Ultra-peripheral nuclear collisions. What we can study here

I.F. Ginzburg
Sobolev Institute of Mathematics,
Novosibirsk, 630090 Russia

What are?

Standard definition:

Ultra-peripheral collisions of heavy nuclei (UPC) are interactions that occur at impact parameters b large enough that no hadronic interactions can occur. In simple terms, $b > 2R_A$, where R_A is the nuclear radius. Only electromagnetic interactions are possible, they can be purely electromagnetic ("two–photon") or photo–nuclear (γA) (G. Baur et al., Hot topics in Ultra–peripheral ion collisions. Proc. Workshop on Electromagnetic Probes of Fundamental Physics, (Eriche, Sicily) *World Sc.* (2003) 235–242; hep-ex/0201034).

In terms of observable (in principle) processes

Ultra-peripheral interactions of heavy nuclei $A_1A_2 \to A_1A_2X$ are those in which parental nuclei don't destroyed. The interaction of produced system with parental nuclei can be either in electromagnetic or strong.

In $pp \to p\gamma^* \otimes \gamma^* pX$ the amplitude $\propto e^2 = 4\pi\alpha$ (one factor e in the $p\gamma$ vertex, the second – from the γX). If the energy of γ^* is ω and its transverse momentum $q_\perp$ is small, this amplitude is enhanced by factor $1/q^2$ with

$$q^2 = q_m^2 + q_\perp^2, \qquad q_m^2 = (\omega/\gamma)^2$$

(γ is Lorenz–factor of incident proton) $\Rightarrow$ This cross section can overcome strong cross section of $pp \to ppX$ at $\alpha/q^2 > \max\{1/m_\pi^2, 1/\Lambda^2\}$ where Λ is the scale of form-factor ($\sim m_\rho$ for proton). The total cross section of such em process is suppressed in comparison with strong process as $(\alpha L)^2$ where $L = \log(\Lambda^2/q_m^2)$.

UPC:

The contribution of each exchanged photon is enhanced coherently by factor Z in amplitude or Z^2 in cross section. The strong interacting cross section in the same coherent region is also enhanced by factor $A^{4/3}$ for each nuclei. To prevent nuclear destruction (keep coherence), the momentum transferred by nuclei should be small enough,

$$|q^2| \le \Lambda^2 = 1/R_A^2, \;\; \Lambda \approx 30 \text{ MeV}.$$

$\sigma_{UPC}^{tot} \ll \sigma_{AA} \Rightarrow$ the first problem is signature of UPC.

Signature of UPC

- Kinematical condition: $q^2 < \Lambda^2 \;\Rightarrow$

The exchanged photon energy and transverse momentum are low:

$$\boldsymbol{q_\perp \lesssim \Lambda \approx 30 \div 60 \; MeV} \,,$$

$$|\boldsymbol{p_z}| < \omega < \boldsymbol{\Lambda}\gamma = \begin{cases} \mathbf{3 \div 6} & \text{GeV for RHIC Au-Au,} \\ \mathbf{90 \div 180} & \text{GeV for LHC Pb-Pb.} \end{cases}$$

These limits are practically identical for each mechanism of system X production – electromagnetic and strong.

- Absence of other produced particles and decay products of A, at least large rapidity gaps.
- Quantum numbers of produced system X

Types of UPC

• In double UPC (2-UPC) kinematical condition hold for both nuclei
⇒ can be checked for the produced system.

• In single UPC (1-UPC) kinematical condition holds for only one nuclei and other nuclei can be destroyed, second condition can be realized in weak form (rapidity gap).

1-UPC

The signature is given only by quantum numbers of produced system + rapidity gaps. The processes are diffractive $AA \to A\gamma \otimes \gamma A \to XA$ where X is vector meson. These experiments deal in fact with photoproduction on nuclei in the experiments with high flux of photon

$$dn_\gamma = \frac{Z^2 \alpha}{\pi} \frac{d\omega}{\omega} L, \; L = max\{ \left[\ln\left(\frac{\Lambda^2 \gamma^2}{\omega^2} \right) - 1 \right], 0 \}.$$

Vector bosons cannot be produced in the Pomeron-Pomeron collision in the central region. The spread of vector mesons in $p_\perp$ is given by diffraction laws.

This effect was observed by ALICE at RHIC as the production of ρ mesons in the central region in the events with large rapidity gap.

One can expect new results here for the production ω mesons and J/Ψ mesons. Perhaps, at LHC one can be see also Υ production.

Problem for future study:

The measurement of the phase of $\gamma A \to \rho A$ amplitude to find phase of "nuclear" Pomeron in comparison with "proton Pomeron" which can be studied at HERA.

At nuclear γA collisions, the interaction of separate "elementary" Pomerons joining to physical diffractive amplitude ("soft Pomeron") can be distributed over protons and neutrons, changing overall phase for the forward scattering amplitude as compare γp case $Rightarrow$ The comparative study of these phenomena at protons and nuclei can help in the understanding of soft Pomeron.

(Method – the study of charge asymmetry of pions due to interference of considered "soft Pomeron" production and Primakoff production $AA \to A\gamma A\gamma \otimes \gamma\gamma \to \pi\pi$).

2-UPC. Signature

To see 2-UPC events unambiguously at the collider with mean number of nuclear collisions per bunch crossing $\nu_{col} < 1$, 3 conditions should be checked:

- Total transverse momentum $\lesssim \Lambda$;
- Longitudinal momentum $-\gamma\Lambda < p_z < \gamma\Lambda$;
- Total energy $\lesssim 2\gamma\Lambda$;
- No other particles in detector

This type final state are separable
if all particles of system X are observed.

If some of this conditions is violated, at least one nucleus can be broken and the decay products are directed to beam pipe or avoid detector for some other reason. The same is valid for the events with rapidity gap(s). $\Rightarrow$ Coherence disappears, strong interactions with possible nuclear breaking become dominant.

> The production of e^+e^-, $\mu^+\mu^-$, Ps, $\tau^+\tau^-$ (at LHC), ... without hadrons will be clear signal of 2-UPC with separate interesting physics.

At RHIC $\nu_{col} < 1$, and the UPC are observable with $\sqrt{s} \lesssim 6 \div 12$ GeV.

The clear signal of 2-UPC mechanism with double electromagnetic production would be observation of f_2 with relatively small energy in c.m.s. Note that the double Pomeron exchange in pp collisions give no f_2 peak in the centre of rapidity scale.

I cannot imagine other interesting problems for 2-UPC here.

At LHC $\nu_{col} > 1 \Rightarrow$

Observation of UPC (even only with rapidity gap) looks very difficult. Nevertheless, I discuss this very opportunity.
Here $\sqrt{s} \lesssim 180 \div 360$ GeV.

In New Physics effects total transverse momentum of produced system cannot be fixed with necessary accuracy of about 30-60 MeV – either due to low efficiency of complete observation of ALL decay products or since at least one of final particles cannot be observed – ν, $\tilde{\nu}$,...
$\Rightarrow$ 2-UPC mechanisms for production of new states cannot be separated from nuclear and (often) from other backgrounds.

Example: Higgs boson production

$M_h \approx 120$ GeV, decay studied $h \to b\bar{b}$.

2-UPC electromagnetic process

$\sigma \sim (Z_1\alpha)^2(Z_2\alpha)^2 L^2 \frac{\Gamma_h}{M_h^3}$, $(L \approx 1-2)$

Strong 2-UPC process (with accuracy to factors given by gluon structure functions)

$\sigma \sim (A_1 A_2)^{4/3} \alpha_s(m_p^2)^2 \alpha_s(M_h^2)^2 \frac{\Lambda^2}{\Lambda_{QCD}^2} \frac{\Gamma_h}{M_h^3}$

Strong incoherent process, $k_\perp$ unlimited

$\sigma \sim (A_1 A_2)^{2/3} \alpha_s(m_p^2)^2 \alpha_s(M_h^2)^2 \frac{\Gamma_h}{M_h^3}$

Background $gg \to b\bar{b}$ for $M_{b\bar{b}} = M_h \pm \Delta M$

$\sigma > (A_1 A_2)^{2/3} \alpha_s(m_p^2)^4 \frac{\Delta M}{M_h^3}$

$\Downarrow$

1) The separation of 2-UPC mechanism for Higgs boson production from other mechanisms looks hardly probable.

2) The $gg \to b\bar{b}$ background makes 2-UPC production of Higgs with $b\bar{b}$ decay unobservable like for gluon fusion at Tevatron.

For the $h \to \gamma\gamma$ channel the 2-UPC cross section is very small for observation while purely electromagnetic background (double bremsstrahlung) is huge.

In 2-UPC collisions at LHC one can study the exclusive $\gamma\gamma \to V_1 V_2$ processes ($V_i -$ vector mesons) in diffractive kinematics up to $\sqrt{s} \approx 200$ GeV.