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LARGE BARYON DENSITIES ATTAINABLE IN HIGH ENERGY NUCLEAR COLLISIONS

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ABSTRACT

Nuclear densities at least four and as much as ten times normal could be achieved and maintained for appreciable periods in U-U collisions with center-of-mass kinetic energies between 1 and 4 GeV/nucleon. If a stable or long lived phase of high baryon density were possible, such collisions could give a good chance to make it.

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The field of nuclear physics traditionally has focused on the properties of nuclear matter at or near "normal" conditions, meaning those prevailing in known nuclei. The properties of systems with very high baryon density are unknown, though there have been interesting speculations about stable or nearly stable high density phases.[1-4] In the absence of spontaneous transitions to such phases,[1] transitions which might well be inhibited by enormous barriers, the only known way to produce high baryon density is bombardment of heavy nuclear targets with heavy nuclear projectiles.[5,6] Let us consider what density enhancements could be achieved in this way.

Uranium is a sufficiently large nucleus so that, at a 10% to 30% level of accuracy, a nearly head-on collision ($\approx$0.1 - 0.2b out of $\approx$6b total reaction cross section) may be described as the meeting of two slabs 15 fm thick with nucleon density about 0.15 fm^{-3}. Of course, in the center-of-mass (c.m.) frame each slab would be Lorentz contracted, with density increased and thickness decreased by the Lorentz factor $\gamma = W/2M$, where W is the total c.m. energy and M is the mass of a uranium nucleus. Suppose that for a given γ each slab is thick enough to stop (in the c.m. frame) a nucleon in the other slab. Then the combined system will eventually be confined to a thickness less than 15 fm/γ, since the back of either slab (assumed to have relativistic velocity) must progress at least halfway to the meeting plane before even a light signal from that plane could reach it. Consequently, at one moment the average baryon density will be at least 2γ times normal.

There remain two critical questions: What is the maximum γ for which such a nuclear slab could stop a nucleon of energy γm_o? How long would the high compression be maintained?

To determine the maximum γ, observe that a nucleon-nucleon cross section of 40 mb corresponds to an average of nine interactions on crossing the slab. This number would be raised if repulsive correlations among the target nucleons were taken into account, but would be lower near the edges of the actual finite spheroidal nuclei. Suppose that the interaction probability is unchanged by prior collisions exciting the nucleon. Compute the collisional deceleration by assuming that the mass excitation per collision is a uniform 0.4 m_o, where m_o is the unexcited nucleon mass, and that the 4-momentum transfer is lightlike. This estimation technique gives a total stopping power in nine collisions of about 2.1 GeV/c, provided that each of the nucleons hit was moving at high speed in the center-of-mass frame. Paradoxically, as the "target" nucleons slow down, their ability to stop "projectile" nucleons increases, since simple energy conservation implies that in nine collisions target nucleons at rest must convert the projectile kinetic energy into projectile mass plus target kinetic energy, giving a stopping power greater than 3.6 m_o projectile kinetic energy, or about 4.2 GeV/c momentum. A perhaps more reasonable "random walk" starting assumption, that at each collision the squared nucleon mass would increase by m_o^2, gives about 1.5 GeV/c stopping power for fast targets and more than 3 GeV/c for stopped targets. Both of these assumptions ignore the phenomenon of "hard" nucleon-nucleon collisions, which give very large (several GeV/c) momentum transfers perhaps once in fifty collisions. Further, both assumptions ignore any

collective effects which could enhance the stopping power. Perhaps most important, the above discussion ignores the well-established phenomenon of "pionization" or production of mesons intermediate in velocity between projectile and target. Pionization contributes to deceleration in two ways. It takes kinetic energy from the colliding particles, and it produces more matter (probably on a time scale of 1 fm/c) which increases the "momentum opacity" for later incident particles. Taking all this together, it seems safe to conclude that the maximum γ is at least 2, and could well be as much as 5. To the extent that the front nucleons in either slab are less effectively stopped than the back nucleons, the former may leak out of the high density region. However, the same effect will lead to an even greater compression for the nucleons remaining. Such "leak-through" effects have been seen in a model fluid-dynamic calculation for somewhat lower collision energies.[7]

Farley[8] in 1970 already considered the question of stopping power and argued that the c.m. energy range from 1 to 10 GeV/nucleon is an important one to explore. More recent discussions on hadron-nucleus collisions do not support the notion that stopping should be expected at 10 GeV/nucleon.[9] Consequently, 1-10 is precisely the range in which one would expect to see a transition from stopping to "transparency," or passage of the two nuclei through each other with some excitation and deceleration. If stopping were still found at 10 GeV/nucleon, that in itself would be a remarkable discovery of a new collective effect.

The duration of high compression depends on the nuclear equation of state. If many degrees of freedom besides nucleon motion can be excited,[10] then a relatively cool, low pressure phase might be formed,

and it would cool further by pion emission from the edges. This suggests a duration of order 10 fm/c, i.e. significantly longer than the typical hadronic time $\hbar/m_\pi c$. On the other hand, if the equation of state were very "hard," so that almost all the energy went into the compression, a fairly rapid explosion would be expected.[11] However, if a low-internal-energy, high-density phase could be formed, the great coherence of the "cold" compressed matter could give a large transition probability to the new phase, even in the short time before explosion.

The above considerations imply that U-U collisions, in the range of center-of-mass kinetic energy 1-4 GeV/nucleon (equivalent to bombardment energy 5-50 GeV/nucleon on a stationary target) might produce important phenomena, perhaps even practical applications. At the moment there are no definite plans to explore this regime, but it is certainly feasible to do so. It should be noted that, unlike hadron collisions, these effects are not duplicated in accessible astronomical processes. They would be unlikely to occur except in gravitationally collapsing objects or in the inverse process of the "big bang" commonly supposed to have begun the Universe (Could the matter-antimatter asymmetry we observe in the near part of the Universe[12] be related to occurrence, and perhaps gravitational collapse, of high-density antimatter objects shortly after the big bang?). In particular, near head-on collisions by cosmic ray U nuclei of energy around 50 GeV/nucleon with interstellar U would have produced during the age of the earth a fluence of reaction productions $\lesssim 1/\mathrm{km}^2$ or $\lesssim 10^8$ for the earth as a whole.[13] This is less than would be produced in one day at the CERN ISR, assuming a U-U luminosity of $10^{28}/\mathrm{cm}^2$ sec.[14]

The lack of astronomical information means that we must depend on theoretical estimates to deduce the consequences of stability of matter with supernormal baryon density. Evidently this would be a potential energy source, since it could swallow up nucleons and disgorge energy,[2] but equally evident is the possibility that the "swallowing" process would be hard to control.[6] There are many questions which have yet to receive careful attention. For example, if collision products were moving rapidly in the laboratory, they might break up in secondary collisions.[15] This could mean that production by colliding beams would be more effective than that by higher energy beams on fixed targets.

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