Disaster caused by Heavy Ion Collisions at RHIC?
Another kind of a “Cup of Theory”

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Contents

Abstract

For some years some crackpots have claimed that there might be risks in doing experiments at particle accelerators every time when a higher range of energy becomes accessible than before. Especially the construction of the RHIC in Brookhaven again triggered such ideas. In order to answer such questions at BNL they ruled different catastrophe scenarios. Since despite the social importance of such debates the verification that these disaster scenarios cannot happen at present accelerators requires some interesting physics at the frontier of our nowadays knowledge in this “cup of theory” we try to give an overview over the possible scenarios and the arguments that these are ruled out by conservative estimates.

1 Introduction

In the March issue of Scientific American Mahusree Mukerjee published an article entitled “A Little Big Bang”. There he described the physics behind the Relativistic Heavy Ion Collider at the Brookhaven National Laboratory.

Then in a letter to the editors Walter L. Wagner proposes the idea that there might be produced a miniature black hole by high energy proton antiproton collisions. Then he argues that this mini black hole might absorb mass before it decays and could destroy our planet.[1]

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[1] He claims that the black hole would wander downwards to the centre of the earth and finally “eating up” the whole planet within minutes ;-)).

To this letter Frank Wilczek (Institute for Advanced Study in Princeton) replied with some statements about such scenarios. There he explains that scientists have to take such ideas seriously to be sure that there really cannot happen any catastrophe. He argues that in the case of RHIC there is no danger because in cosmic rays there appear events like that in RHIC with even much higher energies. So if there could happen some catastrophe due to heavy ion collisions this would have happened already in nature. The second argument was that we still have some insight in the physics of such heavy ion collisions so that we can trust our so far gained theoretical understanding to exclude any disaster scenario.

The idea with the mini black hole can be excluded by estimates about the expected energy density and volumes produced at RHIC. It turns out that there is by far not enough gravitational interaction due to this energy densities to produce a black hole.

Then he tells the readers that there is another expectation which is more probable to happen. There could be formed so called strangelets, i.e., little pieces of cold quark matter with a finite fraction of strange quarks. This new form of matter might incorporate and transform the ordinary matter in its surrounding. On the other hand, if the strangelets exist at all, then they are not dangerous because they are expected to be extremely small so that there also is no danger. The discovery of such new bound states would be an extraordinary scientific breakthrough.

In the following we summarise the physics of some catastrophe scenarios and how they can be ruled out by conservative estimates based on known physics.

2 History of the debate

- **The initial article** Article by M. Mukerjee about RHIC entitled ”A little Big-Bang”. Article published in Scientific American (March 1999).
- **The first fear** Between March and July 1999: many reactions on the topic “Are scientific going to far in creating a Big-Bang?”
- **The letter by Wagner** First reaction with scientific argumentation by Walter Wagner in a letter published in the July issue of Scientific American. Walter Wagner is a physicist who changed to botanic. He argues that although his calculation shows that this event is very improbable to happen, nobody can be sure who that RHIC will not produce a mini black-hole (called Gobelins by Hawking). Because this event takes place at high density, this gobelin could absorb one of the surrounding nuclei and thus becoming stable. The following steps of the scenario are obviously catastrophic!
- **Wilczek’s answer** In the same issue of Scientific American, Frank Wilczek answered to W. Wagner’ letter. He recalled first the calculations done by Fermi et al in Los Alamos to rule out a possible ignition of the atmosphere in a nuclear explosion. Then he explained why the black–hole scenario is rejected because of order of magnitudes, putting also forward the argument of very high energy collisions in space. However, he mentioned at the end of his letter the speculative possibility of strangelet creation and expansion as very improbable but not completely impossible.
- **The medial explosion** While the relative prudence of Wagner’s letter and Wilczek’s answer, many newspapers magnify the discussion to a public affair, maybe because of the lowering of sales during summer, maybe because of a millennium fever. In some articles

they create a mini panic (instead of a mini black hole). For example, the Times in July (see Appendix A), ABC news, (WEB newspaper) in Septembers etc.

- **Responses** Against this panic, can the official explanations like the July 9th statement by the BNL director in response to the Sunday Times article or the September 17 one against the ABC–News attack effect anything? Surely not. Maybe the reassuring scientific articles like in Scientific American (July 99), New scientist (August 99), La Recherche (March 00), Science& Vie Junior (March 00) etc. can better but is it sufficient ?

Note that this affair has been judged at February 25th 2000 in a Californian court [4]. We unfortunately don't know the result. The judgement was intended by Wagner which has already tried the same way to stop Bevalac (Berkeley) in the 80's and a previous accelerator of the BNL. Other people have already tried this for CERN, Fermilab, etc. but never with the same medial impact. Is it a millennium fear? Note that since the beginning of the year we don't hear too much about that.

Two questions:

- How to evaluate and manage scientific risks?
- How to convince people that those risks are managed?

3 Physics behind the debate

In this section we discuss the physics used to rule out three possible disaster scenarios. We refer to the official paper by the official BNL commission [5].

3.1 Formation of Mini Black Holes

The production of mini black holes can be excluded by a simple estimate using the well known Scharzschild metric of general relativity. In local spherical coordinates the proper time element outside the spherically symmetric distributions of matter with total mass M reads

$$c^2 d\tau^2 = c^2 \mathrm{d}t^2 \left(1 - \frac{2GM}{rc^2}\right) - \frac{\mathrm{d}r^2}{1 - \frac{2GM}{rc^2}} - r^2 d^2\Omega, \tag{1}$$

where c is the speed of light and G Newton's constant.

If R is the radius of the matter distribution then the body is described as a black hole if it lies completely inside the horizon which happens if the parameter

$$k_{\mathrm{cl}} = \frac{2GM}{Rc^2} \tag{2}$$

becomes > 1. In Newtonian theory of gravitation it has the meaning that for $k_{\mathrm{cl}} = 1$ the escape velocity becomes the speed of light.

A very conservative estimate for an upper bound for k_{cl} is obtained by the assumption that all the initial collision energy becomes concentrated in a region given by the Lorentz–contracted nuclei. Taking the largest possible mass and the smallest possible distance scale and in addition ignoring the electric charge and the momentum of the constituents one ends up with $k_{\mathrm{cl}} = 10^{-22}$ (as input the authors used $M = 10^4 \mathrm{GeV}/c^2$ and $R = 0.01\mathrm{fm}$.

An estimate of quantum gravitational effects yields an even lower value of $k_{\mathrm{qu}} \approx 10^{-34}$. So all these estimates lead to the conclusion that at now available energies and for the foreseeable future there is no possibility to form mini black holes.

3.2 Strangelets and Strange Matter

Definitions:

- Quark gluon plasma: Deconfined quarks and gluons describable as a hot nearly ideal gas. It is the explained main goal of RHIC's scientific program to find a clear significance for this state of matter and to investigate quantitatively its properties (especially the deconfinement and chiral phase transition(s)).
- Strange Matter: Deconfined quark matter at high chemical potential and low temperatures in equilibrium with weak interactions.

Due to the fermionic nature of the quarks at high chemical potentials (i.e. high particle densities and pressure) the u– and d–quarks are forced to occupy high energy states such that they might be converted into s–quarks made possible by the weak scattering processes (e.g. $u + d \rightarrow s + u$) or semi–leptonic decay (like $u \rightarrow s + e + \bar{\nu}_e$). Thus for high densities in chemical equilibrium with respect to weak interactions there is a finite density of strange quarks present in that new kind of matter and this gave it the name "*strange matter*".

In nature this may occur in the core of a neutron star. Now if our ideas about the mechanism of strange matter formation is true this core has lower free energy than the overlaying ordinary matter which thus is absorbed by the strange matter core during the equilibration which will be stopped if the pressure becomes less than a certain value when ordinary matter is the state of lower free energy. Detailed studies lead to the conclusion that the burning of ordinary matter to strange matter in a neutron star, if it really takes place at all, will not lead to an explosion because the difference of the free energy between the two phases is expected to be small compared to the gravitational binding energy of the neutron star.

Another scenario is suggested by E. Witten in 1984. It might be possible that small bound strange matter objects have lower mass than normal nuclei even at zero external pressure. He shows that this is not ruled out by the fact that nuclear matter is stable.

A small strange matter bound state, a so called "strangelet", could have less energy than a usual nucleus with the same number of quarks. The reason why the nucleus is not converted to a strangelet is, that this requires many weak interactions which take place simultaneously in order to create all the strange quarks necessary to build the strangelet at the same time. A few number of elementary weak processes inside the nucleus are creating a hyper nucleus containing only a few s quarks. Those states are known to be less stable than the ordinary nucleus.

At this time there is no empirical evidence for the existence of strange matter objects in the universe. Such strange matter stars should be found smaller compared to ordinary neutron stars because their binding is caused by strong interactions and not by gravity. It should rotate faster than a neutron star and be observable as a sub–millisecond pulsar.

From the theoretical point of view strange matter can be described (at least qualitatively) by ordinary quark models containing confinement and perturbative QCD properties. Nevertheless the question if strange matter is bound at zero external pressure or not cannot be answered and more detailed studies are needed to draw quantitative theoretical predictions.

The following aspects of strange matter dynamics are claimed to be "robust":

- The Binding Systematics of strange matter

  The overall energy scale at place is the confinement scale in QCD, i.e., in effective models the bag constant. Calculations of gluon exchange corrections show that these lead to a destabilisation of strange matter. To obtain strange matter lower values of the bag constant than the traditionally favoured are necessary. Thus the stability of strange matter at zero chemical potential seems to be very "unlikely".

- Charge and flavour composition

  Ignoring interactions because of the higher s–quark mass (compared to the mass of the u and d quarks) they are suppressed leading to a positive charge of strange matter. Now the gluon exchange tends to be weaken with growing quark masses and thus the repulsion between pairs of type ss, sd, and su is smaller than between the u and d quarks. So the population of s quarks in strange matter is higher than predicted from a ideal Fermi–gas prediction. If in model calculations the gluon interaction–strength exceeds a certain value the stable state of strange matter becomes electrically negative but also unbinds it and very small bag constants are needed to compensate the repulsion by the gluon exchanges. Thus the authors come to the conclusion that negatively charged strange matter is extremely unlikely.

- Finite size effects

  In ordinary nuclear matter fission occurs because of the mismatch between the tendency of the exclusion principle to prefer equal numbers of protons and neutrons and the preference of zero electrical charge from electrostatics. In strange matter this mismatch is not given because an equal number of u, d, and s quarks is nearly electrically neutral.

  On the other hand finite size effects are important. Iron is the most stable nucleus and lighter nuclei are less stable because of the surface energy of the degenerate fermion system. As model calculations suggest also strange matter seems to have a significant surface energy which tends to destabilise small strange matter objects.

  Also shell effects seem not to stabile small strangelets enough. The most bound system should be $uuddss$ and this is evidently not much lighter than the deuteron made of 6 non–strange quarks.

  For larger strange matter nuclei there are only crude studies with filling up a bag and indicate the possible existence of metastable states. But all of these are not stable enough to be really of danger at a heavy ion collider.

- Heavy ion collision characteristics

  Up to now the search for strange matter in heavy ion collisions was not successful. Due to the above given summary of strange matter physics this cannot be expected because strangelets consist of cold bound objects while the heavy ion collision characteristically leads to a hot fire ball and not to cold bound states.

3.3 Vacuum instabilities

Another interesting question is if Uranium–Uranium collisions, which very rarely occur in nature, may lead to another disaster scenario. It could be that the vacuum of the spontaneously broken electro–weak theory we live in is not the stable ground state but only metastable and then such a collision could cause a phase transition to another lower lying energy state.

Many spontaneously broken quantum field theories show local minima of their effective quantum potential which is nearly stable over a certain range of parameter values. It might be that the universe is in a supercooled metastable state and we are not living in "the true vacuum" of the electroweak standard model. The "false vacuum" might be separated by a high and broad enough energy barrier such that the tunnelling rate through this wall is so small that within cosmological time scales this vacuum is nearly stable.

Now an ultrarelativistic U–U collision could form a bubble like region in space time where the real vacuum is reached. This bubble would expand in the false vacuum with a velocity close to the speed of light.

What can be said about this from the theoretical point of view? The first problem is that we do not know if we are living in a "true" or a "false vacuum", i.e., if there exists a state of lower energy. Supposed this is the case we also do not know how big is the difference in free energy between the two vacua and the barrier height etc. It is also a general theoretical problem to calculate nucleation rates for vacuum phase transitions within spontaneously broken QFTs.

Due to this overwhelming theoretical difficulties we look in simple thermodynamical pictures at this problem. If the free energy barrier separating a false vacuum from the true vacuum is much lower than the difference in free energy between these vacua the size of bubbles necessary to enforce the phase transition is rather small because phase transition occurs only if the gain in volume energy is less then the loss of surface energy when a bubble of the true vacuum inside the false vacuum expands. So bigger bubbles are more likely to cause such a phase transition but in turn are more difficult to be formed.

The collisions between particles with the largest energies so far are caused by cosmic rays scattering at nucleons in the upper atmosphere and not in colliders. The highest observed primary energies are of order 10^{20}eV and their flux is $0.1\text{km}^{-2}yr^{-1}$. The cm. energy of such a collision with a nucleon is around 400TeV, with a heavy nucleus up to $7,000$TeV. It is not clear if the primaries of giant air showers are single protons or heavier ions. In the case of iron it corresponds only to 10 to $100A$TeV. So the accelerators in the near future easily exceed this energy density. Rough estimates, extrapolating the known spectrum of high energy particles in cosmic rays, lead to the conclusion that much more heavy ion collisions at cm. energies as high as 10^8TeV (!) already took place in the universe within our past light cone than to be expected for the whole operating time of the RHIC.

The overall conclusion of all this investigations is that it is very likely that mankind survives also the new accelerators already built (like RHIC) or built in the near future (LHC at CERN or perhaps TESLA at DESY)!

A London Times, July 18, 1999

Apocalypse Now

Will the "Big Bang" Machine Destroy the Earth?

Creation of a black hole on Long Island?

A NUCLEAR accelerator designed to replicate the Big Bang is under investigation by international physicists because of fears that it might cause "perturbations of the universe" that could destroy the Earth. One theory even suggests that it could create a black hole.

Brookhaven National Laboratories (BNL), one of the American government's foremost research bodies, has spent eight years building its Relativistic Heavy Ion Collider (RHIC) on Long Island in New York state. A successful test-firing was held on Friday and the first nuclear collisions will take place in the autumn, building up to full power around the time of the millennium.

Last week, however, John Marburger, Brookhaven's director, set up a committee of physicists to investigate whether the project could go disastrously wrong.

It followed warnings by other physicists that there was a tiny but real risk that the machine, the most powerful of its kind in the world, had the power to create "strangelets" - a new type of matter made up of sub-atomic particles called "strange quarks".

The committee is to examine the possibility that, once formed, strangelets might start an uncontrollable chain reaction that could convert anything they touched into more strange matter. The committee will also consider an alternative, although less likely, possibility that the colliding particles could achieve such a high density that they would form a mini black hole. In space, black holes are believed to generate intense gravitational fields that suck in all surrounding matter. The creation of one on Earth could be disastrous.

Professor Bob Jaffe, director of the Centre for Theoretical Physics at the Massachusetts Institute of Technology, who is on the committee, said he believed the risk was tiny but could not be ruled out. "There have been fears that strange matter could alter the structure of anything nearby. The risk is exceedingly small but the probability of something unusual happening is not zero."

Construction of the 350m RHIC machine started eight years ago and is almost complete. On Friday scientists sent the first beam of particles around the machine - but without attempting any collisions.

Inside the collider, atoms of gold will be stripped of their outer electrons and pumped into one of two 2.4-mile circular tubes where powerful magnets will accelerate them to 99.9% of the speed of light.

The ions in the two tubes will travel in opposite directions to increase the power of the collisions. When they smash into each other, at one of several intersections between the tubes, they will generate minuscule fireballs of superdense matter with temperatures of about a trillion degrees - 10,000 times hotter than the sun. Such conditions are thought not to have existed - except possibly in the heart of some dense stars - since the Big Bang that formed the universe between 12 billion and 15 billion years ago.

Under such conditions atomic nuclei "evaporate" into a plasma of even smaller particles called quarks and gluons. Theoretical and experimental evidence predicts that such a plasma would then emit a shower of other, different particles as it cooled down.

Among the particles predicted to appear during this cooling are strange quarks. These have been detected in other accelerators but always attached to other particles. RHIC, the most powerful such machine yet built, has the ability to create solitary strange quarks for the first time since the universe began.

BNL confirmed that there had been discussion over the possibility of ”perturbations in the universe”. Thomas Ludlam, associate project director of RHIC, said that the committee would hold its first meeting shortly.

John Nelson, professor of nuclear physics at Birmingham University who is leading the British scientific team at RHIC, said the chances of an accident were infinitesimally small - but Brookhaven had a duty to assess them. ”The big question is whether the planet will disappear in the twinkling of an eye.

It is astonishingly unlikely that there is any risk - but I could not prove it,” he said.

The London Times, July 18, 1999

References

[1] The original letter of Walter Wagner to Scientific American and the answer of Frank Wilczek. Scient. Am. July 99.

[2] *Taking Serious Risks Seriously*, S.L. Glashow and R. Wilson, Nature 402: 596-597 (1999).

[3] *Review of Speculative ”Disaster Scenarios at RHIC*, Busza, W ; Jaffe, R L ; Sandweiss, J ; Wilczek, F.

[4] *Trou Noir, La menace Fantome*, C. Zeitoun, Science & Vie Junior 126 (2000), 63.

[5] *Review of Speculative “Disaster Scenarios” at RHIC*, W. Busza, R. L. Jaffe, J. Sandweiss, and F. Wilczek, hep-ph/9910333.