THE FASCINATING EVOLUTION OF THE QUESTIONS OF INTEREST IN RELATIVISTIC HEAVY-ION COLLISION PHYSICS*

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The history of the evolution of questions of interest in the study of relativistic pA and AA collisions is presented. It covers the period from 1930 to 2005, however emphasis is placed on the pre-RHIC era.

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At the beginning of a conference like this one, it is good to ponder on questions: Where are we in the understanding of our field of studies? What are the *big* unanswered questions? How will we know we have answered the most important questions? How did we get here? The first two questions will be addressed at this conference. We will know that the third question has been answered if, in a future "Feynman Vol. IV", there is a chapter on QCD, which includes a discussion of the properties of QCD phases at extremes of temperature and energy density. That leaves the last question, how did we get here? I will try to answer it, as best as I can, in the twenty-five minutes given to me. My emphasis will be on the beginnings. A list of recent reviews of this physics is given in [1–4] and [5–8] cites articles which have a significant historical component.

I find the story of the study of relativistic pA and AA collisions fascinating and fun, in particular the evolution of the questions of interest, and it is this aspect of the story that I will focus on. Much insight can be obtained by seeing which questions in the past continue to be of interest today. Also, past questions are a good guide as to which obvious statements of today are in reality not so very obvious.

The study of relativistic heavy-ion collisions had its origins in the 1930s. It was in that decade that we had the discovery of the neutron and resultant beginnings of nuclear physics, and the realization that there must exist a

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strong force field with a corresponding carrier. Furthermore, it was the decade when we finally realized that we had access to high-energy beams of protons and nuclei in the form of cosmic rays [9]. Although cosmic rays had already been discovered in 1912, up till the late 1920s, under the influence of Millikan's strong personality and prejudices, it was taken for granted that cosmic rays interact only electromagnetically! Lastly, by the 1930s, two types of 4π visual detectors became readily available, the newly developed nuclear emulsion and the old workhorse, the Wilson cloud chamber.

The availability of a beam of strongly-interacting particles and 4π detectors led to an obvious question which could be answered by experiment: What happens when strongly-interacting particles collide at high energy?

In 1937, Marietta Blau [10] placed a nuclear emulsion on top of a mountain and observed a "STAR"; a strongly-interacting ("penetrating") cosmic ray which collided with a nucleus inside the emulsion and produced 8 particles, several of which were penetrating. It was the first recorded high-energy AA collision showing multiparticle production, probably a pBr or pAg interaction. In circa 1940, several experiments [11], using a Wilson cloud chamber, observed strange events; a penetrating cosmic ray producing more than one charged particle at a single point along its track. Now, why was this unexpected? At that time, the only understood mechanism of particle production was the process of radiation, and you do not "radiate" more than one particle at a time! So a big question came up: What is the mechanism by which strongly-interacting particles are produced? It is a question that drew the attention of many leading physicists of the time [12–15]: Heisenberg, Heitler, Oppenheimer, Landau, and Fermi, to name a few. It is worth noting here that this question, in the broadest sense which includes all stages of the production process, from the instant of impact of the incoming hadrons, through the creation and evolution of the intermediate state, to the final production of the outgoing particles, is with us to the present day!

Between 1938 and 1949, there were some fascinating exchanges between Heisenberg, Heitler, and Janossy [13], and an interesting question raised: Are the troubling events observed in cloud chambers really pp events? Perhaps they are pA events, in which case the issue of how more than one particle can be radiated at the same time would go away; multiple collisions inside the nucleus would be the explanation! However, by circa 1949, many well-identified pp events were observed in nuclear emulsions, some of which clearly showed that many particles can be produced in a single pp collision and that, therefore, there must be some new mechanism of particle production, which is different from radiation. As a by-product, these considerations raised a new question of interest, which I will discuss later: What happens when a proton collides with a nucleus?

In the 1940s and 1950s, the question of how, in the collision of two strongly-interacting particles, new particles are produced was a vigorously debated topic. The most basic issue being: Is the production a slow or fast process? Heisenberg [13], for instance, thought that it was a slow process; a collision of and evolution of strong fields that accompany the incoming particles, with production times $\gg$ collision times, and with low momentum particles produced isotropically and fast particles produced more forward and backward. On the other hand, others like Fermi [14], realizing how strong are the "strong" interactions, thought that there will be complete stopping of the colliding systems, with a fast production of a hot bosonic gas in thermodynamic equilibrium, which decays isotropically into its component particles without further interacting. Landau [15], too, thought that there will be complete stopping and creation of a system in thermodynamic equilibrium. However, realizing that Fermi's picture is not Lorentz-invariant, he proposed a model in which the stopped system continues to interact during a relativistic hydrodynamic expansion phase.

If one adds the word "gluon" to Heisenberg's "field" and gives the name "quark–gluon plasma" to the system undergoing relativistic hydrodynamic expansion in Landau's model, it is uncanny how similar are the pictures of multiparticle production considered in the 1940s and 1950s to current pictures!

This brings me to the 1960s. It so happens that in the 1960s Kraków had a very active research group which focused on the study of multiparticle production in pA collisions using the nuclear emulsion technique. We are in Kraków and so I thought it appropriate if I say a few words about the Kraków Group and what questions they were asking in the 1960s.

The origins of pA studies at Kraków can be traced to three facts. First, there was this dynamic and gifted experimentalist, Marian Mięsowicz [16] of liquid crystal fame, who became intrigued by the pA phenomena seen in nuclear emulsions when cosmic rays collide with nuclei. Second, emulsions with pA events recorded in them were readily available for study; they were the rejects of the HEP community, which was primarily interested in pp collisions. Third, research using emulsions, though very labor intensive, did not require large sources of funds and allowed groups with minimal resources such as the Kraków Group to participate in forefront research. Questions that interested the Kraków Group include: Why pp and pA collisions are so similar (in other words, why there is no evidence of cascading inside the nucleus, or how can strongly-interacting particles be so transparent)? What is the time of formation of particles? How do newly formed particles interact? Do pA studies teach us something about pp physics or *vice versa* is a very profound question still with us today? Looking at these questions, it is good to remember that in the 1960s nothing was known about gluons and very little about quarks and the structure of nucleons. Also, I point out that it was in the environment of Mięsowicz's group that theorists Białas and Czyż [17] converted the Glauber quantum mechanical analysis of elastic pA collisions into the future, all important, technique for determining the impact parameter of a pA or AA collision, known as the "Glauber Method".

In the 1960s and early 1970s, the construction of higher and higher energy proton and ion accelerators and the discovery of a neutron star led to many new and seemingly unrelated questions and results.

The question "what will be the spectrum of hadrons that will be produced at the future CERN PS" led Hagedorn [18] to conclude that, based on Fermi's statistical model and the statistical bootstrap hypothesis, there is a limiting temperature of about 185 MeV above which hadronic matter cannot exist!

The advent at Fermilab (and later also at CERN and Serpukhov) of a proton accelerator capable of producing hadron beams of energies in the 100's of GeV, led to studies of high-energy pA collisions where all three, the energy, the nature of the beam, and the nature of the nuclear target, were known for the first time. The qualitative question "what is the mechanism of particle production?" evolved into "what is the space-time picture of the multiparticle production process?" [8], and into quantitative studies of the phenomenology of pA collisions [4, 19]. In 1972, Kurt Gottfried [20] proposed "the energy flux cascade model", which became highly influential in the interpretation of pA data. His "energy flux" raised the obvious question: what is this *stuff* which exists between the instant of a pA impact and the production of free streaming particles, and what are its properties? In 1974, the results of Experiment E178 at Fermilab [21] showed that the collision between two hadrons was *more like that between two liquid drops than the shattering of two glass spheres* and raised questions: Why, to a good approximation, the total multiplicity of produced particles scales with the number of participants and why there is extended longitudinal scaling [1]? Questions unanswered satisfactorily to the present day.

At the same time, the observed high matter density inside neutron stars and results from studies of collisions of GeV/u nuclei raised questions [22]: Does superdense nuclear matter exist? What happens if you compress or distort nuclei? Are there different kinds of nuclear matter and vacua?

By the mid 1970s, there were two communities (one with a high energy and the other with a nuclear physics background) that almost did not talk to each other, yet the big questions that they were asking were remarkably similar. One was asking: What is this *stuff* produced immediately after a very high-energy collision of hadrons? The other: What is this *stuff* produced when the nuclear matter is highly compressed? One has a space-time picture of a boost-invariant longitudinally expanding high-energy density hadronic system [23, p. 255], the other of an explosion of highly-compressed baryonic matter [23, p. 134].

In Nov. 1974 an important workshop took place. It became known as the "Bear Mountain" meeting [22]. The introduction to the meeting speaks for itself — *"This workshop addressed itself to the intriguing question of the possible existence of a nuclear world quite different from the one we have learned to accept as familiar and stable".* As does a statement made by T.D. Lee at the meeting — *"So far almost all our nuclear experiments have been restricted to nuclei at a constant density. We have never ventured out to study nuclear physics at any densities other than the normal one. Likewise in particle physics... hitherto, we have concentrated only on experiments in which we distribute a higher and higher amount of energy into a region with smaller and smaller dimensions... We should investigate some "bulk" phenomena by distributing high-energy or high nucleon density of a relatively large volume. The fact that such directions have never been explored should, by itself, serve as an incentive for doing such experiments".* Clearly it is a call for the construction of a high-energy AA collider! Already a few months later at a conference, Pugh asks the question *[24, p.237] — "I wonder if you would like to say a few words about an additional dimension which seems to be on the verge of experimental feasibility. That is the study of collisions between nuclei at relativistic speeds. I am referring to the present feasibility or near-feasibility of accelerating particles up to carbon or so in the intersecting storage rings at CERN and of conceivably designing new facilities like Isabelle to include such possibilities."*

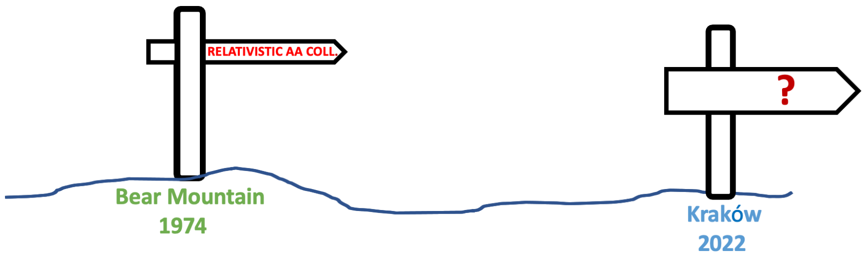
The timing of the "Bear Mountain" meeting was perfect. In theory, there was the parton/QCD revolution — a paradigm shift — with vague terms like "stuff" replaced by well-defined entities "quark" and "gluon". In experiments, shortly afterwards, a very dynamic group evolved at the Bevalac interested in GeV/u AA collisions [5], and there were many surprising results seen in high-energy pA collisions; transparency of nuclei [19], EMC effect, and Cronin Effect [4], to name a few. All of which led to some very "sexy" questions: Can confined quarks be liberated? Can we create on earth the conditions that existed in the early universe? Can we produce new kinds of matter or abnormal vacua? Are free nucleons different from those inside nuclei? [25]. Lab directors saw a need for new facilities. Leaders of research groups saw opportunities to address new fascinating questions; with luck a trip to Stockholm! As a result, meetings sprung up as mushrooms [7]. There was no shortage of speculations regarding the phase diagram of QCD, with interesting phases and phase transitions, in particular, the possible existence of a new phase of non-interacting quarks and gluons named the "Quark–Gluon Plasma" or "QGP". There was a colossal expansion of interest in our field. In short, it was the beginning of a renaissance period in the study of pA and AA collisions [7]!

In the 1980s, the focus shifted towards practical questions [25, 26]: To discover the QGP or other new physics, what are the minimum volumes and energy densities needed? What are the needed baryon (or nuclear matter) densities? For how long must they last to be interesting, achievable, and detectable? What is the stopping power of nuclei? Which existing accelerators can produce interesting AA results? What new accelerators need to be built? What will be the signatures of new physics? What detectors need to be built and what measurements made? It led to enthusiastic AA research programs [5, 27] at the AGS (1986–1997), SPS (1986–1999), and RHIC ($>$1999), and to crucial progress in lattice QCD calculations. In theory, too, new ideas and questions sprung up: chiral symmetry restoration, the possible existence of disoriented chiral condensate states, and color superconductor states, chiral magnetic effects, analogies with cold atom phenomenology, and string theory. See, for example, [1–3, 7].

This brings me to the 1990s and 2000s. There was a flood of interesting AA data, and this data plus lattice calculations at first seemed to give the impression that sufficient energy densities and temperatures were actually achieved to produce a QGP. Thus, the questions of interest became: Has a QGP been produced, and if so, which laboratory saw it first and who can claim discovery? However, it soon became evident that an ideal gas of weakly-interacting quarks and gluons was not being produced. To produce such a system, much higher energy densities and temperatures are necessary, comparable to those in the early universe. The second two questions are thus moot! On the other hand, our search has been anything but a waste of time. As you all know, at the high-energy densities and temperatures produced at RHIC and the LHC, nature has come up with a surprisingly strong interacting system. It flows remarkably well and has no end of interesting properties that need studying, and which bring up a whole new set of fascinating questions [1]. The fact that nature did not cooperate and did not produce an ideal gas of weakly-interacting free quarks and gluons did raise an awkward question, how do we explain to our colleagues and funding agencies that we have not delivered an ideal QGP, which we said must exist and we know how to produce? No problem! We simply redefined the QGP to be the strongly-coupled liquid phase of QCD which we are producing at the highest energies of our accelerators [27–29]!

To conclude, I find it fascinating that many of the questions we are asking today are not that different from those asked in the past and remain as interesting as ever. New questions of course continue to come up. You know them better than I do, and so I will not attempt to list them here except for one, which I find particularly interesting. Before about a nanosecond after the Big Bang, the hadronic part of the universe consisted of a uniform gas of non-interacting quarks and gluons. How did structure begin to evolve from such a structureless system? Presumingly the start was a quantum fluctuation, but then how did it proceed?

Influenced by the questions stimulated by the "Bear Mountain" Workshop in 1974, and T.D. Lee's challenge to build a high-energy *AA* collider, I end with a more modest assignment: State, in as few words as possible and language as simple as possible: What are today the "big" questions that will excite future generations of relativistic heavy-ion collision physicists?



I learnt much about the early history of relativistic heavy-ion physics from the colloquium given in 2013 at MIT by Tetsuo Matsui, and about the Kraków Group from discussions with Roman Hołyński. I wish to thank the organizers of Quark Matter 2022 for giving me the opportunity to give this plenary talk, and acknowledge support of the Office of Nuclear Physics in the U.S. Department of Energy, through grant DE-SC0011088.

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