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Referee's report of the doctoral dissertation entitled:
"Feasibility studies for open charm measurements with NA61/SHINE experiment at CERN-SPS"
written by Yasir Ali, a student at the international doctoral studies at the Jagiellonian University in Kraków.

The doctoral dissertation presents a feasiblity study related to the possibility of a measurement of D^0 mesons in the pion-kaon final state. The studies are related to heavy ion collisions and are closly associated with the NA61/SHINE experiment at CERN. The author presents his Monte Carlo simulations using program AMPT (A MultiPhase Transport model). GEANT4 program is used to implement details of the experiment. The author discusses a usefulness of a new detector for precise determination of the decay vertex. He concludes that such a measurement at low energies $\sqrt{s}_{NN} \approx 17.3$ GeV (and even lower) is possible when using the NA61/SHINE set-up supplemented by the new vertex detector. Some optimalization based on the CMOS technology ss proposed. Counting rates also are presented.

The dissertation consists of seven chapters. In Chapter I a concise introduction into quark-gluon plasma is presented with emphasize on "low" energy experiments. In Chapter II a motivation of the project related to the production of heavy quarks/antiquarks (mesons) in the "low" energy region is presented. Basic informations about the NA61/SHINE experiment are given in Chapter III. Monte Carlo simulation procedure is described in more detail in Chapter IV while some technical details related to the vertex detector are collected in Chapter V. Final results of the simulation procedure are presented in Chapter VI. Summary and Conclusions close the dissertation. In addition an appendix is devoted to an explanation of radiation damages of silicon detectors which is potentially important issue for the discussed experiment.

Now I shall overiew all the chapters one-by-one and try to make crucial remarks, sometimes critical.

Chapter I discusses physics related to phase transition from quark-gluon plasma to hadronic matter. The author does not go into deeper details but rather presents the commonly accepted physical picture. In addition a short review of previous experimental studies related to AGS, SPS, RHIC and the LHC is given. In this chapter the references to the literature are a bit random and incomplete.

In Chapter II a physics motivation for the program of charm production at the relatively low energies is presented. The autor discusses both hidden (J/ψ) and open (D mesons) production. First he concentrates on the J/ψ meson production and shows corresponding results relevant for the considered range of energy. He notices that statistical models are not able to describe production of charm. In this case the mechanism is clearly different.

Furthermore he shows the cross sections for for production of different mesons for central Au + Au collisions as a function of beam energy (fixed target mode). He presents some predictions (lines) for D meson production obtained on the basis of Hadronic String Dynamics and some experimental data points for light mesons (pions, kaons, η and ϕ) from AGS. The open charm mesons were not measured, to my knowledge, at the low energies. This is because the corresponding production cross section is rather low which implies problems with statistics and background subtraction. Therefore the feasibility study presented in this dissertation is well motivated. The author presented some predictions within a certain model. In my opinion it is not clear, at present, how good such predictions could be as the dynamics of charmed meson production at these low energies is not understood. Finally he discusses production of muons by the NA60, NA38/NA50, STAR and PHENIX collaborations and shows some intriguing results which were used to motivate the study. Very interesting is the PHENIX result for nuclear modification factor for J/ψ and nonphotonic electrons showing large difference.

Chapter III is devoted to a short description of the NA61/SHINE experiment. The NA61/SHINE experiment continues physics study of the NA49 experiment. The main goal is to perform an energy scan for various combinations of the projectile and target and to pin down the phase transition. It is located at the SPS of CERN. First the accelerator complex located at

CERN is shown with a focus on SPS. Then the general experimental set up is discussed. The position of a future vertex detector is shown relative to the existing apparatus.

A special section is devoted to Time Projection Chambers (TPC) used for charged particle tracking. Each of three types of TPC's are discussed separately. Another section discusses the role of BPD-TPC and its alignment. Several distributions in the impact parameters of tracks in x and y directions are shown. Different track topologies are discussed. In my opinion this issue is not sufficiently well explained in the dissertation. The histograms for Be+Be scattering shown in different figures are fitted with the so-called Q-Gaussians. It is not well explained how this is used in further analysis. The Time of Flight (TOF) detectors system is used for particle identification, supplementing the energy loss (dE/dx) method. The TOF method allows good particle separation for low momenta. The whole system consists of 64 scintillator bars with photomultipliers.

Finally a forward hadron calorimeter is discussed shortly. Its purpose is to measure the energy of projectile spectators and provide therefore information on the centrality of the collision on the event-by-event basis. Those detectors can be also used to determine the reaction plane event-by-event.

Monte Carlo simulations are discussed in Chapter IV. First the author discusses different decay channels of some D mesons. The decay channel into charged pions and kaons is considered only in the simulation, probably due to its simplicity. The whole simulation was done for $Pb+Pb$ collisions at two different beam energies: 158 A GeV and 40 A GeV and for $Ar+Ar$ collisions at 158 A GeV.The AMPT (A Multi-Phase Transport Model) event generator was used. For example 200 k sample with centrality 0-10% was generated for the $Pb+Pb$ collisions. The same model is used to generate the pion-kaon background. At the considered beam energy the model predicts a rather low average multiplicity of 0.01 for $D^0 + \bar{D}^-$ for the central collisions. This multiplicity is smaller than a number obtained from the PYTHIA with scalling by binary collisions which is 0.21. For comparison the HSD (Hadron String Dynamics) model predicts 0.2. Since the latter model was tuned to describe production of charm in $p+A$ and $\pi+A$ data at similar energies the author rescaled (increased in this case) the results obtained by the AMPT model. This does not need to be the best choice as the $p+A$ and $A+A$ may have slightly different dynamics and some damping of the nuclear modification factor for D^0 mesons may be expected. This was observed, for instance, recently at the LHC. Then the question remains what is done with the background. Two examples of transverse mass spectra obtained from the simulation are shown with extra curve fitted to the pseudo-data by a simple exponential function with effective temperature. In addition an example of pion and kaon trajectories from the GEANT simulation is shown.

Next some details of simulations with the AMPT code are given. The initial conditions are taken from the HIJING model and include the momentum and spatial distributions of minijets (partons). The parton interaction is taken according to Zhang's Parton Cascade model. Hadronisation is done by Lund String Fragmentation model. The scattering between hadrons is done within a relativistic transport model. Some examples of rapidity spectra of pions, kaons and so-called net protons are shown and compared with the NA49 experimental data. One can see some underpredictions for both pions and kaons which suggests that the model estimated background could be underpredicted. This point was not discussed in the presented dissertation. I will return to this point in the following.

Next some details of the future vertex detector are described. Actually the vertex detector consists of four parts located at 5, 10, 15 and 20 cm, respectively, downstream of the target. A specific geometry of the system is presented. Then each station is described in more detail, with emphasis on its composition. A clear figure supplements this presentation.

A realistic sample of minimum bias $Pb + Pb$ collisions was used to estimate the radiation load. The number of tracks of tracks per mm^2 and per event for the central collisions are given. Similar estimate for delta-electrons is presented. The most critical is the first station of the vertex detector. The hit occupancy is illustrated in Figs.4.6 and 4.7. It is a pity that different color coding is used for minimal bias and central collisions which does not allow a comparison.

Next a geometrical size of the vertex detector is discussed. Hit distribution of the signal tracks is shown in Fig.4.8 for the first station. The author discusses that more than 99% of the signal is contained within 2 x 4 cm^2 box.

Next it is discussed how a radiation during the data taking period can deteriorate the sensor performance. Particles produced in hadronic collisions as well as delta electrons are discussed in this context based on anticipated beam intensity and the interaction rate of particles fluxes through the vertex detector. The author concludes that the Minimum Ionazing MOS active pixel sensor can sustained the estimated radiation.

The rest of this chapter is devoted to tracking. Both, the four stations of the vertex detector as well as Vertex Time Projection Chambers (VTPC) are used for the tracking. The estimated position resulution is expected to be about 4 μm. The so-called Hough Transform is a technical tool for realistic tracking. This method was used in the past to identify lines and arcs in photographs from cloud chambers. The idea of the method is shortly presented. There are 4 hits for single track (four stations). As an example a map of hits is shown for one event of the Ar+Ar collisions in the so-called HT space (slope parameters). I would be happy to hear a more pedagogical description of the HT space. The tracks are extracted from so-called clusters by fitting each possible combination of hits in different stations using a weighted linear regression.

There is a special section discussing matching of tracks from the vertex detector and VTPC. This is necesary to obtain information about track momentum and particle identification. The matching procedure is illustrated in Fig.4.13 but its real understanding is not easy. Some distributions in so-called deviations in x, y and deviations in x-slope and y-slope are shown for additional illustration. Sharp peaks at 0 on the top of a combinatorial background correspond to right matching. Application of a cut on each parameter considerably reduces the background. It was found that the widths of the matching peaks depend on the track momenta. The effect is due to multiple scattering. Some auxiliary variable Δ is introduced which represents a combined deviation from a perfect matching, an axample is illustrated in Fig.4.16.

Next track efficiency, defined as ratio of reconstructed trucks to the number of Geant tracks, is discussed in section 4.3.4 and illustrated in Fig. 4.17 and 4.18. Depending on χ^2 cut the obtained efficiency is well above 90 %. Fig. 4.19 looks interesting but it is not well described in the text, the lines are not explained.

The present resolution of the D^0 decay vertex is not sufficient for its reconstruction and the new vertex detector is required. The invariant pion-kaon distribution shown in Fig.4.20 illustrates the situation for central Pb+Pb collisions at 158 A GeV. The background is higher by several orders of magnitude. compared to D^0 and $\bar{D}^0$ signal. It is discussed how the background of combinatorial nature (its origin could be explained in more detail) could be reduced. Four criteria are given. The discussed new detector should provide that some of the required conditions could be fulfilled. It was found that the rejection of low transverse momentum tracks may be very helpful in reduction of the background. Fig. 4.22 shows both signal and background in different somewhat technical variables. In each variable the background is much higher than the signal. A detailed discussion how to reduce the background is given. The cuts imposed were optimized to maximize the signal-to-noise ratio. The optimal cuts are marked at each subfigure of Fig.4.22. The optimal conditions were given explicitly. Fig.4.23 shows how the optimal cut in each of the variable reduces the distribution in invariant kaon-pion mass. The conditions are included one by one. Only inclusion of all cuts causes that the signal of D^0 or $\bar{D}^0$ shows up.

The so-called MIMOSA-26 sensor was chosen as the basic detection element for the discussed vertex detector. A schematic view of the MIMOSA-26 chip architecture is shown. The sensor is composed of 576 x 1152 pixels. The thickness of the epitaxial layer is 14 μm. The readout details are described. Many good features of the MIMOSA-26 system are collected. Finally Table 4.2 compares the MIMOSA-26 technology with other technologies used so far. Finally the author concludes that the MIMOSA-26 can be used by the NA61/SHINE detector as it fulfills the experimental requirement.

Chapter V presents studies related to the vertex detector. In section 5.1 general rules of detection with silicon detectors are discussed. Pixel detector technologies are discussed in section 5.2. Hybrid and charge coupled device technologies are mentioned and some comparison presented. The analysis suggests a preference for hybrid technology. In this case the pixels have typically 50 μm x50 μm. Time resolution is of the order of 20 μs. The hybrid technology has important preference as far as radiation tolerance is considered.

Section 5.3 describes Monolithic Active Pixel Sensors MAPS). Such sensors allow to integrate the read out electronics and detector element. This technology provides a good compromise between rate and sensitivity. A typical spatial resolution is of the order of 3.5 μm. The technology allow for small thicknesses, even below 0.05 % X_0. The tolerance of a non-ionizing radiation dose is 10^{14} n_{eq}/cm^2. A schematic view of MAPS is shown in Fig.5.1. A speed up of read out can be achieved by subdividing the matrix of pixels and performing the readout by several parallel output channels.

A report of development status of the MAPS sensors is presented shortly in section 5.4. The readout time is 115.2 μs. The sensors can be thinned to 50 μm thickness, which means that the sensor is only a small fraction of the total material budget.

A model of detector response is discussed. The model consists of Digitizer and Hit-Finder. The digitizer simulates the signal chargc and docs not react to neutrons and gammas. It defines the trajectory of the particle. The digitizer used in the presented dissertation is so called Lorentz digitizer which provides a good description of the diffusion process. Next a cluster simulation and reconstruction is discussed. A charged particle generates an amount of charge which diffuses until it is collected by diodes, forming a cluster of firing pixels. First the clusters are identifies and next a reconstruction of the impact point is performed. To include the diffusion a bigger number of pixels has to be taken into account. Finally a few examples of distribution of the difference between reconstructed hit and the "true" GEANT hit is shwon in Figs.5.3 and 5.4 for x and y positions, respectively. The reconstruction resolution is about 2 μm

Chapter VI presents the expected kaon-pion invariant mass distributions after the full background reduction as discussed before. Both the result with full particle identification and that with no particle identification are shown in the spectra normalized to unity. The author considers $Pb + Pb$ collisions at two different energies and $Ar + Ar$ collisions at one selected energy.

Clearly the combined D^0 and $\bar{D}^0$ signal shows up above the continum, especially when the particle identification is assumed. For $Pb + Pb$ collisions the simulation result was estimated to correspond to expected experimental results collected in 1-2 months of data collecting. The signal-to-background ratio is 17 (particle identification) and 1 (no particle identification) for the 158 A GeV energy. Similar results are shown at lower 40 A GeV beam energy. In this case the signal-to-background ratio is 11.3 (particle identification) and 2.1 (no particle identification). For $Ar + Ar$ collisions at 158 A GeV the signal-to-background ratio is 6.7 (particle identification) and 3,2 (no particle identification). Figs.6.1-6.3 well illustrate the situation. Table 6.1 collects some global numbers obtained from the author's simulations.

The last Chapter VII summarizes the findings obtained during preparation of the considered dissertation.

An appendix is devoted to radiaton damages of silicon detectors. Mechanisms of the radiation damages are named and shortly discussed. Both ionizing and non-ionazing radiation effects are discussed separately. I had difficulties to understand Eq.(A.1). A figure of so-called displacememt damage function $D(E)$ is shown but not discussed in detail. It is not explained in the appendix what what actually is the displacement damage function, which makes difficult understanding of the figure.

The candidate is a coauthor of a few publications on the subject in refereed journals. Most of them are conference proceedings. He took part in a few conferences. It is not clear to me whether he presented there any talk (I have no clear data). He has some experience in experimental research, software and as a lecturer.

In summary, the dissertation is a well defined project which finishes with conclusions, i.e. definite solutions are presented. This solution seems very useful for future research of the NA61/SHINE experiment and has a practical value. The dissertation is well written. An exception is often used "*on* the order of ..." instead of "*of* the order of ...". In my opinion the dissertation fulfills the standard requirements and the candidate can continue the PhD procedure, i.e. can take part in public defense. I expect that he will answer some of my questions.

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