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STRANGE QUARK MATTER IN THE UNIVERSUM AND ACCELERATOR NUCLEAR BEAMS

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Странное кварковое вещество во Вселенной в ядерных пучках на ускорителях

Имеются сильные аргументы в пользу того, что странное кварковое вещество (СКВ), состоящее из примерно равного числа *u*-, *d*- и *s*-кварков, является основной и абсолютно стабильной формой материи. Астрофизические объекты, которые согласно имеющимся предположениям состоят из СКВ, могут возникнуть в результате Большого взрыва на ранней стадии развития Вселенной или в результате превращения нейтральных звезд в странные. Такие объекты считаются хорошими кандидатами в «чёрные дыры». Уникальную возможность получить СКВ в земных лабораторных условиях (на ускорителях) дают очень жесткие соударения ядер — так называемый «малый большой взрыв». В работе дается обзор ожидаемых сигналов, которые могут быть выявлены при астрофизических наблюдениях особенностей больших СКВ-объектов, а также при поиске легких СКВ-состояний, включая простейшие из них — метастабильный шестикварковый *H*-дигиперон.

Представлены первые результаты дубненского поискового эксперимента в пучках ядер, в котором при центральных ядерных столкновениях был обнаружен значительный разогрев вещества с образованием обогащенного странностью файербола (смешанной фазы?) с большой плотностью. В этих благоприятных условиях был найден один кандидат в *H*-дигипероны и была сделана оценка верхнего предела сечения образования этого СКВ-состояния. В заключение кратко изложены перспективы и преимущества дальнейших поисков легких СКВ-состояний, с использованием нуклотрона — нового дубненского сверхпроводящего ускорителя ядер до энергий 5—6 ГэВ на нуклон.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 1995

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Strange Quark Matter in the Universum and Accelerator Nuclear Beams

An almost symmetric mixture of *u*, *d* and *s*-quarks — Strange Quark Matter (SQM) is strongly argued to be the ground and absolutely stable state of the matter. Astrophysical objects, supposed to be the SQM states, could be formed as the result of the Big Bang (in the early Universe) and the conversion of neutron stars into strange ones. Such objects are considered to be favorable candidates as black holes. The unique possibility to produce the SQM under terrestrial conditions (at accelerator laboratories) are violant relativistic nucleus-nucleus collisions so called «little big bang». The expected singulares of SQM are reviewed which could be revealed from astrophysical observations of peculiarities of large SQM objects as well as from accelerator experiments with searching smaller SQM states including the simplest one — metastable six-quark *H* dihyperon. The first results of the Dubna search experiments, with considerable heating of the matter and formation a dense strangeness abudant fireball (mixed phase?) in central nuclear collisions, is presented. Under these favorable conditions a candidate for *H* dihyperon is observed and an upper limit of production cross sections of this SQM states is estimated. Some prospects and advantages of further searches for light SQM states, using the JINR new superconducting accelerator — Nuclotron with energy 5—6 GeV per nucleon, are briefly outlined.

The investigation has been performed at the Laboratory of High Energies, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna, 1995

1. Strange Quark Matter in the Universum

1.1. General Remarks

There are weighty theoretical arguments to consider the matter which consists of nearly equal numbers **d**, **u** and **s** quarks, to be the true hadronic ground stable state i.e. $(E/A)_{SQM} < (E/A)_{Fe}$ (see [1] and the referencies therein).

One of the most important reason of the dense SQM stability is the Pauli principle : there are no empty energy states (levels) to receive u or d quark from the weak decay e.g. s $\rightarrow$ u $+ e^- + \bar{\nu}$.

In contrast to usual nuclei in which with increasing the number of protons the Coulomb repulsion overwhelms the strong force binding nucleons together, the SQM with $N_d \simeq N_u \simeq N_s$ is nearly neutral and should be free of the size limitation.

Thus huge SQM chunks, being like giant nuclei, could fill the gap between nuclei and neutron stars ("nuclear desert"), and further the the neutron stars could convert into strange ones forming very likely the black holes (see Figure 1).

The mentioned equality is approximate one. The QCD thermodynamics dictates that, at equilibrium, the three quark flavors in the multiquark bag share the available energy equally. The strange quark is more massive than **u** and **d** ones, so will be slightly fewer strange quarks in a SQM chunk .

To make it completely neutral, some admixture of electrons is necessary.

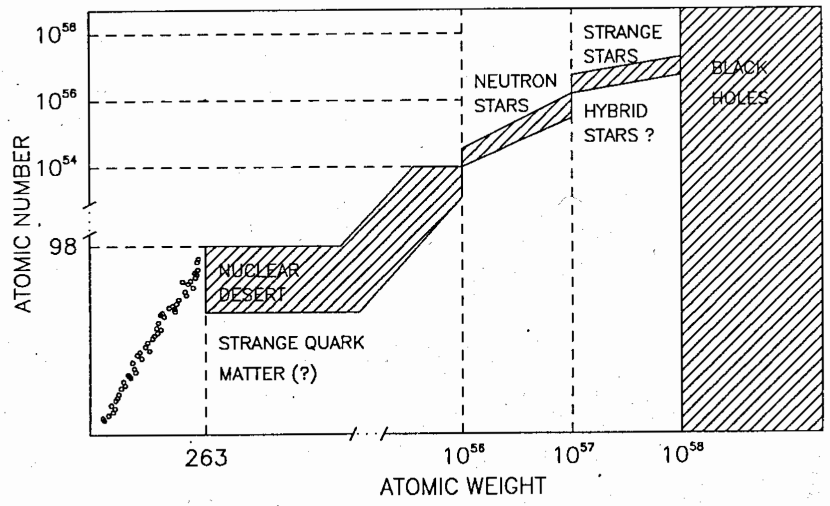

Figure 1. The overall chart of nuclides.

Strictly speaking the stability of SQM itself could be hardly decided regorously by fundamental QCD calculations in the near future, so thus it is now rather experimental question. Nevertheless general fundamental SM and QCD predictions about various astrophysical scenarios, being taken as a working tool, should usefully serve experimentalists to search for possible signatures of SQM.

1.2. Strange Quark Matter as Black Holes

It has been known from detailed astrophysical observations of galaxies that there is far more to the universe than could be seen.

The combined gravitantional fields of all visible stars and luminous galactic dust are not close to being strong enough to produce the motions of the galaxies or individual stars within them. Estimations show that the amount of missing material is enormous: at least 80 percent of all the matter in the universe is apparently cold and dark, undetectable by any radio or optical telescopes.

More than decade ago the fascinating possibility has been raised[2] that the missing mass - that is most of the universe - is largely the strange quark matter hidden in black holes. In the framework of possible scenarios such black holes could be classified in two ranks:

- black holes created directly from the big bang after quark phase formation but before nucleosynthesys;
- black holes of stellar origin when neutron stars or brown dwarfs are converted into strange stars (SQM) with a subsequent cooling.

1.3. Converting Neutron Stars into Strange Stars

Such a conversion phenomenon is predicted to be a quite spectacular event: one strange chunk ("strangelet") can seed a converting process via a neutron absorbtion (consuming) and could liberate more than 10^{52} erg in the binding energy (being more than 10 MeV for SQM).

It has been suggested two main seeding ("triggering") mechanisms:

- due to the seed inside n-star, via the quark-gluon plasma formation
- due to the seed coming from a interstellar medium (relict one from the big bang, from other s-star creations - supernova explosions).

The n-star → s-star conversion is more likely to happen just after a n-star is born then an extra ν-flux (pulse) with a long tail of the ν-emission would be observed on the earth. If an older n-star gets converted, the conversion might be observed by a faster ν-burst accompanied by γ-ray burst. Thus with possibility of ν-detection from supernova we wil be able to confirm or rule out different modes of such a conversion.

1.4. Neutrino Emissivity from Strange Stars

Flavor "chemical" equilibrium is maintained by reactions:

$$s \leftrightarrow u + e + \bar{\nu} \qquad s + u \leftrightarrow d + u \qquad d \leftrightarrow u + e + \bar{\nu}$$

Presense of electrons from these processes garantees charge neutrality but neutrinos are not bound to the quark matter and escape providing very intense fluxes of high energy neutrinos because rather large s-quark mass (m_s)

Such a neutrino emission from s-star has a baryon density threshold at which the s-quark decay starts taking place[3]. This threshold (ρ_t), being depended on the temperature (T), chemical potential (μ_0) and m_s, is estimated to be $\rho_t \simeq 2\rho_0$, where ρ is nuclear density.

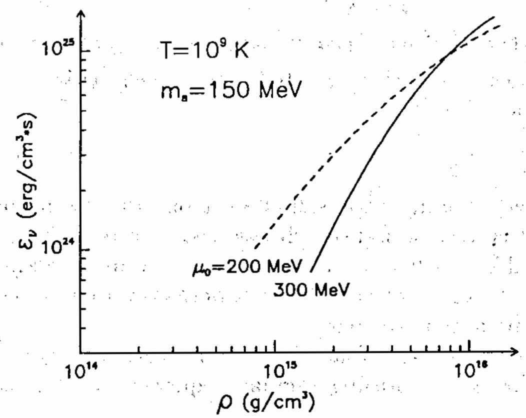

Figure 2. The neutrino emissivity of strange stars versus their density

It is predicted that this neutrino emissivity ϵ increases rapidly with increasing the baryon density ρ (see Figure 2).

1.5. Mergers and Collisions of Strange Stars

Merger of two neutron stars, being members of a close binary, considered to be fairly common events. It is estimated that there might be about 10^5 such events per year within the Hubble distance. Unfortunetly, the efficiency of gamma-ray emission from these colllsions is very low with most neutrino-antineutrino annihilation energy being within background. On the contrary, a merge / collision of two strange stars should produce very powerful, short and hard ($\sim 8MeV$) gamma-ray burst which could be easely detectable out to a distance of 1 Gpc.

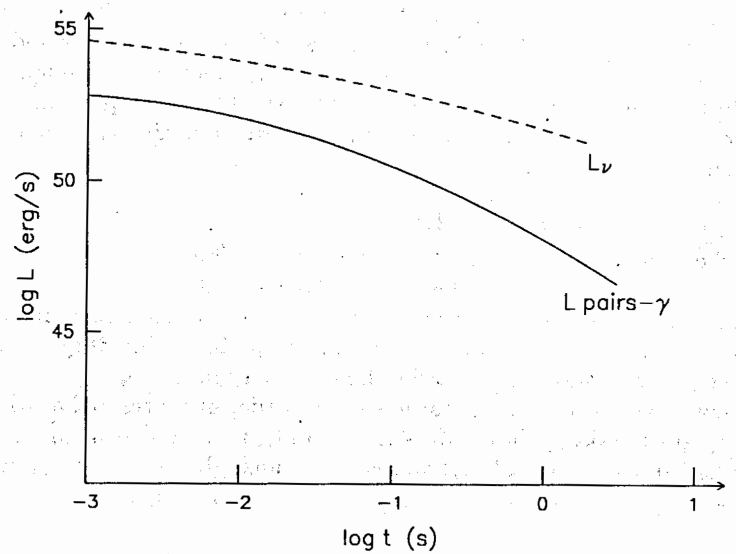

Figure 3. The predicted neutrino and pair plasma (gamma) luminosities versus time.

The Figure 3 demonstrates the expected neutrino and pair (gamma) luminosities on the time scale (from [4]).

1.6. Fast Pulsars as Strange Stars

It has been argued in many papers that neutron stars, being pulsars, could not rotate very vast that is with periods much less than 1 second. Very conservative estimate of the rotational limit on neutron star[5], calculated in the framework rather easy postulates, shows that an observed rotational period below 0.4 ms would signal that this pulsar cannot be a neutron star.

On the contrary strange star pulsars, being much more compact than neutron star ones, should have the higher rotating angular frequencies with periods less than 1 ms.

By this time many submillisecond pulsars have been observed , and their number increases rapidly as the greater sensitivity of radio telescopes is being achieved.

The situation has changed radically with the recent discovery of an anomalously large population of submillisecond pulsars in globular clusters.

Although the recent statements of many astrophysisists that almost all neutron stars (pulsars) are actually the strange ones, should be taken by experimentalists with some care, nevertheless they stimulate searching observations.

The argued predictions are that there is no practically a minimum mass for the strange stars, while the neutron stars have clearly a minimum mass to meet requirements of a dynamical stability (see Figure 4).

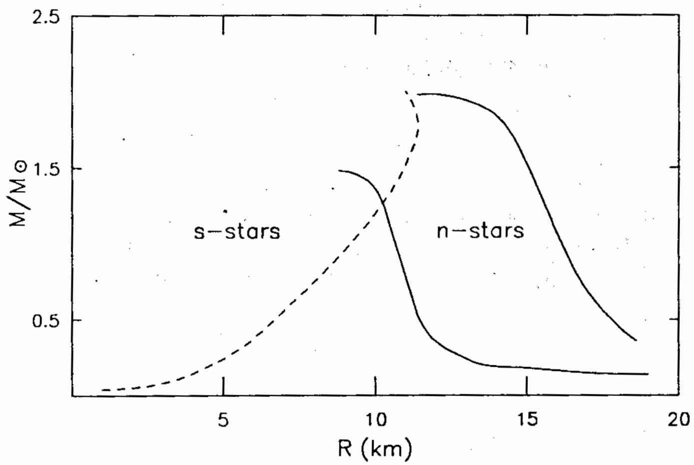

Figure 4. The mass − radius relation for typical neutron stars and strange stars.

However the bulk properties of models of neutron and strange quark stars with masses that are typical for neutron stars ($1.1 \leq M/M_{\odot} \leq 1.8$) are relatively similar, as can be seen from this figure. That is why to distinguish strange star pulsars by their high rotation frequencies is of great importance.

Thus further developments of pulsar detectors with looking (focusing) on globular clusters might discover much more very rapid pulsars and investigate objects which could be treated as strange stars with high confidence.

It should be pointed out that the mentioned separation of stars into two categories seems not to be unambiguous. The borderline family of stars is expected to exsist: these are so called hybrid stars with a strange quark core and a nuclear (neutron) crust (see for instance [6]).

1.7. Strange Quark Matter in Cosmic Rays

If the stable SQM exsists in the universum as a relic from the big bang or as strange stars, then small SQM chunks should be present in cosmic rays. Such SQM lumps could easely be distinguished from ordinary cosmic particles (ordinary nuclei) by an anomalous A/Z ratio or, in more simple approach, by anomalously large Z, which is expected to be much more than 100 when $A >> 5 \cdot 10^3$.

Large-area detectors, space-based and baloon-borne as well as sealevel, underground and mountaintop-based, could set the best limits on SQM of Z > 100 in the cosmic rays. Recently more sophisticated devices have been elaborated and flown to search objects (SQM chunks) with anomalously high A/Z ratio, and few possible candidates of SQM have been found at lower charge.

The Figure 5., compiled in [7], has summarized the available experimental data in comparison with the predicted limits on the flux of SQM chunks (quark "nuggets") from the main possible astrophysical sources.

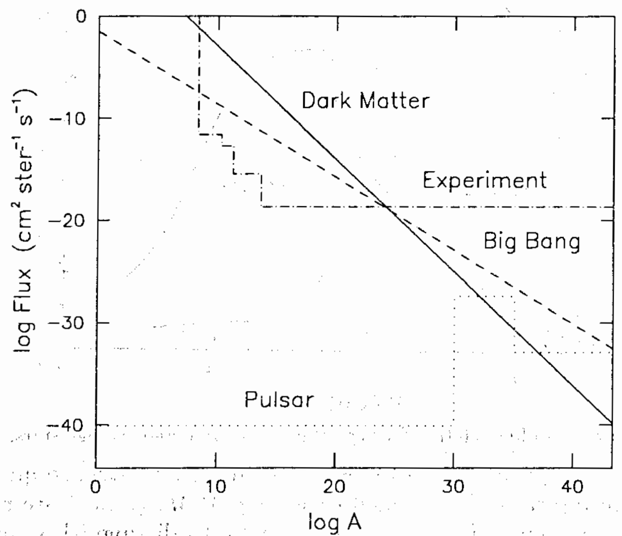

Figure 5. Experimental and predicted astrophysical limits on the flux of quark "nuggets" (SQM chunks) hitting the Earth atmosphere:

* "Experiment" - are experimental upper limits;
* "Dark Matter" - is local flux assuming the galactic galo density to be given solely by quark nuggets;
* "Big Bang" - is the nucleosynthesys with the quark nuggets formation;
* "Pulsar" - is the upper expected limit from the non-capture of nugget in pulsars or their stellar progenitors.

It is well to bear in mind that the above predicted limits are given under rather optimisic assumtions. Anyway an essential increase of detector sensitivities are necessary to get significant results.

There have been also some efforts, using A/Z spectroscopy, to search for SQM chunks (along looking for superheavy nuclei), possibly captured by meteorites, but without positive results so far.

2. Strange Quark Matter in Nuclear Collisions at Accelerators

2.1. Violent Nucleus-Nucleus Collisions - "Little Big Bang"

One of the most important reason to accelerate nuclei is that central collisions of relativistic nuclei could under earthy conditions reproduce (simulate) to a significant extent such astrophysical phenomena as the big bang, neutron star evolution, supernova explosions with a formation of relativly small drops of the strange quark matter (so called "strangelets"). Indeed violent nuclear collisions create a highly excited hadronic fireball with great baryon densities and large s-quark abundance, and thus could provide the basic conditions needed to form composite systems with large amounts of strangeness. On the other hand strangelets are predicted to be the natural result of the evolution of a quark gluon plasma (QGP) formed in nucleus-nucleus collisions, and so strangelets themselves could manifest of a QGP formation[8].

It has been found in early Dubna experiments[9-11] that when going to high degree of nuclear collision centrality at $E_P \sim 4$ A GeV a single dense ($\rho \geq 4\,\rho_o$) and thermalized (at least localy) source is formed with the temperature (extracted from Boltzmann-like Λ and K^o spectra) rising up to $T_B \sim 150$–160 MeV (to inverse slope parameters $T_0 \sim 200$–210 MeV) with a tendency to approach a plateau.

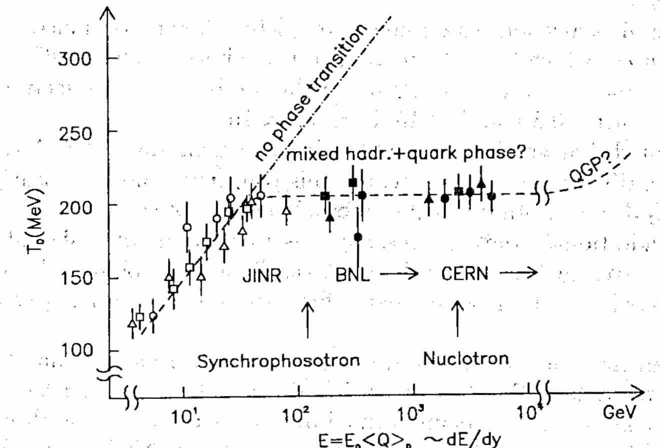

Figure 6. Inverse slope parameter of invariant cross section T_0 versus $E = E_P \cdot Q$, where Q – number of nucleon-participants (degree of centality): open circles, triangles, squares – K^0, Λ, proton data of JINR; black circles, triangles, squares – K, Λ and proton data of BNL[12] and CERN[13].

At the same time an enhancement of the relative Λ yield (N_Λ/N_π) has been observed by a factor of ~10 (at the transverse momentum cut $P_T \geq 1$ GeV/c to eliminate a background from "trivial" N-N collisions).

More recent BNL and CERN data have confirmed the observed strangeness enhancement and not only for the relative yield of Λ hyperons but also for those of $K^{\pm}$ and $\bar{\Lambda}$ particles (at different cuts of $P_T \geq 0.4 - 0.6$ GeV/c).

Furthermore, these experiments have corroborated the evidence of the above mentioned plateau, extending it to much higher energies with the Boltzmann temperatures $T_B \sim$ 150–160 MeV, which correspond to the inverse slope parameters of invariant cross sections $T_0 \sim$ 200–210 MeV. (see Figure 6).

This regularity is a prominent feature of the mixed phase formation in the first order transition. Although more detailed studies and looking for some alternative interpretatons (besides QGP formation) are necessary to make a final conclusion, the obtained results provive a strong experimental evidence that a hot and dense fireball (mixed phase?) is created in central nucleus-nucleus collisions, which is predicted[14] to be a prolific source of multistrange hadronic/quark objects, and this encourages searches for states of the strange quark matter in relativistic nuclear beams at accelerators.

2.2. Experimental Searches for Strange Quark Matter at Accelerators

The simplest approach to search for modestly-sized SQM states with $A \leq 20$ (called "strangelets") is similar to that used in cosmic experiments with looking for much larger SQM states, namely to measure both the electric charge and the mass of particles.

Another approach is to reconstruct the mass of objects by measuring their energy and time-of-flight.

There are several heavy ion experiment, completed, being continued with data taking and proposed, which have the main goal to look for strangelets[15].

At the present time the best upper limits on the production cross section of strangelets with $Z/A \sim 0.1 - 0.3$ and $A \leq 15$, is $\sigma_s/\sigma_{tot} \leq 10^{-5}$.

It should be noted that an observation of objects with an unusual Z/A ratio is not sufficient to identify strange states because this property is not necessary a peculiar feature of SQM but of other possible anomalous form of the matter.

Therefore an additional study of possibly observed candidates should be needed to proove the "strange" nature of detected candidates (probably through an investigation of their interactions with looking for a subsequent strange particle emission).

The another unsufficiency of the above mentioned approaches is that they are insensitive to metastable SQM states with life times $\leq 10^{-9} - 10^{-8}$, predicted by many models for light strangelets being formed in a hot and dense fireball with rather large cross sections. That is why searches for strangelets by their decays into strange particles are of the great importance.

Having favorable conditions for the strangelet creation, which have been realized in very central nucleus-nucleus collisions (AA) at the JINR synchrophasotron (see 2.1.), we have undertook such studies.

At the first stage of this investigation we are looking for H-dihyperon (the simplest six-quark SQM state) by re-analyzing anomalous events which have been detected in an open (4π) geometry from central AA-collisions in streamer chambers and recorded in DST but failed to be fitted as decays of "usual" strange particles. The requirement of a coexistence with 3 double hypernuclei, observed by now,

provides the most probable properties of H-particle[16] M_H=2.220–2.231 GeV/c^2 and $\tau \sim 0.1 - 10$ ns with the main decay mode $H \to \Sigma^- p$ followed by $\Sigma^- \to n \pi^-$.
We have carefully re-analyzed[17] data, obtained by the use of our streamer spectrometer, with $2 \cdot 10^4$ extremely central MgMg- collisions detected: $\sigma_{cent}/\sigma_{tot} = 4 \cdot 10^{-4}$. Amongst ~1200 identified Λ and K^0_s decays and ~100 conversions $\gamma \to e^+e^-$, a small sample of "anomalous" V^0 events (~20) was revealed. After an additional analysis the latter appeared to be e^+e^- pairs with one exception. This V^0 event is characterized by rather large open angle and enhanced track density of the negatively charged secondary which can not be an electron or pion. Being fitted as $H \to \Sigma^- p$ this event exhibits M_H= 2228 ± 2 MeV/c^2, which falls into the narrow gap of expected H mass mentioned above. Kinematical parameters of the considered event are also in good agreement with those predicted by thermodynamical models (see Fig.7).

It stands to reason that a single observed candidate can not be treated as an evidence for the existence of the H dihyperon. However this provides possibilities to estimate an upper limit of production cross sections of a metastable (rather short-lived) H particle which escapes usually a detection in mass spectrometric experiments. Such an estimation gives: $\sigma \leq 0.12$ μb if τ=1ns and $\sigma \leq 0.36$ μb if τ=10ns (under our conditions mentioned above).

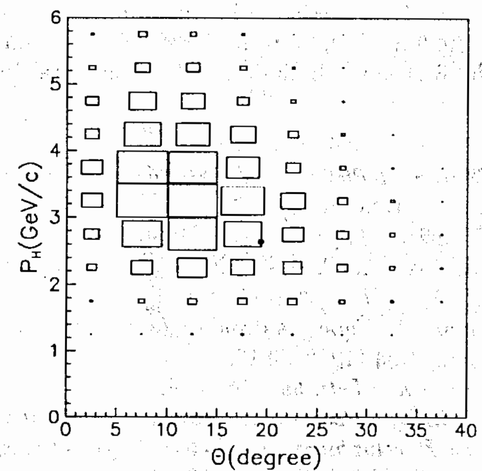

Figure 7. The expected angular and momentum distributions of H dihyperons formed within a fireball with T_B= 150 MeV in central Mg-Mg collisions: the black circle detected event.

Our further plans in this research field are connected with a development of the new approach which has been proposed[18,19] and successfully realized at JINR. This will make possible to increase sensitivities by a factor of 10^3 10^4, using an elaborated detector system[18,19] with a fast coordinate spectrometer in heavy nucleus beams of our new superconducting facility Nuclotron (5 6 A GeV), which can provide more than 1 TeV of the released energy in cental U-U collisions.

In conclusion I would like to oppose the wide-spread statement "the higher the better" when considering projectile energies wanted for QGP creation, and adduce weighty arguments in favor of the baryon-rich regime at several GeV per nucleon for SQM formation from QGP or mixed phase:

- many models predict QGP creation at as low energies as 2–5 A GeV for some equations of states, being near to those within strange stars;
- the alternative fundamental phenomenon (besides the deconfinement) is expected to cause QGP/SQM formation– the chiral symmetry restoration with its predicted high density/low temperature effects;
- such processes could more adequately reproduce (simulate) astrophysical phenomena (Big Bang, neutron star evolution, supernouva explosions);
- the strangeness enhancement as QGP/SQM signature should be more pronounced within a high density enviroment due to the Pauli principle;
- the background contributions to the studied QGP and SQM signals (e.g. from hadronic gas) are much smaller due to lower energies of secondaries.

I believe most of physicists to be convinced now that more concerted approaches are necessary to attack efficiently as complicated problems as the QGP and SQM matter, using not only distinct signatures but also different phase trajectories to reach QGP (mixed phase) with a following adequate comparision of data obtained at various energies.

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