FUNDAMENTAL SHORT TIME-SCALE RELATIVISTIC PHYSICS: COLLECTIVE PHENOMENA. PARTICLE ACCELERATION AND PRODUCTION IN FEMTOSECOND LASER-MATTER INTERACTION

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Outlook

• Relativistically invariant self-similarity approach in nuclear physics.
• Similarity of extreme states of nuclear matter and ultrashort laser-matter interaction.
• Correlation between geometric characteristics in Lobachevsky space and measurable parameters.
Schematic diagram illustrating the role of symmetry in fundamental physics.

Chen Ning Yang
“Symmetry and Physics”, 1988
Self-similarity is a special symmetry of solutions which consists in that the change in scales of independent variables can be compensated by the self-similarity transformation of other dynamical variables. This results in a reduction of the number of the variables which any physical law depends upon.
This is the way in which the self-similarity laws following from dimensionality considerations in the region $P^2 \gg M^2$ are extensively applied.

$$x = -\frac{q^2}{2P_2q}$$
\[ P_1 + xP_2 = P'_1 + \sum P'_i \]

\[ \left( P_1 + xP_2 - P'_1 \right)^2 = \left( \sum P'_i \right)^2 \]

\[ P_1 - P'_1 = q \]

\[ (q + xP_2)^2 = \left( \sum P'_i \right)^2 \]

\[ q^2 + 2xP_2q + x^2P_2^2 = M^2 \]

\[ x = -\frac{q^2}{2P_2q} \]

\[ 2\sum_{k>1}(\gamma_{kl} - 1)M_kM_l \]
The relationship between $X_1$ and $X_2$ is described by the conservation laws written in the form:

$$\left( X_1 M_1 u_1 + X_2 M_2 u_2 - M_3 u_3 \right)^2 = \left( M_n X_1 u'_1 + M_n X_2 u'_2 + \sum_{k=4} M_k u_k \right)^2$$

Essentially, we are using the correlation depletion principle in the relative four-velocity space which enables us to neglect the relative motion of not detected particles, namely the quantity

$$2 \sum_{k>l} (\gamma_{kl} - 1) M_k M_l$$
In the case of production of antiparticle with mass $M_3$, the mass $M_4$ is equal to $M_3$ as a consequence of conservation of quantum numbers. In studying the production of protons and nuclear fragments $M_4 = -M_3$ as far as the minimum value of $\Pi$ corresponds to the case that no other additional particles are produced. The values $X_1$ and $X_2$ obtained from the minimum $\Pi$ are used to construct a universal description of the $A$-dependencies.

\[
S = \left(P_1 + P_2\right)^2
\]

\[
\Pi = \frac{1}{2} \left(X_1^2 + X_2^2 + 2X_1X_2\gamma_{12}\right)^{1/2}
\]

\[
E \frac{d^3\sigma}{d^3p} = C_1 A_1^\alpha \left(X_1\right) A_2^\alpha \left(X_2\right) f\left(\Pi\right)
\]
Cumulative processes


Twice cumulative

Inclusive pion spectra
(various experiment types)

\[ \frac{\sigma_{inv}}{A_1 A_2} \]

\[ \pi^- \]

- $^{12}\text{C} + ^{181}\text{Ta}$ 3.65 GeV/n
  - $10^0, 35^0, 45^0, 60^0, 100^0, 120^0$

- $^{20}\text{Ne} + ^{64}\text{Cu}, ^{119}\text{Sn}, ^{209}\text{Bi}$ 1.5-1.9 GeV/n

- $^{58}\text{Ni} + ^{58}\text{Ni}$ 1.7-1.9 GeV/n 0°
Inclusive pion spectra in selected high-multiplicity events

Antimatter production

\[ \sigma_{\text{inv}} A_1^{-\frac{1}{2}} A_2^{-\frac{1}{2}} [\text{mb GeV}^{-2} \text{c}^{-3} \text{sr}^{-1}] \]

\[ p(240 \text{ GeV}) + \text{Be} \rightarrow h + \ldots (0^\circ) \]
$^{24}\text{Mg} + ^{24}\text{Mg} \rightarrow \pi^-$

$<N_{\pi}> = 8.24$

$10^{-4}\sigma_{\text{inv}}$

Fundamental short time-scale relativistic physics: new collective phenomena

Laser powers $>10^{19}$-$10^{20}$ W/cm$^2$;
Times $<100$ fs;
Electron densities $>10^{20}$ cm$^{-1}$;

High efficiency ($\sim$20%)
Quasi-monochromatic electron spectrum
Low emittance
Very short acceleration distance (100µm – 1mm)

\[ E' + xP_1 = xP'_1 + P_3 + P_4 \]

\[
x = \frac{E_{\gamma}(E_3 - P_3 \cos \alpha_3)}{M_1(E_{\gamma} - E_3 - M_4)}
\]

\[
\sigma_{inv} = C_1 \exp\left(-\frac{X}{C_2}\right) \quad \sigma_{inv} = C_1 \exp\left(-\frac{\Pi}{C_2}\right)
\]
Relativistic pair production: three steps

• Generation of MeV electrons in subcritical laser plasma

\[ 10^{18} \text{ W/cm}^2; \quad n_e = n_c \exp(-x/\Delta); \quad n_c = 10^{21} \text{ cm}^{-3}; \quad \Delta = 30 \text{ mkm} \]

\[ \frac{dN_e}{dE} \approx 3 \cdot 10^{10} \cdot E \cdot \exp(-1.2 \cdot E) \]

• Bremsstrahlung conversion of MeV electron energy into MeV photons in a high-Z solid target

\[ 8 \cdot 10^7 \text{ photons with the energy higher than 1 MeV} \]

• \(e^+e^-\) pair production (photonuclear reactions)
$e^+e^- \rightarrow e^+ + 3e^-$

10 MeV $e^- + e^- \rightarrow e^+ + 3e^-$


FIG. 1. Measured energy distribution of the primary electrons (closed-circles, exponential fit as dashed line) used to produce positrons (expected spectrum as solid line). The line-shaded stripe gives the energy range covered by the detector. It encompasses $\sim5\%$ of the total number of positrons.
\[
\sigma_{inv} = C_1 \exp \left( - \frac{\Pi}{C_2} \right)
\]
Protons accelerated by 1 MeV "photons"

Protons accelerated by 10 MeV "photons"
Self-similar solution connects the initial and final states.

**Initial state:**
- intensity (energy);
- frequency; phase;
- duration;
- geometric dimensions of acting volume;
- target density, $Z$, $A$, temperature

*Prepulse (dynamic target preparation).*

**Final state:**
- fraction of four-momentum transferred;
- angular, energy spectra of registered radiations;
- time characteristics of final state.

The goal of the self-similarity approach is to reduce the number of variables = find a symmetry in the phenomenon of transition from initial to final state.
Lobachevsky Space

Longitudinal rapidity
\[ y = \frac{1}{2} \ln \frac{E + p_\parallel}{E - p_\parallel} \]

Transverse mass
\[ m_T = \sqrt{m^2 + p_T^2} \]

Transverse rapidity
\[ \text{ch} \ h = \frac{m_T}{m} \]

Angle of Parallelism
\[ \Pi_L(h) = 2 \cdot \text{arctg} \left( e^{-h} \right) \]

Defect
\[ \text{defect} = \pi - \alpha_1 - \alpha_2 - \alpha_3 \]

Perimeter
\[ \text{perimeter} = \rho_1 + \rho_2 + \rho_3 \]
Proton distribution for two angular intervals in $p(10\text{GeV/c})+C$

Normalized distributions of defects of triangles formed by all combinations of protons and all combinations of mesons registered in $p(10\text{GeV/c})+C$.

Note, that the model adequately reproduces inclusive spectra of both protons and $\pi$-mesons. The distribution of trios of $\pi$-mesons, however, differs noticeably from experimental data.
\[ \text{defect} = \pi - \alpha_1 - \alpha_2 - \alpha_3 \]
\[ \text{perimeter} = \rho_1 + \rho_2 + \rho_3 \]
It is important to underline that, unlike the Euclidean space, the area-to-perimeter ratio for triangles in the Lobachevski space is limited.
Analysis of Lobachevsky geometry

Regular polyhedrons with n=3, 4, 5, 10, 100, and 1000 inscribed in a circle with an increasing radius
\[ tg \frac{\Pi_L(h)}{2} = e^{-h} \]

\[ \Pi_L(h) = 2 \cdot \arctg(e^{-h}) \]

\[ \Delta_{12}^3 = 2\Pi_L(h_3) - \alpha_3 \]
$\Pi_L(\rho_{12}) = 0.0945$

The diagram shows a plot with two datasets:
- Blue dots: $p(10\text{GeV}/c)+C \rightarrow \pi$
- Red dots: $p(10\text{GeV}/c)+C \rightarrow p$

The diagram also includes a triangular geometry with angles $\alpha_1$, $\alpha_2$, and $\alpha_3$.
pC (10 GeV)

Protons, 3 GeV/c

Protons, 16.5°

Pions, 500 MeV/c

Pions, 16.5°
\[ n+p \rightarrow \pi^- \]

\[ L(h3) - \alpha_1 \]

5 GeV/c, 3 GeV/c, 2 GeV/c, 1 GeV/c, 1.4 MeV/c
Directed Nuclear Radiation

\[
\cos \alpha_2 = \sqrt{\frac{1 + \text{th}(\rho_1)}{2}} - \text{sh}(h_3) \sqrt{\frac{1 - \text{th}(\rho_1)}{2}}
\]
Directed Nuclear Radiation
\( P + C \rightarrow \text{pions at 10GeV} \)
\[ f(h) = 2 \left( \Pi_L(h) - \arctg \frac{\tan \frac{\rho_1}{2}}{\sh(h)} \right) = 2 \arctg \left( \frac{1 - \tan \frac{\rho_1}{2}}{\sh^2(h) + \tan \frac{\rho_1}{2}} \right) \]
Lobachevsky Space

\[ n+p \rightarrow \pi^- \quad 5\text{GeV} \]

\[ \text{defect} = \pi - \alpha_1 - \alpha_2 - \alpha_3 \]
Common features of relativistic nuclear physics and ultrashort laser-matter interaction:

- Extreme states of matter;
- Relativism;
- Collective phenomena;
- Multiparticle interactions.
The XX International Seminar on High Energy Physics Problems "Relativistic Nuclear Physics and Quantum Chromodynamics", organized by the Joint Institute for Nuclear Research will be held October 4-9, 2010 in Dubna, Russia.

Important Deadlines

- Abstracts submission before **August 31, 2010**. Abstracts should be sent to ishepp@theor.jinr.ru