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THE ALICE HEAVY-ION EXPERIMENT AT THE CERN LHC

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Abstract

ALICE (A Large Ion Collider Experiment) is a dedicated heavy-ion detector designed to exploit the physics potential of nucleus-nucleus interactions at the LHC. As a general-purpose experiment, it will allow a comprehensive study of hadrons, electrons, and photons produced in the collision of heavy nuclei, up to the highest particle multiplicities anticipated at the LHC.

The central part of ALICE, which covers $(90 \pm 45)^\circ$ ($|\eta| < 0.9$) over the full azimuth, is embedded in a large magnet with a weak solenoidal field. The base-line design consists (from inside out) of a high-resolution inner tracking system, a cylindrical TPC, a particle identification array (TOF or RICH detectors), and a single-arm electromagnetic calorimeter. Possible upgrades under study include large-acceptance electromagnetic calorimeters and a muon identification system. We will trigger on central collisions with a zero degree calorimeter and measure multiplicity distributions over a large fraction of the available phase space.

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1 INTRODUCTION

The aim of high-energy heavy-ion physics is to study strongly interacting matter at extreme energy densities (QCD thermodynamics).

Statistical QCD predicts that, at sufficiently high density, there will be a transition from hadronic matter to a plasma of deconfined quarks and gluons — a transition which in the early universe took place in the inverse direction some 10^{-5} s after the Big Bang and which might still today play a role in the core of collapsing neutron stars.

The present exploratory programme with light ions at CERN and Brookhaven has established the feasibility of high-energy ion-ion experiments with their abundant particle production. It has shown that high-energy densities can indeed be obtained in these reactions and produced first hints for the onset of new, collective phenomena.

The upcoming experiments with really heavy ions, both at BNL and CERN, should determine to what extent it is actually possible to get into a regime of thermodynamic behaviour. They should lead to baryon densities close to or even exceeding the ones in the core of neutron stars, and — if present estimates are correct — should have a chance of obtaining more conclusive evidence for quark deconfinement.

In the future the Large Hadron Collider (LHC), with a centre-of-mass energy of ≈ 6 TeV per nucleon, will bring us into the *true* high-energy heavy-ion regime; it is the only machine that will reach and even extend the energy range probed by cosmic-ray nucleus-nucleus collisions.

Extrapolating from present results, all parameters relevant to the formation of the Quark-Gluon Plasma (QGP) will be more favourable: the energy density, the size and lifetime of the system, and the relaxation times should all improve by a large factor, typically by an order of magnitude, compared to Pb-Pb collisions at the SPS. It should then be possible to get *average* energy densities well above the deconfinement threshold, and to probe the QGP in its asymptotically free ‘ideal gas’ form. Unlike at lower energies, the central rapidity region will have nearly vanishing baryon number density, similar to the state of the early universe. Heavy-ion collisions at the LHC [or the Relativistic Heavy Ion Collider (RHIC)] are generally believed to provide a more suitable environment for the study of strongly interacting matter than existing accelerators.

1.1 LHC Heavy-Ion Programme

The main aim of the planned LHC at CERN will be the exploration of the TeV mass region (Higgs, SUSY) in proton-proton collisions. In addition, the study of nuclear collisions (up to Pb on Pb) is included as an integral part of the initial experimental programme with running times comparable to the present SPS ion programme ($\approx 10\%$ per year). It is foreseen to install only one dedicated heavy-ion detector; and consequently ALICE [1] has emerged as a common design by the heavy-ion community presently engaged in the CERN heavy-ion programme, and a number of groups new to this field from both nuclear and high-energy physics.

The pp Collaborations at the LHC have also expressed their interest in nuclear collisions [2, 3]. The dedicated pp detectors are potentially well suited to addressing a subset of high-mass, high- p_t phenomena, in particular high-mass dimuons (Υ production).

The LHC and its experimental programme are currently being evaluated in the relevant committees, and, provided there is a positive decision in the near future, it could start operation by the beginning of the next decade.

1.2 ALICE Physics Goals

The ALICE Collaboration — presently over 200 physicists from more than 40 institutes — aims at exploring nuclear collisions at the LHC by searching in a comprehensive way for qualitative and quantitative changes in composition and structure of the final states as a function of energy density. A dedicated, general-purpose detector is being designed, which will be operational at the start-up of the LHC. It is based on experience gained with the existing programmes at CERN and BNL, and will address a majority of the known sensitive observables. Our strategy is to study a number of *specific signals* in the same experiment together with *global information* (e.g. impact parameter, particle multiplicity) about the events.

The signals accessible to our detector include hadronic *particle ratios* and p_t *spectra*, (strangeness production, collective flow, jet quenching), particle *interferometry* (expansion dynamics), multiplicity *fluctuations* and event *structures*, *direct photons* (thermal radiation), and vector meson decays ($\rho, \omega, \phi, J/\Psi$) into *lepton pairs* (resonance line-shape parameters and chiral symmetry restoration at low masses, colour screening and deconfinement at high masses).

The acceptance of ALICE will be sufficient to measure some of these signals with good accuracy, not only on an average but also on an *event-by-event* basis.

2 DETECTOR LAYOUT

The overall detector layout of the ALICE experiment is shown in figs. 1 and 2. The central part, which covers $\pm 45^\circ$ ($|\eta| < 0.9$) over the full azimuth, is embedded

Figure 1: Three-dimensional view of the ALICE detector

in a large magnet with a weak solenoidal field. It consists of an inner tracking system (ITS) with five layers of high-resolution tracking detectors, a cylindrical time projection chamber (TPC), a particle identification array (TOF or RICH detectors), and a single-arm

Figure 2: Transverse view of the ALICE detector

electromagnetic calorimeter. A number of smaller trigger detectors [zero-degree calorimeters (ZDCs) and the multiplicity counter array (MCA)] are not shown. The dashed areas (labelled FEC, NEC, and BARC) show the place that could be occupied by large-acceptance electromagnetic calorimeters, whose feasibility is currently under investigation.

2.1 Magnet

A weak and uniform solenoidal field has been chosen for ALICE because, together with continuous tracking in a TPC, it considerably eases the task of pattern recognition. The field strength — a compromise between momentum resolution, low momentum acceptance, and tracking efficiency — will be 0.2 T, allowing full tracking and particle identification down to ≈ 120 MeV/c in p_t . Lower momenta are covered by the inner tracking system. The inner radius of the magnet has to be sufficiently large to accommodate a single-arm electromagnetic calorimeter for prompt photon detection, which must be placed at a distance of ≈ 6 m from the vertex, because of the particle density.

The magnet of the LEP experiment L3 would fulfil all these requirements. It could be left at its present position centred 1.2 m below the LHC beam height. If it should not be available, a new solenoid will have to be built with somewhat smaller dimensions (outer diameter 10 m), which would fit into any of the standard LEP intersection regions. The present design foresees a non-welded Al solenoid subdivided into 10 equal coils with a simple arrangement of iron slabs serving as flux return and end-caps.

2.2 Inner Tracking System (ITS)

The basic functions of the inner tracker — secondary vertex reconstruction of hyperon decays, particle identification and tracking of low-momentum particles, and improvement of the momentum resolution — are achieved with five barrels of high-resolution

detectors. The number of layers and their position have been optimized for efficient pattern recognition and good momentum resolution. Because of the high particle density, the innermost three layers ($7.5 \leq r \leq 22$ cm) need to be truly two-dimensional devices, e.g. silicon pixel or silicon drift detectors. For the second superlayer at $r \approx 50$ cm, at least one and possibly both layers could be equipped with microstrip detectors. Three or four layers will have analog readout for independent particle identification via dE/dx in the non-relativistic region, which will give the ITS a stand-alone capability as a low- p_t particle spectrometer.

R&D for the inner tracking detectors are carried out partially in the framework of the CERN detector development programme (pixels [4], strips [5], microstrip gas chambers [6]), and a first attempt to produce silicon drift detectors in industry is well under way.

2.3 Time Projection Chamber (TPC)

The need for efficient and robust tracking has led to the choice of a TPC as the main tracking system. In spite of its drawbacks concerning speed and data volume, only a conservative and redundant tracking device can guarantee reliable performance at up to 8000 charged particles per unit of rapidity. The inner radius of the TPC ($r = 100$ cm) is given by the maximum acceptable hit density (0.1 cm^{-2}), the outer radius of 250 cm by the length required for a dE/dx resolution of $< 7\%$. With this resolution the TPC can serve, in addition to doing tracking, as a detector for electron identification up to momenta of $\approx 3 \text{ GeV}/c$. The design of the readout and of the end plates, based on ongoing developments for other heavy-ion TPCs, as well as the choice of the operating gas, are optimized for good double-track resolution [7].

2.4 Particle Identification System

A number of technologies are under study for the hadron identification system. For the first alternative, based on time of flight (TOF), three different options are currently under test: Pestov spark counters, parallel-plate chambers (PPCs), and a scintillator grid with position-sensitive photomultipliers. First prototypes have been operated in a test beam and shown a timing resolution of < 100 ps (r.m.s) for the Pestov counter. The PPCs, which are less demanding in terms of construction and operation, have reached a resolution of ≈ 250 ps.

The second alternative is a proximity-focusing RICH detector with a liquid-freon radiator, solid photocathode, and pad readout. A small prototype with a CsI photocathode has shown a performance in the beam comparable to conventional TMAE UV detectors [8].

Depending on the performance achieved by the chosen detector, the particle identification system will be placed at radii between 3 m and 4.5 m. In addition, a small-area TOF array will be located in front of the e.m. calorimeter at $r \approx 6$ m in order to improve the particle identification for inclusive ratios at high p_t .

2.5 Photon Spectrometer (PHOS)

Prompt photons, π^0 's and η 's will be measured in a single-arm, high-resolution electromagnetic calorimeter. It is located 6 m from the vertex and covers 25 m^2 with $\approx 50,000$ channels. It is necessary to build it from material with a small Molière radius, to reduce the occupancy, and high light-output, to reduce the readout noise for the low energy

of interest (a readout with silicon photodiodes is foreseen because normal photomultipliers are excluded in the magnetic field).

We are currently favouring PbWO_4 , a scintillating crystal, which seems well suited to our application. In addition, it is comparatively cheap, and easy to grow, to machine and to handle. A single calorimeter size crystal has been tested with very encouraging results (expected energy resolution in PHOS: $\sigma_E/E = 3\%/\sqrt{E} \oplus 3\%/E \oplus 1\%$) and a complete small calorimeter should be available before the end of 1993.

2.6 Large Rapidity Detectors (MCA, ZDC)

A multiplicity counter array close to the interaction region will measure the pseudo-rapidity distribution of charged particles over a large fraction of the phase space ($|\eta| < 5$). A number of options are under study, including a set of microchannel plates inside the vacuum of an enlarged beam pipe, and silicon pad detectors or microstrip gas chambers outside the beam pipe.

The ZDC consists of a set of small calorimeters ($13 \times 13 \text{ cm}^2$ and $22 \times 22 \text{ cm}^2$ wide, 100 cm deep), which will be used to measure and trigger on the impact parameter of the collisions. They are made of tungsten with embedded quartz fibres, read out by photomultipliers, and are located on both sides of the interaction region, $\approx 90 \text{ m}$ downstream in the machine tunnel.

2.7 Trigger and Data Acquisition (DAQ)

The average event rate for Pb–Pb collisions at the LHC will only be about 2000–4000 minimum-bias collisions per second (i.e. of the order of 100 central collisions per second). The low interaction rates lead naturally to an approach which combines large geometrical acceptance with simple central collision triggers and a high data-taking rate. The total event size will be in the range of 50 Mbytes (including zero suppression) to 20 Mbytes (including, in addition, cluster finding in the TPC). Together with the requirement of an $\approx 50 \text{ Hz}$ data-taking rate, the data flow will reach about 1.5 Gbytes/s. In order to handle such a data volume, we intend to have a number of parallel event builder and storage devices and connect these to the front-end readout system with parallel data paths via a switching matrix.

2.8 Future Options

The present detector, with its modular design and open geometry, is flexible enough to allow, at some later stage, modifications or upgrades if these should be desired. In particular, the free space available in the L3 cave, both in the radial and in the longitudinal directions, could be equipped with additional detectors, if the physics should justify a larger acceptance or suggest focusing on specific signals (e.g. physics outside mid-rapidity, continuum lepton pairs with $m > 1\text{--}3 \text{ GeV}$). If the experiment should be housed in the L3 magnet, the outer two layers of muon chambers and part of the forward muon system planned as an L3 upgrade could be left in place. By exchanging the inner tracker with a passive absorber, a measurement of high-mass dimuons could be feasible with only minor modifications already in the first years of operation.

3 PHYSICS CAPABILITIES

3.1 Track Finding and Momentum Resolution

The track finding starts in the TPC from the outermost pad rows, where points are less affected by the limited two-track resolution. For the highest particle density considered

we find a reconstruction efficiency in the TPC of $\approx 93\%$, practically independent of p_t down to 100 MeV/c and with a negligible number of ghosts.

The TPC tracks are then connected to the ITS. Finally, tracks with very low momentum are reconstructed using only the ITS, the main objective being identification and rejection of asymmetric Dalitz pairs.

In the momentum range of interest the resolution is mainly determined by multiple scattering. The dependence of $\Delta p/p$ can be approximated by $\Delta p/p = (1.2 \oplus 0.3 \times p) \%$, except for very low momenta where the $1/\beta$ term in multiple scattering dominates. The angular resolution for both polar and azimuthal angles is well below 1 mrad. The effective mass resolution of a particle decaying into an e^+e^- pair is $\Delta m/m \approx 1\%$, i.e. 8 MeV/ c^2 for ρ and ω , 10 MeV/ c^2 for ϕ , and 30 MeV/ c^2 for J/ψ .

3.2 Particle Identification

Particle identification is achieved with a combination of TOF or RICH and dE/dx measurements in the tracking system (ITS and TPC). The combined separation power of TPC and TOF is shown in Fig. 3 for the large-acceptance TOF at $r = 3$ m (solid lines) and the small solid angle covered with TOF at $r = 6$ m (dashed lines). For hadrons,

Figure 3: Combined particle separation with TPC ($\sigma = 7\%$) and TOF ($\sigma = 100$ ps) at $r = 3$ m (solid lines) and $r = 6$ m (dashed lines).

Figure 4: Transverse momentum distribution of pions (full line) and kaons (circles) of a single event including particle decays and tracking efficiency.

we have more than 3σ separation for pion and kaon identification below 2 GeV/c and for protons below 3 GeV/c, which is sufficient for event-by-event particle ratios, particle interferometry analysis, and decay reconstruction, because it includes the majority of all produced hadrons. Inclusive ratios can be measured up to ≈ 4 GeV/c (≈ 6 GeV/c for $r = 6$ m), i.e. well into the minijet region. Figure 4 shows the transverse momentum spectrum of a single event generated with $dN_{ch}/dy = 8000$.

Including tracking efficiency and particle decays, we would reconstruct ≈ 8000 pions (full line) and ≈ 1200 kaons (circles) inside the acceptance; adequate for measuring the shape of the momentum spectra and the particle ratios in a single event.

Secondary vertices from hyperon decays are identified in the ITS with an impact parameter resolution of $< 200 \mu\text{m}$ for $p > 600$ MeV/c. Including efficiencies and acceptance, we will reconstruct of the order of 10 Λ 's, 0.15 Ξ 's, and 0.02 Ω 's per event with $dN_{ch}/dy = 8000$.

3.3 Particle Interferometry

The main application of boson interferometry in heavy-ion physics is the estimate of the parameters characterizing the space-time evolution of the system after the collision. Its feasibility depends, in particular for large radii and correspondingly narrow correlation functions, on two-track resolution, momentum resolution, and acceptance.

Figure 5: Correlation function for a single-event with $dN_{\text{ch}}/dy = 8000$. All three effective sizes were equal to 15 fm ($R = R_{T_{\text{side}}} = R_{T_{\text{out}}} = R_L$).

Figure 6: Invariant-mass distributions, after cuts, in the ω/ϕ region for 5×10^7 central events, including tracking efficiency and momentum resolution ($dN_{\text{ch}}/dy = 8000$).

Single-event pion interferometry should be feasible with a relative error of $\approx 20\%$ up to effective sizes of 15 fm. An example of a single-event ($dN_{\text{ch}}/dy = 8000$) correlation function for $R = 15$ fm ($R = R_{T_{\text{side}}} = R_{T_{\text{out}}} = R_L$) is shown in Fig. 5

For inclusive measurements, the resolution ($\Delta Q_{T_{\text{side}}} = 0.4$ MeV/c, $\Delta Q_{T_{\text{out}}} = 3.5$ MeV/c, $\Delta Q_{T_L} = 0.6$ MeV/c) will be sufficient to measure effective source sizes up to ≈ 40 fm.

3.4 Lepton Pairs

Leptonic final states are of particular interest, because they can relate information from the early and dense phase of the system owing to their weak final-state interactions. Unfortunately, they are also amongst the most difficult to observe because of combinatorial background from the large number of Dalitz decays in the electron channel or π/K decays in the muon channel.

We have chosen a weak field together with good tracking and electron identification extending down to very low momenta (a few 10 MeV/c) in order to efficiently recognize and remove these low-mass pairs, in this way improving the signal-to-background ratio by about an order of magnitude. The signal-to-background ratio will be inversely proportional to the multiplicity density, i.e. a factor of four better for the lowest multiplicity anticipated in central Pb-Pb collisions ($dN_{\text{ch}}/dy = 2000$).

The invariant-mass spectrum of electrons passing all our cuts is shown in Fig. 6 in the mass region of the ω and ϕ mesons for 5×10^7 recorded events. The importance of excellent mass resolution ($\Delta m/m \approx 1\%$) is evident and should allow us to observe

significant changes in the natural width or mass (in-medium modification, chiral symmetry restoration) of ω and ϕ .

The statistics for the J/Ψ will allow a cross-section measurement to $\approx 3\%$ accuracy. Because of insufficient e/π discrimination power at large electron momenta, the accepted J/Ψ 's are all at $p_t < 2$ GeV/c, where the primary production via gg fusion is favoured over J/Ψ 's from bottom mesons, which decay long after freeze-out.

3.5 Prompt Photons

Prompt photon production is one among very few signals which can provide direct information on the partonic, early phases of the interaction (thermal radiation from the QGP and mixed phase around 1–3 GeV/c pre-equilibrium phase ≈ 3 –6 GeV/c, initial hard processes > 6 GeV/c).

It is, however, only a small fraction (of the order of 10%) of the inclusive photon yield that is dominated by hadronic decays (mainly π^0 and η). The photon spectrometer therefore needs sufficient acceptance to measure the cross-section of these mesons in their $\gamma\gamma$ decay channel over the p_t range of interest. Because of the large combinatorial background ($S/B = 10^{-2}$ to 10^{-3}), the statistical error for direct photons will be determined by the accuracy of this background subtraction.

The electromagnetic calorimeter PHOS will detect about 800 γ 's and 500 charged particles in a single central collision, i.e. the cell occupancy is $\approx 3\%$. Based on existing experience from fixed-target heavy-ion experiments, where similar occupancies are reached, the systematic error on the reconstruction efficiency should be $\approx 4\%$.

For 10^7 events, the statistical error on the π^0 cross-section will be $< 1\%$ up to 5 GeV/c, while the error on the η/π^0 ratio will be $\approx 2\%$. At larger p_t , both errors increase and reach 5% at 10 GeV/c. Taking into account the systematic error of 4% in the γ reconstruction efficiency, the overall error on γ/π^0 will be of the order of 5–10% between 1 and 10 GeV/c.

4 CONCLUSIONS

By the end of this century, a new regime of very high energy density but low baryon density will be accessible at the RHIC and LHC. In particular, at the LHC with Pb on Pb at a total centre-of-mass energy of more than 1200 TeV, we expect extreme particle densities (several thousand per unit rapidity), large systems approaching 100,000 fm³, and initial energy densities 50 to 100 times larger than that in normal nuclear matter. By exploring nuclear collisions and the 'macroscopic' properties of QCD, ALICE will be well prepared to add a third dimension to the planned LHC experimental programme, i.e. the high-energy (Higgs, SUSY) and the precision (CP-violation, B-physics) frontiers.

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