Electromagnetic fields in heavy ion collisions at MPD-NICA energies

Winter MexNICA meeting 2020

Alejandro Guirado García

Universidad de Sonora
Departamento de investigación en Física

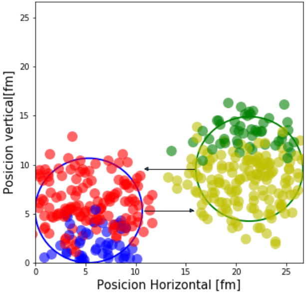
December 16, 2020

Content:

1. Introduction
2. Event generator: UrQMD
3. Electromagnetic fields in heavy ion collisions
4. Hadron flow at NICA energies

Introduction: Heavy-Ion collisions

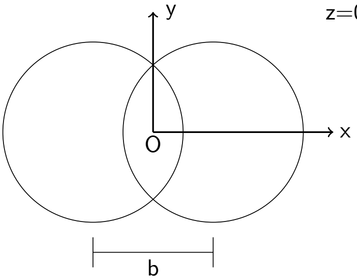
The study of nuclei collisions at relativistic speeds allows us to explore at matter under extreme conditions, that is, studying deconfined nuclear matter (quarks and gluons), forming quark gluon plasma (QGP) for very short periods of time.



Illustrative drawing of a heavy ion collision.

Introduction: Impact parameter

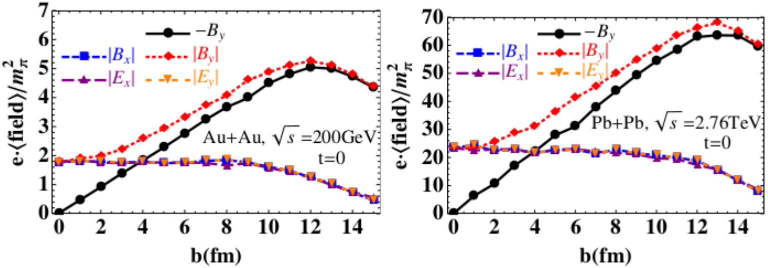
In heavy ion collisions it is possible to determine the centrality of a collision by means of some observables (multiplicity of charged particles, spectator hits in forward detectors, etc.). Geometrically, the centrality can be associated with the distance between the two nuclei to collide.



The separation between the centers of the nuclei is called the impact parameter (b), in UrQMD the impact parameter is always added in the x direction [1].

Introduction: Electromagnetic fields

Electromagnetic fields in heavy ion collisions are very strong at the order of $10^{14}\ T$ for the collision energy range of the experiment RHIC($\sqrt{S_{NN}} = 200\ GeV$) [2] y LHC($\sqrt{S_{NN}} = 2.7\ TeV$) [3].

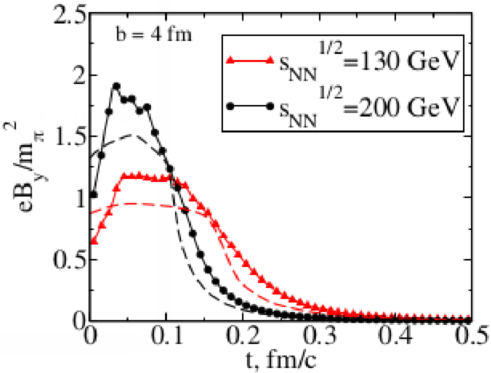


Dependence of electromagnetic fields at $t = 0$ y $\mathbf{R} = 0$ on the impact parameter b and scaled to the square Pion mass [1](m_π^2).

[1]International units system: $m_\pi^2 \approx 10^{14}T$

Introduction: Electromagnetic fields II

The magnetic field time evolution has been previously study at RHIC energy [4].



Magnetic field time evolution in y direction with a fix impact parameter (b) equal to 7 fm in $AuAu$ collisions at different energies [4].

Brief description

The Ultra relativistic Quantum Molecular Dynamic (UrQMD) event generator is widely used in Heavy Ion Collision Physics for RHIC and LHC energies [1]. The stages involved in the collision are:

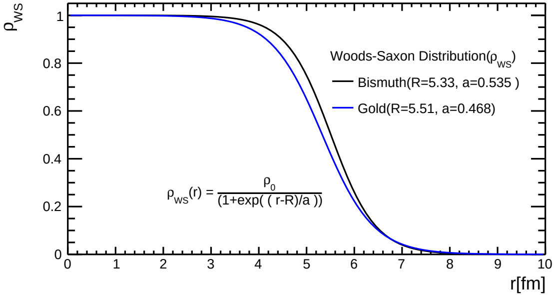
- Initiation: Distribution of nucleons within the nucleus using Glauber's Monte Carlo (MCG).
- Propagation: The propagation of particles can be with potentials or without potentials.
- Collision: The collision process is given using a geometric criteria.

UrQMD: Glauber Monte Carlo

To distribute the nucleons within the nucleus, the Woods-Saxon distribution is used.

$$\rho(r) = \frac{\rho_0}{1 + e^{\frac{r-R}{a}}} \tag{1}$$

Where R is the radius and a is a parameter related to the nucleus thickness.



Woods-Saxon distribution for the Gold and Bismuth nucleus. Parameters obtained from Glauber's Monte Carlo article [5].

UrQMD: Particles propagation

The propagation of particles in UrQMD is calculated with the Hamilton equations, however it can be done in two ways:

$$\dot{\mathbf{r}} = \frac{\partial \mathcal{H}}{\partial \mathbf{p}} \qquad \dot{\mathbf{p}} = -\frac{\partial \mathcal{H}}{\partial \mathbf{r}} \tag{2}$$

The Hamiltonian in each case is:

- Without potentials(eos=0).

$$\mathcal{H} = T \tag{3}$$

- With potentials(eos=1)

$$\mathcal{H} = T + V_{skyrme} + V_{Cb} + V_{Pauli} + V_{Yukawa} \tag{4}$$

Electromagnetic fields of L-W at constant velocity

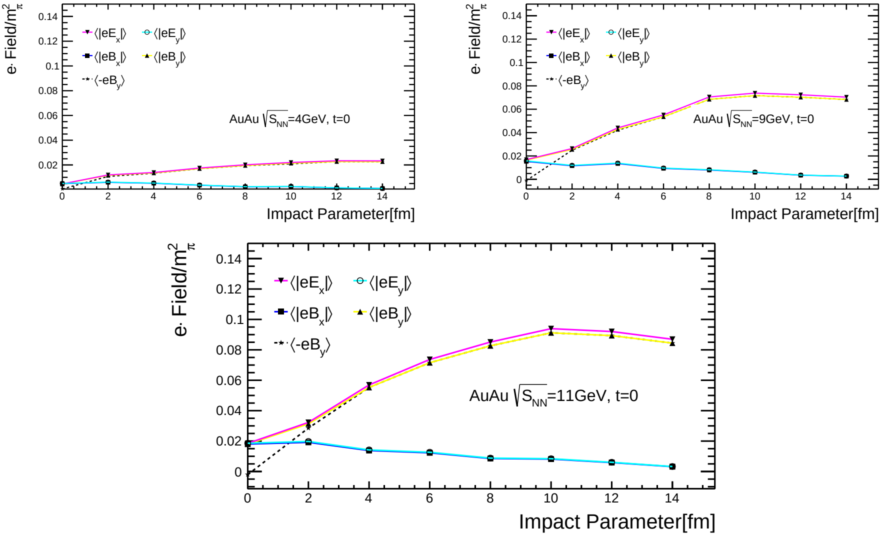
The Lienard-Wiechert equations allow us to calculate electromagnetic fields at any point in space and at any time.

$$e\mathbf{B}(\mathbf{r},t) = \alpha \frac{\mathbf{v}\times\mathbf{R}(1-v^2)}{R^3(1-\frac{(|\mathbf{R}\times\mathbf{v}|)^2}{R^2})^{3/2}} \qquad e\mathbf{E}(\mathbf{r},t) = \alpha \frac{\mathbf{R}(1-v^2)}{R^3(1-\frac{(|\mathbf{R}\times\mathbf{v}|)^2}{R^2})^{3/2}} \tag{5}$$

$$\begin{aligned} \frac{\mathbf{qB}(\mathbf{r},t)}{m_\pi^2} &= \alpha\left(\frac{197}{135}\right)^2 \frac{\mathbf{p}\times\mathbf{R}(E^2-|\mathbf{p}|^2)}{((RE)^2-|\mathbf{R}\times\mathbf{p}|^2)^{3/2}} \\ \frac{\mathbf{qE}(\mathbf{r},t)}{m_\pi^2} &= \alpha\left(\frac{197}{135}\right)^2 \frac{\mathbf{R}(E^2-|\mathbf{p}|^2)}{((RE)^2-|\mathbf{R}\times\mathbf{p}|^2)^{3/2}} \end{aligned} \tag{6}$$

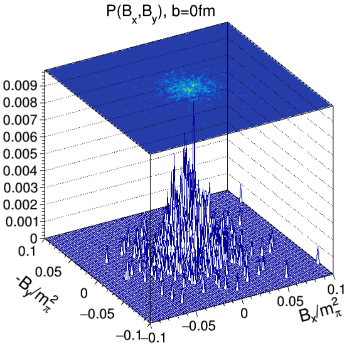
The equations in (6) are used to calculate the EM at NICA energies [6].

[1] The scaling factor (197/135) arises from dividing by the mass of the pion and making the change from fm to eV $(1fm = 197MeV^{-1})$. The fine structure constant is used $(\alpha = 1/137)$.


e· Field/m_π^2
⟨|eE_x|⟩ ⟨|eE_y|⟩
⟨|eB_x|⟩ ⟨|eB_y|⟩
⟨-eB_y⟩
AuAu $\sqrt{S_{NN}}$=4GeV, t=0
AuAu $\sqrt{S_{NN}}$=9GeV, t=0
AuAu $\sqrt{S_{NN}}$=11GeV, t=0
Impact Parameter[fm]

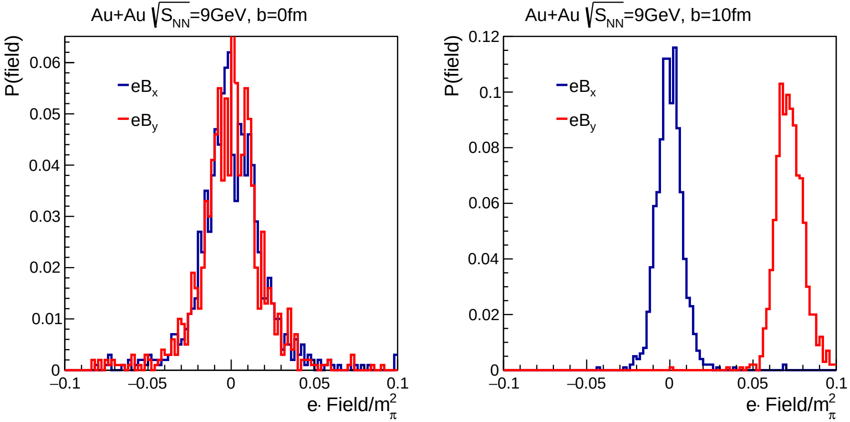
The probability of obtaining the electromagnetic fields is the selection of events in a given number of bins.

$$P(B_x, B_y) = \frac{1}{N}\frac{d^2N}{dB_x dB_y} \tag{7}$$

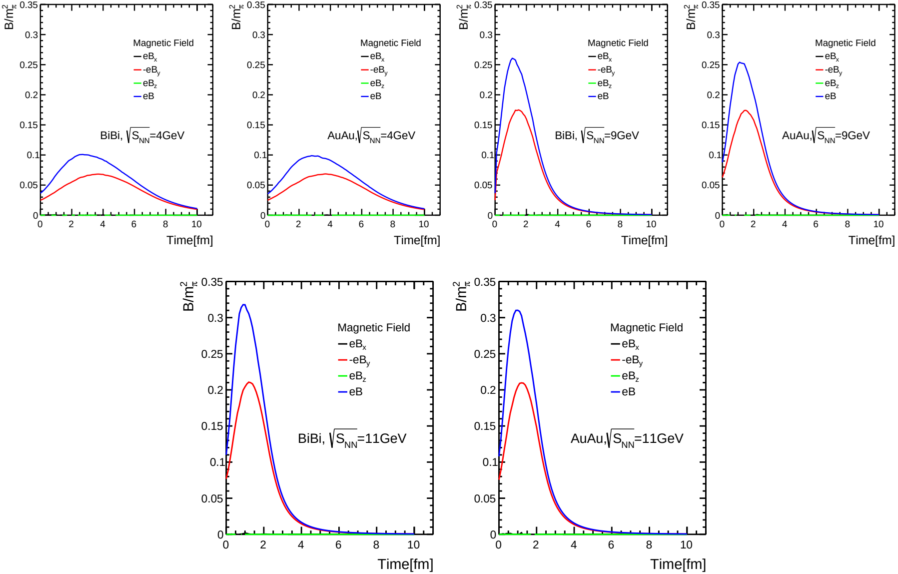


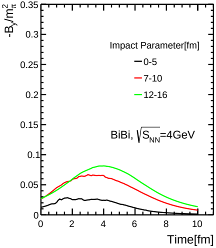
Probability distribution $P(B_x, B_y)$ for collisions from $Au + Au$ to collision energy ($\sqrt{S_{NN}} = 9\ GeV$), at $\mathbf{r} = 0$ and $t = 0$ with b fixed equal to 0 and 10 fm.

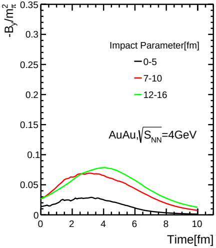
The one-dimensional distribution for the EM fields is:

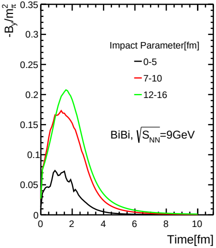


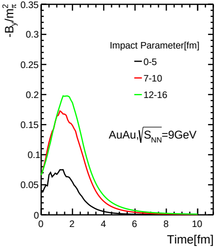
Probability distribution $P(B_x), P(B_y)$ for collisions from $Au + Au$ at collision energy ($\sqrt{S_{NN}} = 9\ GeV$), in $\mathbf{r} = 0$ and $t = 0$ with b fixed equal to 0 and 10 fm.

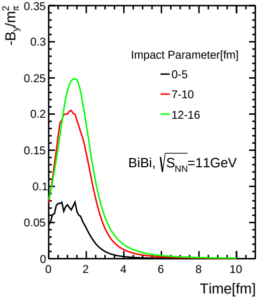

B/m_π^2
Magnetic Field
eB_x
$-eB_y$
eB_z
eB
BiBi, $\sqrt{S_{NN}}$=4GeV
AuAu,$\sqrt{S_{NN}}$=4GeV
BiBi, $\sqrt{S_{NN}}$=9GeV
AuAu,$\sqrt{S_{NN}}$=9GeV
BiBi, $\sqrt{S_{NN}}$=11GeV
AuAu,$\sqrt{S_{NN}}$=11GeV
Time[fm]

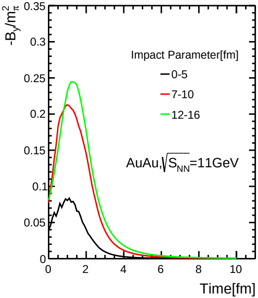

$-B_y/m_\pi^2$
Time[fm]
Impact Parameter[fm]
0-5
7-10
12-16
BiBi, $\sqrt{S_{NN}}$=4GeV

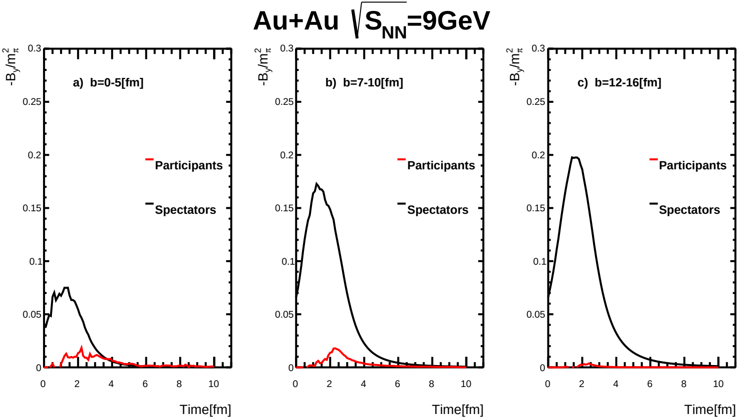

$-B_y/m_\pi^2$
Time[fm]
Impact Parameter[fm]
0-5
7-10
12-16
AuAu,$\sqrt{S_{NN}}$=4GeV


$-B_y/m_\pi^2$
Time[fm]
Impact Parameter[fm]
0-5
7-10
12-16
BiBi, $\sqrt{S_{NN}}$=9GeV

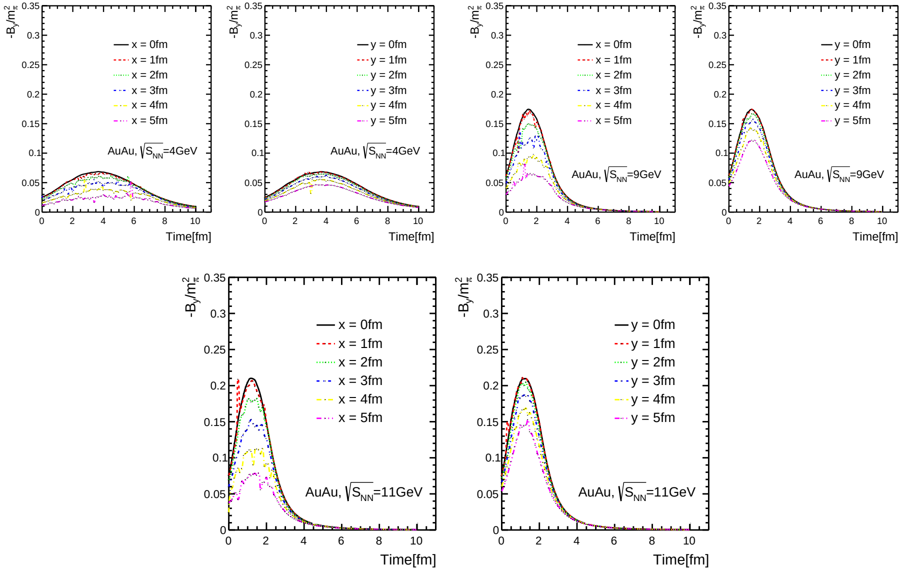

$-B_y/m_\pi^2$
Time[fm]
Impact Parameter[fm]
0-5
7-10
12-16
AuAu,$\sqrt{S_{NN}}$=9GeV


$-B_y/m_\pi^2$
Time[fm]
Impact Parameter[fm]
0-5
7-10
12-16
BiBi, $\sqrt{S_{NN}}$=11GeV


$-B_y/m_\pi^2$
Time[fm]
Impact Parameter[fm]
0-5
7-10
12-16
AuAu,$\sqrt{S_{NN}}$=11GeV



Temporal evolution of electromagnetic fields produced by spectating and participating protons at $\mathbf{r} = 0$ in $Au + Au$ collisions with collision energy of 9 GeV in impact parameter ranges.


-B_y/m_π^2
Time[fm]
x = 0fm
x = 1fm
x = 2fm
x = 3fm
x = 4fm
x = 5fm
y = 0fm
y = 1fm
y = 2fm
y = 3fm
y = 4fm
y = 5fm
AuAu, $\sqrt{S_{NN}}$=4GeV
AuAu, $\sqrt{S_{NN}}$=9GeV
AuAu, $\sqrt{S_{NN}}$=11GeV

Hadron flow analysis

Knowing the event plane angle, it is possible to calculate the coefficients of the angular azimuth distribution [7].

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1 + 2\sum_{n=1}^{\infty} v_n(p_T, y) cos[n(\phi - \Psi_{RP})]\right] \qquad (8)$$

The Fourier coefficients of the azimuthal distribution of particles are defined as:

$$v_n = \langle cos[n(\phi - \Psi_{RP})] \qquad (9)$$

Usually the first two coefficients are called directed flow (v_1) and elliptical flow (v_2). In terms of momentum:

$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle \qquad v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle \qquad (10)$$

The $\langle\rangle$ are not averages, they represent a selection of particles in a range of speed and transverse momentum.

Electromagnetic L-W fields in UrQMD

To simulate electromagnetic fields effect on UrQMD dynamic propagation we added the Lorentz force at the canonical equations (2)

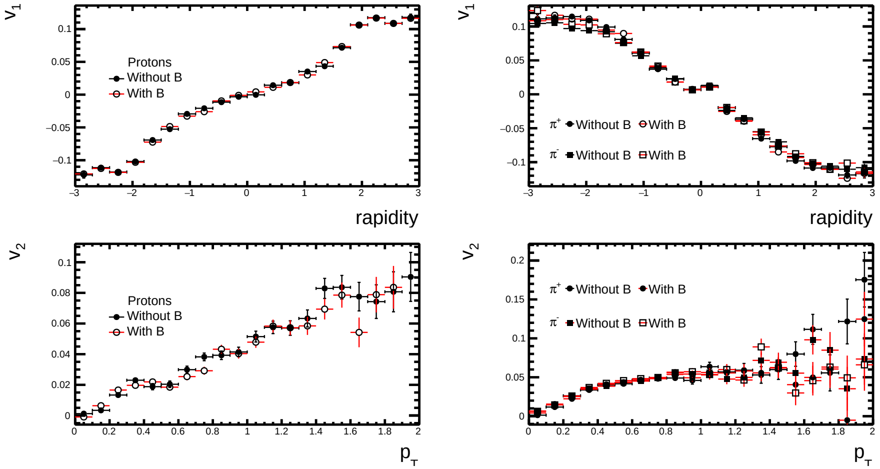
$$\dot{\mathbf{r}} = \frac{\partial \mathcal{H}}{\partial \mathbf{p}} \qquad \dot{\mathbf{p}} = -\frac{\partial \mathcal{H}}{\partial \mathbf{r}} + e\mathbf{E} + \frac{\mathbf{P}}{E} \times \mathbf{B} \tag{11}$$

Where the Hamiltonian is:

$$\mathcal{H} = \sum_j E_j^{kin} \tag{12}$$

However, if it is needed, it is possible to use the other potentials of equation (4).

Magnetic field effects on flows



Direct and indirect flows of charged protons and pions adding the effects of magnetic fields to the dynamics of UrQMD. $Au + Au$ events at collision energy $(\sqrt{S_{NN}} = 11\ GeV)$ and $b = 7\ fm$.

Future work

In order to conclude the electromagnetic field work is needed to:

- Create an automatic script in order to calculate the EM fields in a more efficient manner.
- Test and do better approximations when adding the EM fields in UrQMD dynamics. We need to prove if the native Coulomb model approximation in UrQMD is correctly implemented for NICA energies.
- Improve the comparison from the UrQMD moment fluxes when the propagation is done with and without potentials.

Conclusions

As a conclusion to this work, it can be noted that at NICA energies:

- The electromagnetic fields for $Au + Au$ and $Bi + Bi$ collisions are of the order of 10^{13} T.
- The temporal evolution of the magnetic field in a direction perpendicular to the plane of the reaction is longer and less intense at lower energies.
- The magnetic field is primarily produced by spectators throughout the NICA energy range.
- It was thought that the magnetic field could affect hadron fluxes more at low energies than at RHIC or LHC energies due to the duration of it, but as it had been reported at energies close to NICA energies [8], EM fields do not affect flows significantly.

References I

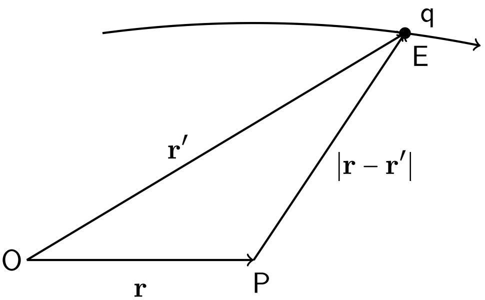
- M. Bleicher , E. Zabrodin, C. Spieles.J.Phys.G25:1859-1896,1999. arXiv:hep-ph/9909407
- A. Bzdak, V. Skokov. Physics Letters B 710 (2012) 171–174
- Y. Zhong, C. Yang, X. Cai, S. Feng.Advance In High Energy Physics, 2014 (2014), 193039. arXiv:1408.5694
- V. Skokov, A. Yu. Illarianov,V. Toneev. Estimate of the magnetic field strength in heavy-ion collisions. arXiv:0907.1396
- C. Loizides, J. Kamin, D. d'Enterria. Improved Monte Carlo Glauber predictions at present and future nuclear colliders.arXiv:1710.07098
- NICA. Nuclotron-based Ion Collider fAcility (NICA). Website: http://nica.jinr.ru/physics.php

References II

Arthur M. Poskanzer Sergei A. Voloshin y Raimond Snellings. Collec-tive phenomena in non-central nuclear collisions. arXiv:0809.2949.

Y. Sun, Y. Wang, Q. Li, F. Wang Physical Review C 99, 064607 (2019)

Retarded time: L-W equations



A charge q moves in space. Points O and P are the origin and observation point, respectively. $|\mathbf{r}-\mathbf{r}'|$ is the distance between the load and the observation point.

Retarded time: L-W

Looking at the previous figure, we can obtain an equation to calculate the retarded time. Since natural units are used in this analysis, the speed of light c is equal to 1.

$$c = \frac{|\mathbf{r} - \mathbf{r}'(t_{ret})|}{t - t_{ret}} \tag{13}$$

$$1 = \frac{|\mathbf{r} - \mathbf{r}'(t_{ret})|}{t - t_{ret}} \tag{14}$$

Computing the delayed time based on the positions and the non-retarded time.

$$t_{ret} = t - |\mathbf{r} - \mathbf{r}'(t_{ret})| \tag{15}$$