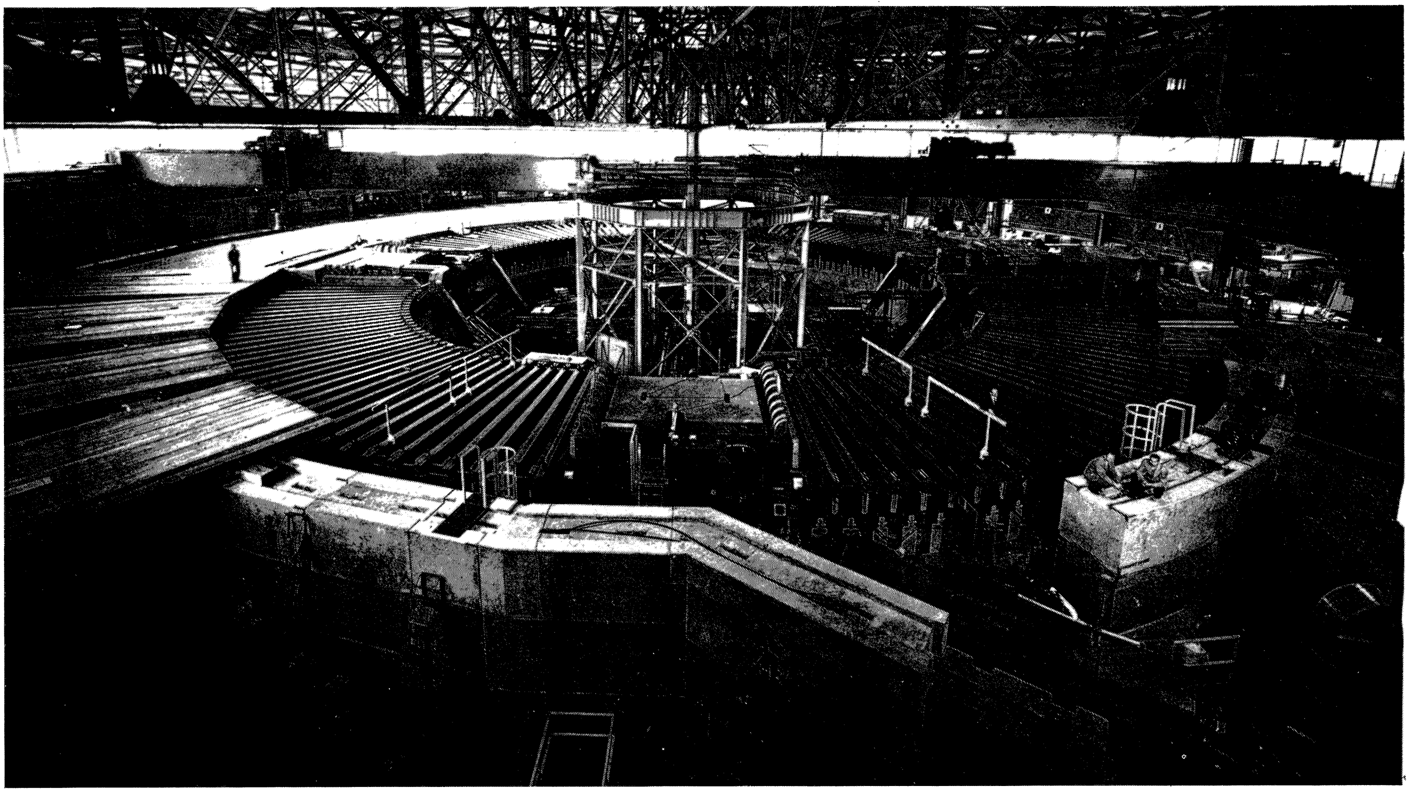
New possibilities with nucleus-nucleus collisions

by W. Willis

The Bevatron at Berkeley, now part of the Bevalac and scene of experiments with high energy heavy ion beams. However these energies of several GeV per nucleon may be insufficient to reveal important phenomena in nucleus-nucleus collisions.

(Photo LBL)

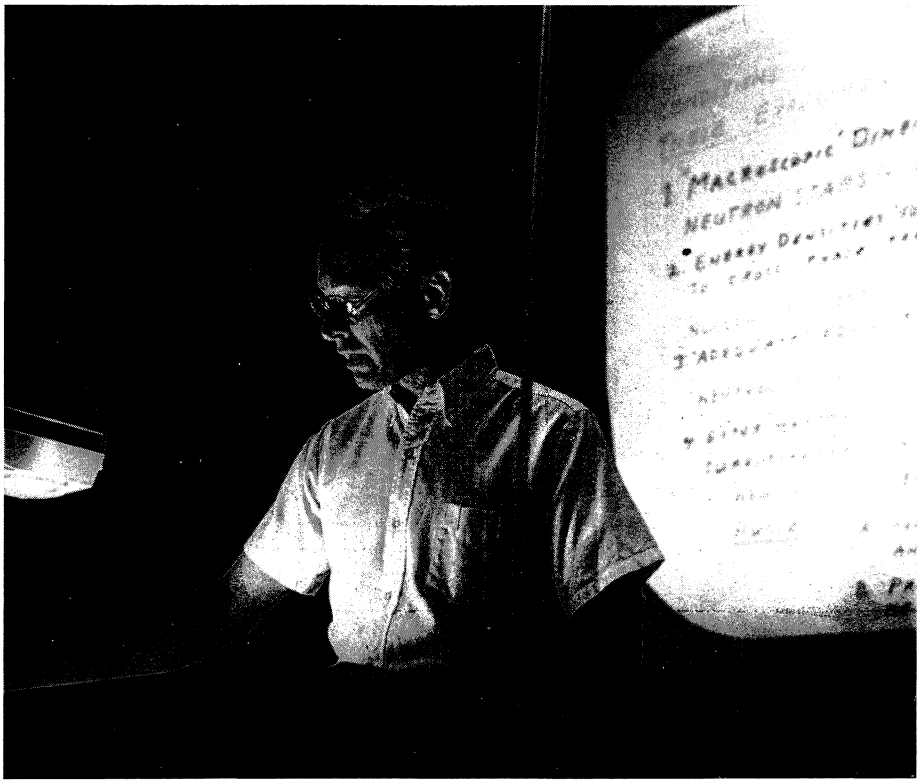


Quarks and gluons exist; they are nearly massless, but it is very hard or even impossible to knock them out of the proton. It is now widely believed that this strange state of affairs is due to the properties of the physical vacuum state as it now exists in our part of the Universe. In this view, the ground state of the vacuum is not that familiar from quantum electrodynamics (QED). That state is basically empty space, perturbed by fluctuations which occasionally give rise to a virtual electron-positron pair. In the quantum chromodynamic (QCD) theory of quarks and gluons, the stronger and more complicated forces give rise to a state which cannot be described as a perturbation on empty space. Instead, the physical vacuum has properties which resemble those of a physical medium. For example, the colour field is completely excluded, or at least strongly repelled, from a definite macroscopic volume of physical vacuum. This effect confines the quarks and gluons, which carry colour, inside the hadrons. On the scale of hadrons, quantum fluctuations make the phenomena more complex, but a simple picture postulates that the strong colour fields inside the hadron create a local volume of space which behaves more like the perturbative vacuum state, reverting to the physical vacuum state outside. This concept has been quantitatively expressed by the bag model, with some success.

This physical vacuum is also supposed to explain the origin of broken symmetries. An analogy is a perfectly symmetric sphere of iron. Above the Curie temperature the state has spherical symmetry. At low temperature, the ground state will be magnetized, with the magnetic field pointing in an arbitrary direction determined by quantum fluctuations. The symmetry of the state has been broken, without any arbitrary direction entering in the laws of nature. By a quite similar mechanism, the parameters of the physical vacuum could determine the seemingly arbitrary breaking of symmetries in particle physics, though the fundamental laws remain symmetrical.

It seems that the physical vacuum has acquired properties reminiscent of Maxwell's ether. At least, so we are asked to believe. Maxwell introduced his ether for plausible reasons, but crucial experimental tests were found, and the theory was found wanting. Experiments could test the idea that the physical vacuum is not identical to the perturbative one.

Our vacuum state has no consequences for the testing of special relativity and probably none for (macroscopic) general relativity. Fortunately, another classical experiment on the vacuum is predicted to show striking results. The effect is due to the predicted instability of the physical vacuum state in the presence of high energy density or matter density. Under these conditions, the lower energy state is that based on the perturbative vacuum: empty space with real and virtual quarks and gluons traversing it, without colour confinement. This change to a qualitative different state is in fact expected to occur, under suitable conditions, as a sharp phase transition. The origin in this transition is that the physical vacuum state is supposed to arise from ordered virtual constituents which are disrupted by thermal agitations, or the colour fields of dense matter. The analogy of the iron sphere is again valid: the spontaneous symmetry breaking of the physical vacuum is a low-temperature phenomenon. The 'Curie temperature' of the vacuum is of the order of the QCD scale parameter.



Bill Willis – proposing new ways to measure the properties of the vacuum.

An idealized experiment

Planck showed how far-reaching conclusions can be arrived at by analysing a volume of vacuum surrounded by walls in thermal equilibrium with the radiation in the interior. Let us follow him, adding equipment which will measure gluons as well as photons. Imagine a large box with thick walls at a certain temperature. The radiation emitted through a small aperture is measured. Alternatively, if we want to be sure of what happens in the middle of the box, a high energy proton beam is sent through the aperture, and Compton scattering of photons and gluons is measured.

At low temperature, we will detect photons filling the box with the Planck distribution, but no gluons. Why not, since massless thermal gluons should be emitted by the walls? The answer is supposed to be that the physical vacuum filling the box forces a thermal gluon back into the wall.

As the temperature of the wall is raised, there are more — and more energetic — thermal gluons emitted. They penetrate slightly further into the vacuum. Finally, the temperature approaches where the ordered structure of the virtual particles in the physical vacuum is so much disrupted that the perturbative vacuum state is energetically preferred. Very near this temperature, large-scale fluctuation appears in the vacuum, with a mixture of colour-confining and unconfining regions. The phenomenon of critical opalescence will render the box opaque to the high energy protons at that point.

Above the transition temperature, we will find freely propagating gluons and quarks filling the box. The situation at the small aperture is more complex, since it is a boundary with the physical vacuum in the world outside. Only constituent combinations which are colourless can make it to the outside world.

Suppose the walls are heated further so that the constituents enter the regime of asymptotic freedom and their interactions are decreasing as they are heated. It seems there is no limit to the temperature. The 'limiting temperature' observed in hadronic interactions must be a confinement effect, and indeed the Hagedorn temperature of 160 MeV is close to that estimated for the critical temperature.

The elements of this analysis which must be transferred to a real experiment are the following:

- The size of the box. The scale is given by the QCD scale parameter, about half a fermi. The box must be larger than that. Evidently, the proton is not large enough.

- The temperature. One should be able to sweep through the region 100–400 MeV, or thereabouts.
- A sufficient degree of thermal equilibrium must be established.
- The probes must be able to examine the interior of the 'box' — affording measurements of sufficient subtlety to distinguish the conditions above and below the transition, and the critical phenomema.

Real experiments

First, some possible approaches along conventional experimental lines. Consider, first, proton-proton collisions. We know that the distributions of the particles in the 'beam jets' as well as in high transverse momentum jets closely resemble those in the jets from high energy electron-positron annihilations. The latter reflect the characteristics of the fragmentation of single quarks. It follows that ordinary proton-proton collisions show no signs of the presence of many constituents, spread over a volume and in some sort of equilibrium — the conditions we wish to produce. It is possible that some rare events are somewhat more suitable for our purpose, but it does not seem likely that they will go far enough towards satisfying the first three conditions above.

We can think of using protons incident on a nuclear target. Here again we can profit by a considerable body of knowledge from recent experiments. For example, if we consider the system in which the proton is at rest, and consider the proton fragmentation products after it has been struck by the incident nucleus, we know that they are not very different from those after the proton has been struck by another proton. Consider, instead, the nucleus to be at rest. The proton passes through, making several collisions. The fast forward products do not fragment until they have left the nucleus (see the previous remark). The slower particles are emitted at larger angles, and do fragment inside the nucleus. Their fate is a hard one, however. These fragmenting particles have energies of a few GeV or less, and they enter a volume of cold nuclear matter where they are outnumbered by 'stationary' nucleons at the odds of typically ten to one. They create feeble cascades, where the creation of a few pions is partially counterbalanced by pion absorption. No wonder that the observed increase in pion multiplicity, in comparison with proton-proton collisions, is only between two and three in the heaviest nuclei. There is no possibility of heating a large volume to an interesting temperature. Instead, the energy provided is dissipated in a large mass of cold nuclear matter.

We come rather naturally to consider nucleus-nucleus collisions at high energy. First we note that accelerators, linear or circular, act upon the charge. A fully stripped heavy ion has charge Z times that of a proton, and A times the mass, with A roughly twice Z. The total energy of a nucleus produced by the accelerator is thus about Z/2 times that of a proton from the same accelerator. Even for a medium size nucleus, say argon, this is a big factor. Given that we needed to heat a large volume, the fact that the energy is distributed over a number of particles is not a disadvantage. Quite the contrary, since this energy can be deposited in the target with reasonable efficiency, which is of course not the case when trying to heat a nuclear volume with one very high energy proton.

Some idea of the character of these collisions can be gained by considering the number of pions produced. In proton-proton collisions at the energy of the CERN Intersecting Storage Rings, about 20 pions are produced. In central collisions of nuclei, essentially all the nucleons interact. Cascading is not very important, so one might expect that pion multiplicities are roughly linear in A, consistent with cosmic ray results. Collisions of heavy nuclei at very high energies should give thousands of pions.

Naïvely, we could suppose that these pions are created in the volume of the two nuclei before the system has had time to disassemble. Note, however, that if each pion is supposed to occupy the volume attributed to it in the bag model, there is not room for that many pions. We may suppose that the matter is rather in the form of quarks and gluons, forming pions as the density falls to the appropriate value. Here, however, we make contact with the considerations on the role of the physical vacuum.

We know that the nucleus is made of nucleons, not a big bag of quarks. In fact, most of the volume inside a nucleus is occupied by the vacuum — not by the nucleon bags. In the collisions just described, it seems very likely that the conditions are created where that physical vacuum is unstable, and at each point there is a transition to a perturbative vacuum filled with quarks and gluons. We then indeed have a big bag. The surface presumably emits pions as long as the temperature is high enough. In suggestive language, 'the surface boils pions at the Hagedorn temperature'.

We can begin the discussion by noting that most of the common observables are not very useful. Most hadrons will have at last scattered near the surface of the interaction volume, largely erasing the information about their previous history. It is not sensible to go to such trouble to

People and things

provide a good surface-to-volume ratio, and then selectively to observe the surface. Weakly interacting probes are called for. Most of our considerations must then deal with photons, or virtual photons observed as lepton pairs.

The emitted photons and leptons, for example, could be used in an attempt to observe the phase transition. The energy of the nuclei is varied, and the temperature indicated by the transverse momentum and mass distribution is determined. The rate of photon emission is then determined as a function of temperature. As the transition temperature is passed, the character of the particles producing the radiation changes, and one would expect a change in the number of the photons produced, or in the slope of the photon production versus temperature.

It may be too naïve to suppose that spectral measurements will show such a subtle effect as the disappearance of bag boundaries. Correlation measurements may be required, such as searches for changes in the small mass lepton pair spectra, or in the identical particle interference measurements.

Since we have only rough estimates of the transition temperature, only rather crude notions of 'temperature' in collisions, and as yet no direct data relevant to the temperature inside nuclear collisions, we cannot say anything precise about the energies necessary to produce temperatures above the critical temperature. It seems clear that the energies investigated at Berkeley and Dubna, a few GeV per nucleon, are not sufficient and the further investigation of these phenomena must await the availability of much higher energy nuclear collisions.

Workshop

A Workshop on Quark Matter Formation and Heavy Ion Collisions is being held from 10-14 May at the University of Bielefeld, Federal Republic of Germany. Its aim is to study both theoretical aspects of the formation of a quark-gluon plasma in heavy ion collisions and the experimental problems arising in its detection. The meeting will consist of a four-day session for about 80 participants, followed by a general session on 14 May open to anyone interested. For further information, contact H. Satz, Department of Physics, University of Bielefeld, D-48 Bielefeld, Federal Republic of Germany.

LEP authorization

The project to build a large electron-positron storage ring, LEP, at CERN already had the backing of the twelve CERN Member States (see December 1981 issue, page 439), but three votes remained subject to conditions. At a CERN Council meeting in December this 'ad referendum' was lifted by the Netherlands, Norway and Sweden. The LEP project thus has the unconditional support of all Member States.

Meanwhile the LEP project team has continued to work on the optimization of the designs for the machine components and of the location of the underground LEP ring itself. A new location is to be proposed to the Host States (France and Switzerland) which reduces the length of ring under the Jura mountains. It is also planned to tilt the plane of the ring. More information soon.

Also at its December session, the CERN Council elected Sir Alec Merrison as its President, in succession to Jean Teillac. V. Telegdi and K. O. Nielsen were re-elected as Chairmen of the Scientific Policy Committee and Finance Committee respectively. K. Tittel was appointed a new member of the SPC.

At CERN, Roy Billinge was appointed as Leader of Proton Synchrotron Division and Maurice Jacob as prospective Leader of Theory Division. Tributes were paid to Gordon Munday (Proton Synchrotron), Constant Tièche (Finance), and Gunther Ullmann (Personnel) for their exceptional contributions to the work of CERN during their many years as Division Leaders.

Warm tributes were paid to Jean Teillac at the December session of CERN Council. Professor Teillac had served as President of Council for almost four years.