beams of fast charged particles were shot through that magnetic field, then they would be deflected, and hence transfer momentum to the loop. The maximum transfer would occur if the field were just intense enough over just the right-sized region to cause the charged particles to make a 180° U-turn.

So by aiming the output of charged-particle accelerators (e.g. for protons and/or electrons) located on the moon at our loop, we could accelerate it. One of the major performance-limitations for the graphene light-sail scheme had been optical diffraction, forcing beam-spread. Overcoming that is why we needed a huge (3 km diameter) sheet of graphene. That fundamental issue no longer arises with a beam made of particles, not waves. Actually, de Broglie informed us that particles *are* waves, so it still is an issue; but hopefully now a much less serious one because their wavelengths are very tiny. (That is why electron microscopes provide much better resolution than optical ones.) The Compton wavelength (which is what is relevant for relativistic particle speeds) of an electron is 0.00243 nm, i.e. over 10^5 times smaller than the 290nm photons in the lightsail-scheme's laser beam. For a proton, the Compton wavelength is only 1.321×10^{-6} nm, i.e. over $K\approx2\times10^8$ times smaller than 290nm laser photons. This in principle (if everything else were unchanged) would permit K times more precise beam-aiming, K times less beam-spread, and hence would permit accelerating the spaceprobe over K times longer distance before we'd need to switch off beam-power, yielding roughly $\sqrt{K}$ times the final speed.. And in principle arbitrarily *sub*Compton wavelengths could be got by going to *ultra*relativistic particle beams, although that probably would be overkill.

The fact that beams of relativistic charged particles have been "stored" inside synchrotron rings for many hours also supports the notion that very precise beam-aiming ought to be possible. Example: The Australian synchrotron in Clayton can hold 200 mA of stored current, with particle energies up to 3 GeV and beam lifetime>20 hours. [Another source claimed "days."] Its storage ring has circumference 216 meters. During this 20 hours their beam, despite traveling 144 AU making 10^{11} circuits of the ring, remains "on target" to better than ±1 centimeter error.

Similarly the LEP (large electron positron collider, circumference=27km, formerly at CERN in Geneva) claimed single-beam storage lifetime of 50 hours and storage lifetime for counter-rotating double-beams (one e^-, the other e^+) of 20 hours (Burkhardt & Kleiss 1994).

But unfortunately, although *in principle* particle beams can be aimed much more precisely than light beams, this is not necessarily true in present-day *practice*. And we shall see later that the preceding argument about the Australian synchrotron is naive and probably misleading.

Unfortunately, charged particle beams will be deflected by magnetic fields created by the sun and planets, causing them (unlike laser light) to follow *curved* trajectories, making aiming more difficult. I'll discuss that more soon. For now let us just assume some sort of fedback-control aiming scheme is possible to overcome that problem and attain high accuracy.

Another issue (with, say, a proton beam) is beam-spread caused by inter-proton Coulombic repulsion. But if proton and electron beams were *mixed* together the resulting net-neutral beam would not have that problem, and indeed at some beam-temperatures and densities should actually have *negative* pressures causing the beam to contract, not spread. It probably would be better to use a neutral mixture of electrons and *positrons* to make everything *symmetric*. It in some ways is better to regard such a mixed overall-neutral beam not as a "particle beam" but rather a "plasma jet." With that view our spaceprobe's propulsion mechanism then is an instance of "eddy-current braking." That is: any magnet placed near a metal surface (or plasma, or any other lossy electrical conductor), e.g. flying through a metal tube, will, if its speed differs from the metal's, tend to be accelerated or deaccelerated to cause its speed to match the metal's. This is because the moving magnet induces "eddy currents" in the stationary metal, which then ohmically lose energy to heat; so therefore by conservation of energy the magnet must get slowed down. But this view sacrifices the factor of 2 obtainable from 180° U-turns.

To work out a rough design, we shall employ the following well-known formulae. The "cyclotron radius" R_{cyc} of a charge=q with mass=m, moving at speed=v, within a plane in which there is a uniform magnetic field B perpendicular to that plane, (nonrelativistic approximation) is R_{cyc}=mv/(qB). The magnetic field B_{cent} at the center of radius=R circular current-loop carrying current=J in vacuum is $B_{cent}=\mu_0 J/(2R)$. Within the plane of the loop, the magnetic field B increases with distance s to that center, reaching infinity when $s\to R^-$ for a zero-thickness wire (for real wires the magnetic field of course is finite everywhere); then changes sign and decreases in magnitude from infinity toward 0 as we continue to increase s from R^+, ultimately asymptotically to $B_{far}=\mu_0 JRs^{-3}/2$. Here $\mu_0\approx1.256637\times10^{-6}$ Newton/Ampere^2 is the "magnetic permeability of free space."

Commercially available high-T_c superconductor tape ("amperium" brand name, type 8700 from American Superconductor Co.) with 4.4×0.4mm cross section will carry 70-180 amps of supercurrent at 77°K, even if subjected to up to 200 MPa tensile stress, which is 352 newtons of tension. The permitted current ("70-180 amps") depends on grade; this product is available in many different quality-grades. They also sell **type 8612 tape with 12.1×0.33mm cross-section, capable of carrying 400-500 amps at 77°K even if subjected to up to 200 MPa tensile stress**, which is 799 newtons of tension, equivalent to about 81kg times 1 gee.

I'll consider a loop made of a bundle of 5 of the latter tapes in parallel, thus carrying J=2500 amps, with radius 100 meters. If the averaged mass-density of amperium tape is 7 grams/cc, then it weighs 28 grams per meter, causing **total spaceprobe mass≈90 kg**. The central field then would be B_{cent}=15.7 microTeslas. For comparison, the Earth's magnetic field where I live is about 51 microTeslas. Also note: the Lorentz-force "magnetic pressure" on J=500 amps in a B=16 microtesla field is JB=8 milliNewton/meter, which hopefully is enough to beneficially keep the whole thing stably "inflated" into a perfect-circle shape. The finite tensile strength of the tape comes nowhere near posing any problem to us if the loop just statically resists its own magnetic pressure. However, it could become a limiting factor under *acceleration*. Specifically, under 9 gees of acceleration, our 90 kg tape (assuming highly pessimistically that the accelerating forces were applied *only* to the Eastern half of the tape) would experience 3972 Newtons of tension, nearly reaching the maximum 3995 Newtons allowed by American Superconductor's spec sheet. This depends on how the stresses from that acceleration are distributed, which I do not know. We here are trying to design a spaceprobe that accelerates at 1-2 gees, and then the maximum permitted hoop-radius might be between 100 and 1000 meters. Certainly our choice – 100 meters – seems safe. The cyclotron-radius formula for a lightspeed electron in that field, then gives R_{cyc}=108.6 meters. Therefore, suitable relativistic electrons and/or positrons traveling in any plane near the plane of the loop ought to provide near-maximal momentum transfer (i.e. twice the electron momentum) to our loop. Here "near" could mean, e.g, "within 20 meters."

We here are considering just the loop alone, with negligible payload, as our "spaceprobe" – again utterly useless. Optimally beam aim would be so precise that no beam electrons would ever actually hit the loop – they'd only pass near it. However, if some tiny percentage of them did hit it, damage ought to be avoidable because the stopping distance of 1 MeV electrons in (say) iron is about 600 microns, i.e. 0.6mm, suggesting a metal outer layer on the sunward side of the tape-assembly could be enough to protect it. Unfortunately these collisions still would *heat* the tape, probably easily enough to get well above 77°K thus ending superconduction. So it is important to prevent them. That makes clear the necessity of good beam-aim and/or of active control on the spaceprobe to "tack" sideways to stay optimally positioned with respect to the beam.

It is no problem to accelerate electrons to energies far above the ≈1 MeV we need here; a "betatron" built in Urbana Illinois in 1950 achieved 300 MeV with a beam current of 0.1 amperes (Kerst et al 1950). Betatrons with diameter≈80 cm were built in the 1980s allegedly achieving 2-5 MeV electron energies with beam currents of 1-3 kiloAmps. A **3 kiloAmp beam** is about 2×10^{22} electrons per second, which for 1 MeV electrons would be a momentum flux on the order of 6 kg meter/sec^2 and an energy flux (1 MVolt)×(3 kAmp)=3 gigawatts. So **100 such betatrons** would already be enough to accelerate our 90 kg spaceprobe at order 1 "gee" for about 400 AU (note 400AU is about 2 light-days), reaching speed 0.11c after 40 days, whereupon we'd switch off the beam. That would be fast enough to reach Alpha Centauri in 40 years. In a 100-meter radius beam at this 2×10^{24} lepton/second flux (assuming speed≈c) the lepton number-density is equivalent to each electron being packed in a cube with sidelength≈168 microns, which should be rarified enough to prevent a 50-50 electron-positron mixture from annihilating. (The lepton number density inside the LEP counter-rotating double beams at maximum beam current 6.2 milliamps was equivalent to about 1 lepton per L×L×L cube with L≤31.4 microns [Tyapkin 2001]; and despite speeds very near c clockwise for electrons and anticlockwise for positrons the double-beam lifetime was about 20 hours, actually limited not by annihilations but rather by bremsstrahlung [Burkhardt & Kleiss 1994]. Since for our spaceprobe the lepton number densities are over 100× smaller and the e^+-e^- relative velocities should arise from thermal velocity randomness at beam temperature and thus hopefully should be far below c, the lifetime of our mixed beam against self-annihilation, bremsstrahlung, and all other mechanisms, ought to vastly exceed 20 hours.)

Published energy efficiencies of cyclotrons (I regard betatrons as a subset of cyclotrons) have ranged from 0.13% to 32%, and mechanical electrostatic generators such as Van de Graaffs can also achieve quite high efficiencies ≈50%.

Worrying Question: might magnetic fields present in the solar system act to *separate* the positrons from the electrons in our mixed/neutral beam? This is related to the issue raised earlier that such magnetic fields should cause beams of charged particles to follow *curved* not straight paths in space, making "aiming more difficult."

Worry-inspiring calculation: The sun is a magnetic dipole which reverses polarity about every 11 years (for reasons I do not understand). Its dipole moment allegedly was plotted in figure 1 of Jaswal, Saha, Nandy 2024, showing oscillations between about -80 and +80 microTesla with period indeed about 22 years. Unfortunately it did not occur to those authors that the correct units of "magnetic dipole moment" are *not* "microTesla." (Engendering the suspicion they are idiots. Meanwhile wikipedia, claims that Jupiter's magnetic dipole moment is 2.83×10^{20} Tesla·meter^3, which is a different, but also incorrect, unit for magnetic dipole moment – although actually their source Russell 1993 had said 1.55 not 2.83 – then claims this corresponds to an equatorial magnetic field 417 microTesla. Are particle physicists the only ones with enough brain power to use correct units Joule/Tesla=meter^2Ampere for magnetic moment? Fortunately I found Dinculescu 2004 who gave in "table 1" these magnetic moments 1.69×10^{29}, 1.60×10^{27}, 4.60×10^{25}, and 7.80×10^{22} meter^2Ampere, for Sun, Jupiter, Saturn and Earth. These at least have the correct units; and Dinculescu's references supposedly justify each number. The sun's magnetic moment normally dwarfs Jupiter's, which in turn dwarfs all the other planets combined. For comparison, our hypothetical spaceprobe's dipole moment is 7.854×10^7 meter^2Ampere.) If we assume/guess Jaswal et al meant "magnetic field at the sun's North pole" rather than "dipole moment" (?) then the solar field at distance S (measured in astronomical units, AU) away from the sun ought to be at most $8/S^3$ picoTesla. The cyclotron radius for a relativistic electron [1 MeV or so; I just substituted c as the velocity v in the nonrelativistic cyclotron radius formula] in an 8 picoTesla field is only about 1 light-second – which sounds like a total disaster for the whole plan!! Oops?

Answer: Weak magnetic fields should be unable to separate the electrons from the positrons in our mixed beam, if their local Coulombic attractions exceed the separating force. (Analogies: a chunk of rock salt NaCl does *not* separate into Na^+ and Cl^- ions if moved through a magnetic field – at least not with the magnetic field strengths and speeds accessible to humans, although it would separate if it were moving at 10000 km/sec through a 500 Tesla field. Hot plasma flowing inside the sun does *not* separate into positive and negative charges; rather, magnetic fields induce circulating electric currents inside it.) Let us contrast the Lorentz force on a speed=v electron (for the purposes of this rough calculation, I use v=c and B=8 picoTesla) $F_{lorentz}=Bev=3.8\times10^{-22}$ Newton versus the Coulombic attraction between electron and positron L=200 microns apart, $F_{coulomb}=e^2/(4\pi\varepsilon_0L^2)=5.8\times10^{-21}$ Newtons. This suggests that the solar magnetic fields at distances ≥1 AU from the sun are >15 times too weak to separate the electrons from the positrons in our mixed beam. In contrast, the fields near (generated by) the spaceprobe *are* easily large enough. If so, that's all good – it also implies the (overall-neutral) beam travels *straight*, making aiming easier, and also means the "total disaster" above, isn't, and finally might mean that beam-spread is inherently automagically prevented, diminished, or even reversed.

The time-reverse of the worrier's magnetic-separation process actually could be intentionally beneficially employed to mix two (one electron and one positron) beams from different cyclotrons with the aid of a nearby magnet.

Our whole analysis seems quite conservative, suggesting probably better performance should be attainable.

Conclusion: Rather surprisingly, the "magnetic-loop riding particle beam" spaceprobe plan does *not* seem outrageously crazy, unmanufacturable, or infeasible!

3. Less-rosy critical re-look at "magnetic-loop riding particle beam" scheme

a. My argument about the Australian synchrotron whose beam, even after 20 hours and 144 AU beam travel distance still is "on target" to within ±1 cm... was *naive*. The reason: Approximate it as a 216-meter circumference (34.4 meter radius) circle. Suppose pessimistically that the particle orbits are *not* circles, but rather ellipses randomly perturbed up to a few millimeters away from that circle, but all having exactly equal time-periods. If so, then the observed "tremendous accuracy" after 10^{11} orbits does *not* imply 10^{11} times better accuracy in each single orbit! Instead its beam collimation accuracy then would be more like (5mm / 216 meters) = 2×10^{-5} radians.

CERN's LEP with 27km circumference and typically beam size 4mm horizontally and less than

1mm vertically, would by the same pessimistic calculation have beam collimation accuracy at worst about (8mm / 27km) = 3×10^{-7} radians.

Oops. Does something like this pessimistic scenario, in fact, happen? What *are* the actual collimation accuracies of today's particle accelerators? I do not know. Although many basic performance specs have been advertised for many accelerators, this particular one seems instead to be a big secret. (I have no idea why the purveyors of particle accelerators behave that way. But they do. There also is a vast and difficult many-pronged literature on the related topic of "beam cooling" systems, which seem to be important components of most high performance accelerators today, but simple numerical answers about actual beam temperatures in Kelvin and collimation accuracies in radians seem stunningly absent from that literature. It has been claimed that SLAC is capable of producing *spin-polarized* 3 GeV electron beams. The fact that $(1\ \text{Tesla})\mu_e \approx (0.67°\text{K})k_B$ then suggests that their beam temperature is of order 1 Kelvin. That, rather surprisingly, is far below both ambient temperature and also the ≈1000°K temperature of any hot filament (if that is what SLAC's electrons originally came from). It is not obvious, at least to somebody like me with a complete lack of expertise in beam-cooling, how is it possible to cool beams that cold; nor what the ultimate limitations on beam cooling are. This 1°K number in turn might suggest a collimation accuracy for SLAC around 2×10^{-7} radians? This all also suggests that virtually all modern high performance particle accelerators depend heavily, for their successful operation, on beam-cooling systems.

Is it possible in practice to cool beams near the ultimate limits on collimation accuracy set by quantum uncertainty principles?

In view of the ellipse counterargument, I suspect that my initial argument about the Australian synchrotron probably was very over-optimistic, and that the truth is somewhere *between* 2×10^{-5} and 2×10^{-16} radians – and probably more like the former than latter, although I do not know.

We ideally would want beam-aim accuracy to be about ±20 meters at the maximum distance≈400 AU, i.e. beam collimation accuracy around $\pm3\times10^{-13}$ radians. This is about 300× better than the angular resolution (somewhat better than 10^{-10} radians) achieved by the "event horizon telescope" collaboration effectively coupling numerous radio telescopes in many geographic locations together at 230 GHz!

Our previous arguments about the inherent limitations on angular accuracy set by de Broglie wavelength and/or (what ought to be almost equivalent) quantum uncertainty principles, presumably still are valid. But they merely describe the best that we can do *in principle*. Nearing those theoretical limits might be infeasible *in practice*. For that reason, the whole plan currently appears to be more "science fiction" than "engineering."

b. Another problem is this: Yes, huge-beam-current (kiloAmps) betatrons have been built, *but* only for electrons. Not positrons. How could we also generate a huge-current made of positrons? That might not be feasible – and anyhow certainly nobody so far ever did it. The "LEP" formerly at CERN (Large Electron-Positron collider) with 27 km circumference, stored both electrons and positrons simultaneously in counter-rotating beams, but its maximum beam current was only 6.2 milliamps according to wikipedia. Presumably suitable relatives (e.g. "pelletron") of Van de Graaff generators would work equally well for generating either electron or positron beams with currents up to about 1 Amp, provided positron sources could be developed for use inside them.

> Positrons are most commonly made today by shooting high-energy electrons at matter, thus stimulating pair-production, then separating out the positrons using high-field magnets, with net efficiency unfortunately probably between 10^{-4} and 10^{-2}. However, in *principle* I do not see why it should be impossible to produce positrons with *high* efficiency by that same method provided the "matter" is isolated nuclei and the high-energy e-beam is reused repeatedly rather than largely wasted. *What are the ultimate efficiency limitations for creating antimatter?*

Even as electron-only devices, I feel a certain amount of suspicion regarding large-beam-current betatrons. E.g. I have observed a suspicious pattern of considerable discrepancies between the delicious performances reported in "progress reports" they wrote for funding agencies, and the less-tasty performances in papers they published in journals. And although classical cyclotrons output a continuous beam for as long as the power is switched on, the high-current betatrons described in the 1980s papers apparently could only achieve their high current specifications in brief pulses (20 nanosec to 1 millisec?) powered from, e.g, capacitor banks. That is understandable because they did not have enough money to pay for that amount of electrical power for long durations – but that left it unclear how long these machines could have been made to run continuously if they *had* been granted multigigawatt continuous power. (I'm confident at least some modifications would have been needed.) It is conceivable that continuous operation at high current would not even be possible. I did not see anybody in any of the papers on these machines even mention that issue.

It perhaps might be possible to use proton-electron rather than positron-electron mixed overall-neutral beams for the spaceprobe plan. E.g. mix 1 MeV electrons with same-speed protons (2 GeV). However, that would make it 1000 times less efficient.

Revised conclusion: I think the beam-aim precision requirement is too severe, and high-current positron sources not presently practical; so this whole spaceprobe scheme is impractical until and unless those issues can be overcome.

4. Cold electron positron plasma (CEPP) – an interesting substance to investigate

I have reason to believe e^+/e^- plasma is a superfluid and superconductor and perhaps also ferro- or antiferromagnetic in some regimes, which all is a quite remarkable combination, e.g. no simultaneous superfluid & superconductor has ever been seen before. Akhiezer et al 1995, on the right side of their page 550, give this critical-temperature estimate:

$$T_{crit} \approx (k_B)^{-1}\, \gamma\, E_0\, X \exp(-8^{-1/2}\pi\sqrt{X}), \quad \text{where} \quad X = 2\pi^{4/3}\,(3\, n\, a_0^3)^{2/3}$$

where $\gamma \approx 0.57721$ is the Euler-Mascheroni constant, $E_0 \approx 13.606$eV is the Rydberg energy (ionization energy of hydrogen atom with infinite-mass proton), $a_0 \approx 52.9177$ picometers is the Bohr radius,

k_B=1.380649×10^{-23} Joules/Kelvin is Boltzmann's constant, π≈3.14159, and 2n is the lepton number-density (n for electrons plus another n for positrons). This supposedly is valid whenever the annihilation time scale "considerably exceeds" the Coulomb-relaxation time scale; and they claim this conditon is fulfilled automatically whenever the temperature T obeys $k_BT \ll m_ec^2 \approx 511$ keV, i.e. T≪6 gigaKelvin. They then claim that if 2n=7×10^{24}/cm^3, then T_c≈25000°K while I instead compute T_c≈22695°K. With 2n=(13.4 microns)$^{-3}$, the lepton number density contemplated in our spaceprobe design, their formula gives T_c≈17 microKelvins.

If we genuinely had 1 MeV lepton beams cold-enough so that beam-spreading was only about about ±20 meters at the maximum distance≈400 AU, then the beam temperature would need to be of order 10^{-17} °K or below! That is well below T_c. So if we believe Akhiezer et al's theory, then our beams should indeed be superconductive superfluids. What implications would this have?

Re the possibility that this plasma also can be ferro- or antiferromagnetic, see Brodin & Marklund 2007. Provided "the spin relaxation time exceeds the reciprocated collision frequency" their EQ 18 would predict ferromagnetism with estimated Curie temperature

$$T_{curie} \approx (k_B)^{-1} (m_e)^{-1} c^{-2} \hbar^2 \omega^2 \quad \text{where} \quad \omega = (\varepsilon_0 m_e/n)^{-1/2} e \text{ is the "plasma frequency."}$$

Here e≈1.60218×10^{-19} Coulomb denotes the electron charge, $\hbar$≈1.05457×10^{-34} Joule second the reduced Planck constant, and n is the charged-particle number-density. At Akhiezer et al's lepton number density n=3.5×10^{24}/cm^3, we compute ω≈1.5×10^{17} Hz and T_{curie}≈221°K, and at the number-density 2n≈(31.4 microns)$^{-3}$ contemplated for our spaceprobe scheme, we find ω≈321 MHz and T_{curie}≈10^{-15}°K. What are the implications of this ferromagnetism? Might it greatly improve spaceprobe performance?

Given the fact (as §2 demonstrated) that CEPP could actually be a *useful* substance, I want to encourage further theoretical and/or experimental work on it.

5. Acknowledgement

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6. References

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