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IS IT SAFE TO DISTURB THE VACUUM?*

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Ultra-relativistic U^{238} - U^{238} collisions, which are now being envisioned for the next generation of heavy ion accelerators, do not occur in large quantities anywhere in the universe at present. Nor have they ever occurred abundantly in the past. When U^{238} nuclei were first synthesized the universe had grown already far too cold. This raises the question whether such a novel type of experiment could trigger a catastrophic phase transition of the vacuum to a lower energy state, a possibility naturally occurring in many spontaneously broken quantum field theories.

Theoretical calculations of the collisionally induced nucleation rate of critical bubbles precipitating such phase transitions are not yet available, and nothing is known about the parameters describing the barrier separating our vacuum from a possibly lower energy state.

Fortunately, available cosmic ray evidence suggests that sporadic individual U^{238} - U^{238} collisions have indeed occurred at ultra-relativistic energies inside our past light cone, which would imply that the proposed experiments do not tread potentially dangerous new ground. Direct confirmation of the predicted small abundance of U^{238} and other actinides in cosmic rays at energies in the interesting range 10^{13} - 10^{15} eV, corresponding to 40 GeV/n - 4 TeV/n, is not feasible at present. Nevertheless, even indirect detection of at least some ultra-heavy nuclei in the actinide group ($Z > 88$) in this energy range would more affirmatively answer the question: "Do we dare disturb the vacuum?"

1. INTRODUCTION

It is possible that the vacuum state we happen to live in is not the absolute lowest one. In many spontaneously broken field theories a local minimum of the effective potential can be nearly stable for a range of parameter values. The Universe, starting at a high temperature, might have supercooled in such a local minimum. If such a metastable minimum is separated by a high enough barrier from the absolute minimum, the tunneling rate from the 'false' to the 'true' vacuum may be slow enough to not have occurred anywhere in our past spacetime-volume. In that case our vacuum state (and civilization as we know it) might suddenly disappear if a critical nucleation event would appear somewhere in the Universe, since this would give rise to a bubble of real vacuum, expanding

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in the false vacuum at close to the speed of light under enormous energy release[1,2].

The persistence of our present vacuum for some 10^{10} years implies that a spontaneous transition via tunneling is unlikely to occur in the immediate future. However, we should ask whether a new generation of particle accelerators might possibly trigger such an unfortunate event. It turns out that on purely theoretical grounds no answer can be given. First of all, we do not know whether there exists a lower vacuum state, and if so, we have no idea about the likely magnitude of the relevant parameters such as barrier height and difference in free energy density between the two vacuum states[3]. Secondly, nobody has come up with a completely general and reliable calculation of the collisionally induced nucleation rate for vacuum phase transitions in spontaneously broken quantum field theories, although some progress has been made[2].

It is this doubly uncertain theoretical situation which has led us to look for an observational answer[4]. Although we cannot assess the risk of new experiments from first principles, we can try to check whether the next generation of accelerators will be able to perform really novel types of experiments. If they lead to collisions more energetic than ever happened before on earth, this does not need to disturb us. But if new experiments can induce collisions of a type which have never before occurred in the observable part of our universe, we might start to worry!

The philosophy described above does not formally provide a watertight guarantee. Even though a certain experiment has been done before, it is always possible that a very small non-zero transition probability exists which might lead to a phase transition only after many collisions have taken place. But this should not bother us too much. After all, if a lower vacuum state exists, we run a continuous risk of being hit by a spontaneous phase transition even if we do not do any experiments at all! Therefore our main concern should be simply to check whether our newest proposals have already been carried out by nature in similar circumstances.

This last proviso is important. According to the hot big bang model, arbitrarily energetic reactions have already occurred very early in the history of the universe, since the temperature continues to rise when going back in time. However, we do not know which vacuum state the universe was in at such early times, and we also do not know how finite temperature corrections modify collisionally induced nucleation rates at such high temperatures. Therefore, we should limit ourselves to a comparative study of laboratory experiments and cosmic events after the universe had reached an age of, say, one second when the temperature had dropped to low-energy values (< 1 MeV).

If indeed it turns out to be possible to induce vacuum decay by, *e.g.*, heavy ion collisions, the experiment to end all experiments will not come as an unpleasant surprise for anyone. Its devastating effects will simply reach us at the speed of light, and we will never know it even happened. From this point of view we can make the following interesting methodological observation. The conservative idea that we inhabit the absolute lowest vacuum state, and that therefore nothing *can* go wrong with our vacuum is, technically speaking, not falsifiable; as long as there is anybody left to check this statement it has not (yet) been falsified!

In the next two sections we will discuss cosmic counterparts of terrestrial collisions between single particles (e.g. p, $\bar{p}$, e^-, e^+, ν, etc.) and between heavy ions, respectively.

2. COLLISIONS BETWEEN INDIVIDUAL HADRONS AND/OR LEPTONS

In analogy with more familiar phase transitions, e.g. the boiling of a superheated fluid, a vacuum phase transition is triggered by the formation of a critical bubble of real vacuum ("steam") inside the false vacuum ("superheated fluid")[1]. Smaller bubbles will shrink and disappear because their gain in volume energy is less than their cost of surface energy. Larger bubbles will expand, but are less likely to form.

Even without any detailed knowledge of the nucleation rate of critical bubbles precipitating a phase transition in spontaneously broken quantum field theories, it is still possible to make some simple thermodynamic observations. If the free energy barrier separating metastable (false) vacuum and stable (real) vacuum is much lower than the difference in free energy between the two vacuum states, the critical bubble size will be rather small, typically of order of the natural length scale of the theory (e.g. 10^{15} GeV for Grand Unified Theories, or 10^{-15} fm). In this case a phase transition can be triggered by a single very close and therefore very energetic collision between point-like particles such as leptons or individual quarks in, e.g., pp-collisons. Reaction rates for this type of phase transition will be discussed below. The alternative possibility of large critical bubbles, where heavy ion collisions might be more effective, will be treated in the next section.

2.1 The most energetic collisions on earth

Collisions in elementary particle accelerators are not the most energetic ones occurring on earth. Sporadic collisions between cosmic rays and nucleons in the upper atmosphere exceed present day laboratory energies by more than an order of magnitude. Cosmic ray primary energies up to 10^{20} eV have been observed, with an incident flux of 10^{-1} km^{-2} yr^{-1}. [cf. 5,6]. A collision of such a primary with a single nucleon (a proton from a hydrogen atom) has a center of mass (c.o.m.) energy of 400 TeV. A heavier nucleus in the atmosphere will be hit at a slightly larger c.o.m. energy, up to 7×10^3 TeV.

These energies are probably not far from the highest ever reached in collisions on earth. Although an extrapolation of the observed spectrum of very high energy cosmic ray primaries would predict the (very rare) occurrence of even much more energetic events, this spectrum is expected to drop much more steeply instead, above the observed 10^{20} eV, because of interactions with the 3K background photons (c.o.m. energies > 0.1 GeV, high enough for photopion interactions)[7,8].

It is not yet clear whether the majority of the primaries of giant air showers are single protons or heavier ions, possibly even iron nuclei[5,9]. In the latter case the highest energy per nucleon is only 2×10^{18} eV, or 10 - 100 TeV/n in the c.o.m. frame of atmospheric collisions. Even 10 TeV exceeds the highest energies attainable with present-day accelerators, but not by a large margin. Therefore, if (in the next century) new types of accelerators would reach energies around, say, hundreds of TeV, these could trigger reactions mo energetic than ever before occurred on Earth.

2.2 The most energetic collisions in the universe

Despite the rareness of the particles inducing the largest air showers, collisions between *two* such particles, yielding c.o.m. energies above 10^8 TeV may have occurred somewhere in the Universe. We can estimate the collision rate as follows Their flux is[5,6]

$$\Phi(E > 10^8\ \mathrm{TeV}) = 4 \begin{bmatrix} +2 \\ -1.4 \end{bmatrix} 10^{-16}\,\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

corresponding to a density

$$n(E > 10^8\ \mathrm{TeV}) = 4\pi c^{-1}\ \Phi(E > 10^8\ \mathrm{TeV}) = 1.7 \begin{bmatrix} +0.8 \\ -0.6 \end{bmatrix} 10^{-29}\,\mathrm{cm}^{-3}\ .$$

For an order of magnitude estimate we can take all particles to have the same energy $E = 10^8$ TeV, with density $n = 10^{-29}\ \mathrm{cm}^{-3}$.

It is not clear what the value is for the effective cross section for collisionally induced vacuum phase transitions. However, we can give two limiting extreme estimates. In the present section we consider phase transitions wher the free energy barrier between false and real vacuum is much lower than the difference in free energy between the two vacuum states. Here the size of a critical bubble is expected to be small, and head-on collisions which provide the maximum amount of energy density must be the most effective. Of course, the uncertainty principle limits the maximum energy density available, and al collisions with impact parameters smaller than the de Broglie wavelength will b nearly as effective as exact central collisions. Therefore, a natural guess for the effective cross section is $\sigma \simeq \frac{1}{E^2}$. This expression might turn out be much too conservative, and the real cross section could well be significan ly larger. Therefore, in the next section we will simply take the geometric cross section for heavy ion collisions, for the other extreme case of a very high energy barrier and large critical bubbles.

The above cross section gives $\sigma \approx 10^{-48}$ cm^2. This leads to a collision rate per particle of $n\sigma c = 3.10^{-67} s^{-1}$. The total collision rate per space-time volume is then

$$n^2\sigma c = 3 \times 10^{-96}\ s^{-1} cm^{-3}\ .$$

Our past light cone has a space-time volume of order

$$V \approx c^3\ T^4 \approx 3 \times 10^{101}\ s\ cm^3\ ,$$

where $T \approx 10^{10} y$ is the Hubble time. Therefore, the expected number of collisions between ultra-energetic cosmic ray primaries with a c.o.m. energy $E > 10^8$ TeV inside our casually connected past is

$$n^2\sigma c^4 T^4 \approx 10^5\ ,$$

a remarkably modest number, compared to the previous astronomical figures!

The number derived above only counts collisions between particles of comparable energy; an extra contribution arises from collisions between, say a 10^6 TeV and a 10^{10} TeV particle with the same c.o.m. energy. However, for a power law spectrum of cosmic ray energies this adds only a logarithmic factor (raising the total number of collisions by at most an order of magnitude), and taking into account the 3K attenuation mentioned above suggest that this factor is even smaller.

For higher energies, $E > 10^8$ TeV, probably not even one collision has taken place in the history of the observable Universe. Even an optimistic extrapolation of the ultra high energy cosmic ray flux, neglecting any 3K attenuation, gives [5,6]

$$\Phi(E > E_0) \propto E_0^{-1.5}\ ,$$

leading to an expected number of collisions

$$n^2\sigma c^4 T^4 \approx \left[\frac{E}{10^9 \mathrm{TeV}}\right]^{-5}\ .$$

This derivation has assumed a homogeneous distribution of ultra high energy particles. If these particles are clumped on, say, the scales of galaxy clusters then the effective volume for collisions is smaller than $c^3 T^4$ by a factor of $\sim 10^{-2}$. This could reduce the normalization of the energy scale in the previous formula by a factor 2 or 3. But at the place of production of ultra high energy particles the collision probability will have been higher than measured at the Earth, counteracting the effect of the smaller space time volume available.

3. HEAVY ION COLLISIONS

If the free energy barrier separating metastable (false) vacuum and stable (real) vacuum is much larger than the difference in free energy between the two vacuum states, the critical bubble will be rather large. The bubble wall will contain a relatively large surface energy density, which can only be compensated for if the radius of the bubble is much larger than the thickness of the wall, the ratio of the two being inversely proportional to the drop in free energy between real and false vacuum. This situation is more tractable theoretically, and a number of analytic results have been derived in what has come to be known as the thin-wall approximation[1,2].

Phase transitions of a type for which the thin-wall approximation is valid might be triggered most effectively in a collision where an extended volume of space-time is simultaneously energized with respect to the surrounding cold vacuum. Here heavy ion collisions will be more dangerous than collisions between single paticles, and we have to modify the previous discussion, taking into account the lower abundances but larger critical bubble nucleation cross sections of heavy nuclei in cosmic rays.

3.1 Light nuclei ($Z < 20$)

For a given type of nucleus, or group of nuclei, we can parametrize the relative abundance in cosmic rays by f, the fraction (in number) of cosmic ray primaries which are of this type. The abundances are known to depend on energy, but the observed f-values for light nuclei at different energies differ by much less than an order of magnitude [9,10,11]. The largest energy range for which direct measurements are available has recently been extended to 200 TeV, for the case of Helium nuclei, and no change in f has been detected in this range [12]. As we will see below, significant variations do occur for heavier nuclei.

In calculating the number density of heavy ion collisions in the universe, we have to make an estimate of the cross section for inducing vacuum phase transitions. For the present discussion the best estimate is an effective cross section of order of the cross section for the formation of a quark-gluon plasma, which for high enough energies is expected to be a significant fraction of the geometric cross section of the nuclei. Therefore we can parametrize the cross section as $\sigma = gZ^{2/3}$ mb, with $g \approx 1 - 10$.

The integral flux of cosmic ray primaries can be approximated surprisingly well by a simple power law:

$$\Phi(E) \approx 10^{-5} \left[\frac{E}{1\ \mathrm{TeV}}\right]^{-1.7} \quad \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

which is valid over ten decades in energy, from 10 GeV to 10^8 TeV, to within an order of magnitude [9]. The main deviation sets in only above 10^4 TeV, where the spectrum steepens somewhat, resulting in an increasing overestimate when using the above expression, up a factor of about six around 10^8 TeV. The corresponding number density of a group of nuclei with abundance f and energy higher than E is

$$n(E) = 4\pi c^{-1}\Phi(E) \approx 10^{-14.4} f \left[\frac{E}{1\ \mathrm{TeV}}\right]^{-1.7} \mathrm{cm}^{-3} \quad .$$

The average rate and density of collisions in our part of the galaxy between two nuclei of the type under consideration and of comparable energy, is then

$$n^2 \sigma c = 10^{-45.3}\, f^2 g Z^{2/3} \left[\frac{E}{1\ \mathrm{TeV}}\right]^{-3.4} \mathrm{s}^{-1}\ \mathrm{cm}^{-3} \ .$$

At TeV energies and higher, the density of cosmic radiation is expected to be more or less homogeneous through the galaxy, except of course close to the sources of acceleration. We do not know anything about the flux in intergalactic space, except at the highest energies for which observations are available, since there the gyration radii of protons and light nuclei around galactic magnetic field lines exceed the dimensions of our galaxy. These particles can not be confined in our galaxy, and in fact provide our only sample of extragalactic matter.

To arrive at the total number of collisions at intermediate energies, we should therefore multiply the above expression by that part of the space-time volume of our past light cone in which conditions have been similar to that in our galaxy. For this factor we can simply take the fraction of the universe presently occupied by galaxies, since we are only interested in order of magnitude extimates. This fraction is not accurately known, but a conservative under-estimate leads to an effective space-time volume $10^{-7.5} V \approx 10^{94}$ s cm^3. The number of collisions which have taken place in this volume has been of order

$$N \approx 10^{49}\, f^2 g\, Z^{2/3} \left[\frac{E}{1\ \mathrm{TeV}}\right]^{-3/4}$$

Thus we can conclude that the number of collisions which already have taken place in the universe is extremely large, for all conceivable accelerator energies.

3.2 Heavy nuclei ($20 < Z < 30$)

The same analysis applies to heavier nuclei, and laboratory energies will not be able to probe really novel reactions in the foreseeable future, *unless* the abundance factor f in the last equation is rediculously small (f would have to drop by some twenty orders of magnitude with respect to lower energies). In fact, the relative abundance of heavier nuclei seems to be rising for higher energies, although it might drop again above 10^4 TeV [cf. 11].

The relative abundances in cosmic rays show systematic differences with respect to abundances in the solar system, of up to three orders of magnitude. These deviations are caused by differences in (i) chemical composition at the sources; (ii) efficiency of acceleration; (iii) rate of spallation in collisions with interstellar gas and dust; (iv) rate of escape from our galaxy. The last two effects seem to be the most important, and are relatively well understood[10].

Direct detection of iron nuclei ($Z = 26$) show a significant rise in relative abundance in the range 0.1 - 10 TeV [cf. 11], an extrapolation of which would suggest that Fe should become the dominant component of cosmic radiation around 1000 TeV. Unfortunately, direct detection by *e.g.* exposure of detectors at high altitude balloons, becomes very difficult at these energies because of the low flux, in total about $10^{-1}\ m^{-2}\ day^{-1}$ for all types of cosmic ray events above 1000 TeV. Therefore, the composition of cosmic rays at higher energies has been studied only indirectly, from estimates obtained by observing air showers initiated by energetic primaries in the upper atmosphere.

Several observational quantities can be used to infer the nature of the primary in an air shower, such as the lateral structure of high energy muons, variations in the total number of muons with air shower size, the depth of shower maxima and the arrival time distribution of hadrons near air shower cores [9,11]. Such indirect determinations do indeed suggest that the Fe content in cosmic rays continues to rise above 10 TeV, although recently a detection has been reported suggesting a leveling off around 100 TeV [13]. At much higher energies the composition is still subject to considerable debate. It has been argued that above 3×10^4 TeV cosmic ray primaries are again predominantly protons[14], although others arrive at a heavy nuclei fraction of 30-40% of all primaries from measurements at 2×10^5 TeV[15].

We conclude that a significant abundance of iron nuclei is present in cosmic rays at least up to 5×10^3 TeV, or 100 TeV/n. This implies that a very large number of Fe-Fe collisions have taken place at these energies in our past light cone, and therefore heavy ion collisions with iron nuclei can be safely carried out in the laboratory up to at least 100 TeV/n.

3.3 Very heavy nuclei ($Z > 30$)

The abundance of nuclei with $Z > 30$, "ultra heavy nuclei" in cosmic ray terminology, is much smaller than that of the iron group, by several orders of magnitude. This corresponds with solar system abundances of the chemical elements, and shows that at least at low energies ($\lesssim 1$ GeV/n) cosmic ray primaries have been accelerated roughly in proportion to their natural abundance, without strong preference for higher or lower Z.

Let us concentrate on the abundance f_U of uranium, the heaviest nucleus accelerated to relativistic energies in the laboratory, which thus forms the potentially most dangerous type of heavy ion collision with respect to vacuum decay. At low energies an extrapolation from iron, using solar system abundances, predicts an abundance $f_U \approx 10^{-7} f_{Fe} \approx 10^{-10}$. Only recently has it become possible to measure such low abundances, using balloon experiments and observations from skylab.

The latest results, obtained by the HEAO-3 and Ariel VI satellites launched in 1979, indicate a somewhat higher uranium abundance than solar, but by less than an order of magnitude [cf. 11]. To indicate the observational problems it suffices to mention that the total numbers of primaries detected in the actinide group ($89 \leq Z \leq 103$) by the two satellites mentioned above are one and three, respectively! The main elements in the actinide group with a life time long enough to survive the interstellar travel are thorium, uranium, plutonium and curium.

It seems reasonable to expect the uranium abundance to stay constant with respect to iron, at least up to energies of 3×10^3 TeV, or 10 TeV/n, where the observations indicate iron to still have a nearly unchanged abundance with respect to energy ranges where direct measurements are possible. All the data at lower energy and smaller Z suggest a normal abundance of uranium at the cosmic ray sources, and a more or less Z - independent acceleration mechanism. The two most important differences with respect to iron are then a smaller probability of escape out of the galaxy, and a larger spallation probability. The latter effect probably dominates, changing the mean free path from 2.5 g cm^{-2} for Fe to 1 g cm^{-2} for uranium (mainly from the difference in geometric cross sections). The two effects, acting in opposite ways, are expected to lead to a correction of less than an order of magnitude.

The number of heavy ion collisions in our past light cone, derived in Sect. 3.1, can be rewritten as

$$N \approx 10^{48} f^2 g Z^{-2.7} \left[\frac{E}{1\ \mathrm{TeV/n}}\right]^{-3.4} .$$

This implies a total number of uranium-uranium collisions at center of mass energies E per nucleon of about

$$N_{U-U} \simeq 10^{43} f_U^2 g_U \left[\frac{E}{1\ \mathrm{TeV/n}}\right]^{-3.4} \approx 10^{23} g_U \left[\frac{E}{1\ \mathrm{TeV/n}}\right]^{-3.4} .$$

This result suggest that ultra-relativistic U^{238} - U^{238} collisions can be safely carried out in the laboratory up to 10 TeV/n, where this formula is expected to still be reliable. If indeed the relative abundance of actinides remains roughly constant at higher energies, as would be suggested in analogy to the abundance of iron as derived by some groups [15], than the above expression would lead to a safe upper limit of 10^6 TeV/n!

Comforting as these conclusions may be, it is important to realize that they are based on indirect extrapolations from low-energy direct measurements. A more direct confirmation would therefore be very welcome. To affirm the safety of ultra-relativistic heavy ion experiments involving U^{238} - U^{238} collisions up to, say, a few TeV/n, we need to know the abundance of uranium (or the general group of actinide nuclei) in cosmic rays in the energy range 10 - 1000 TeV.

A direct measurement in this region will be rather difficult, since the expected flux of uranium nuclei drops from 10^{-17} cm^{-2} s^{-1} sr^{-1} around 10 TeV to 10^{-20} cm^{-2} s^{-1} sr^{-1} around 1000 TeV; of order of one event or less per km^2 per year! Detection of at least some actinides in or above this energy range would of course be very valuable, even if such a detection would be indirect, e.g. from the analysis of the characteristics of air showers. In the absence of such information, any improved abundance at lower energies would already be very helpful, since that would enable us to make more reliable extrapolations.

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