THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
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Electromagnetic Interactions

in Ultraperipheral Heavy Ion Collisions

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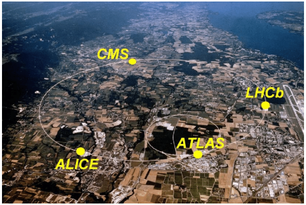
Heavy Ion Collisions

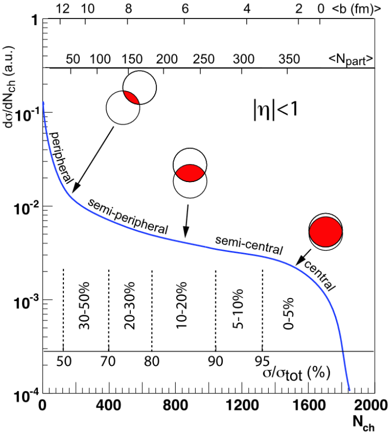
- The first ultrarelativistic heavy ion collisions were conducted in 1986.
- The main goal of the first experiments was to obtain a quark-gluon plasma (QGP). The first observation of this state of matter took place in 2000.
- Heavy-ion experiments are still carried out today because of their characteristics. Strong electromagnetic fields and a specific combination of nuclear and particle physics are among such features.

The Relativistic Heavy Ion Collider at Brookhaven National Laboratory.

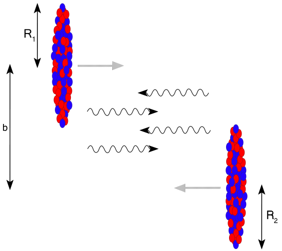


The Large Hadron Collider at The European Organization for Nuclear Research.

Ultraperipheral Heavy Ion Collisions



Dependence of centrality on the number of participants and the impact parameter.



Collision Geometry.

If impact parameter b is larger than $R_1 + R_2$ we talks about ultraperipheral collisions.

Advantages of research conducted on ultraperipheral collisions:

- Clear signal.
- Easy to define final state.
- Scaling of the cross section with the number of protons.

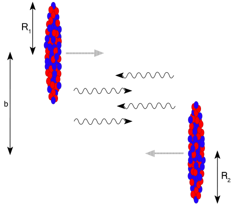
We can calculate the cross section for given process via Equivalent Photon Approximation.

- Nuclear cross section:

$$\sigma_{A_1 A_2 \to A_1 A_2 X_1 X_2} \sim \int \frac{d\sigma_{\gamma\gamma \to X_1 X_2}(W_{\gamma\gamma})}{d\cos\theta} \times N(\omega_1, b_1) N(\omega_2, b_2)$$

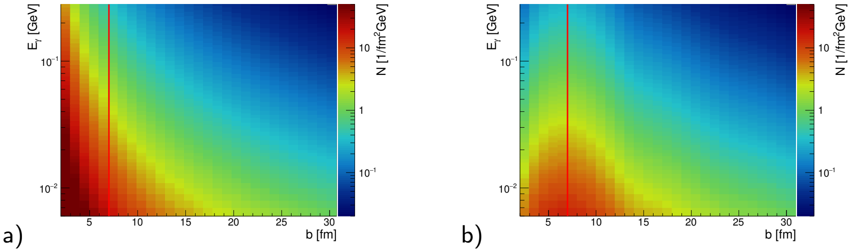
- Photon flux:

$$N(\omega, b) \sim Z^2$$



Collision geometry.

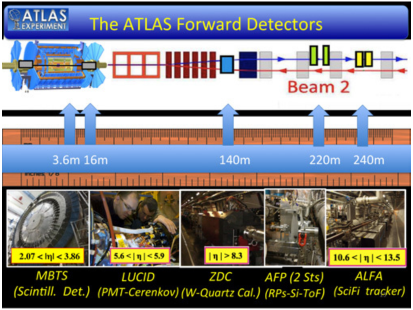
$$N(\omega, b) = \frac{Z^2 \alpha_{em}}{\pi^2 \beta^2} \frac{1}{\omega b^2} \times \left| \int d\chi \, \chi^2 \frac{F\left(\frac{\chi^2 + u^2}{b^2}\right)}{\chi^2 + u^2} J_1(\chi) \right|^2 \qquad u = \frac{\omega b}{\gamma \beta} \qquad \chi = k_\perp b$$



Photon flux dependence on photon energy and impact parameter for: a) point-like model, b) realistic model.

My research subjects

- Main framework: Equivalent Photon Approximation.
  - testing the limits of EPA.
  - developing corrections.
- Study of light-by-light scattering:
  - Analysis of different processes like box continuum, VDM-Regge, meson resonances.
  - Predictions for future experiments.
- Developing codes for nucleus evaporation calculations.



Light-by-Light Scattering

$$\gamma\gamma \rightarrow \gamma\gamma$$

O. Halpern, *Scattering processes produced by electrons in negative energy states.*, Physical Review 44:10 855-85, 1933.

- In the limit of weak e-m fields:

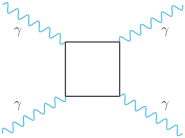
$$\sigma \sim (\frac{e^2}{mc^2})^4(\frac{\hbar}{mc})^2 \cdot \frac{1}{\lambda^2}$$

H. Euler, B. Kockel, *Über die Streuung von Licht an Licht nach der Diracschen Theorie*, 1935*

- For visible light:

$$\sigma \approx 10^{-76}\text{cm}^2 = 10^{-52}\text{b} = 10^{-43}\text{nb}$$

* "The experimental test of the deviation from the Maxwell theory is difficult since the noteworthy effects are extraordinarily small."



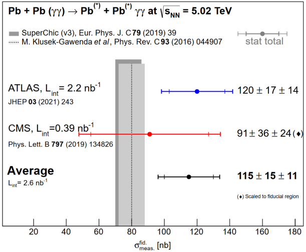
Feynman diagram of the fermionic box.

- W. Heisenberg, H. Euler, *Folgerungen aus der Diracschen Theorie des Positrons*, 1936

Experimental measurements

Year	Experiment	$p^{\gamma}_{t,min}$ [GeV]	$M_{\gamma\gamma,min}$ [GeV]	$\sigma^{exp.}_{tot.}$ [nb]	$\sigma^{theo.}_{tot.}$ [nb]
2017	ATLAS	3	6	70 ± 29	51 ± 5
2018	CMS	2	5	120 ± 55	103 ± 10
2019	ATLAS	2.5	5	120 ± 22	80 ± 8

Total cross section for light-by-light scattering in collisions with energy $\sqrt{s_{NN}} = 5.02$ TeV, in range of photon rapidity $|y| < 2.4$; $p^{\gamma}_{t,min}$ is a minimal measured value of photon transverse momentum of single photon, $M_{\gamma\gamma,min}$ is a diphoton invariant mass.



The average light-by-light scattering cross section value along with the individual cross section measurements at 5.02 TeV by ATLAS and CMS.

Current experiments have a high minimum threshold for transverse momentum of photon and diphoton invariant mass:
$p^{\gamma}_{t} > 2$ GeV
$M_{\gamma\gamma} > 5$ GeV

G. K. Krintiras, I. Grabowska-Bold, M. Kłusek-Gawenda, É. Chapon, R. Chudasama and R. Granier de Cassagnac, *Light-by-light scattering cross-section measurements at LHC.* arXiv:2204.02845, 2022.

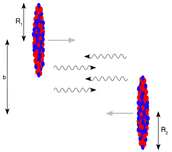
Equivalent Photon Approximation

- Nuclear cross section:

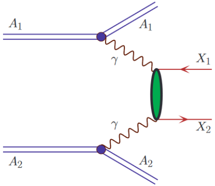
$$\sigma_{A_1 A_2 \to A_1 A_2 X_1 X_2} = \int \frac{d\sigma_{\gamma\gamma\to X_1 X_2}(W_{\gamma\gamma})}{d\cos\theta} \times N(\omega_1, b_1) N(\omega_2, b_2) S^2_{abs}(b)$$
$$\times \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma} dY_{X_1 X_2} d\bar{b}_x d\bar{b}_y d^2 b \times \frac{d\cos\theta}{dy_{X_1} dy_{X_2} dp_t} \times dy_{X_1} dy_{X_2} dp_t$$

- Photon flux:

$$N(\omega, b) \sim Z^4$$

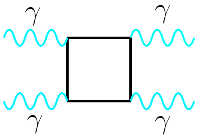


Collision geometry.

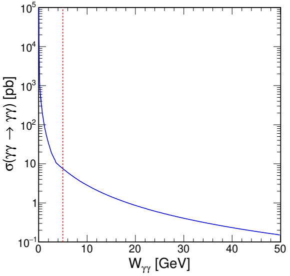


Photon fusion.

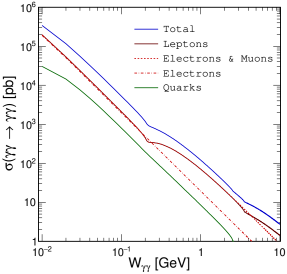
Elementary cross section - box continuum



Main mechanism of light-by-light scattering which is described by creation and annihilation of fermion - anti-ferimion pair.

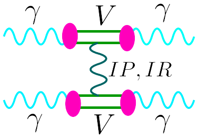


Elementary cross section of the light-by-light scattering box mechanism as distribution of energy.

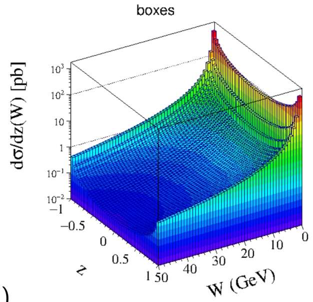


Different box mechanism components.

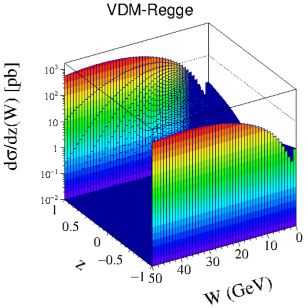
Elementary cross section - VDM-Regge



Vector Meson Dominance model involves oscillations of photons to the light mesons like ρ, ω, ϕ.

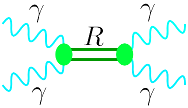


a)

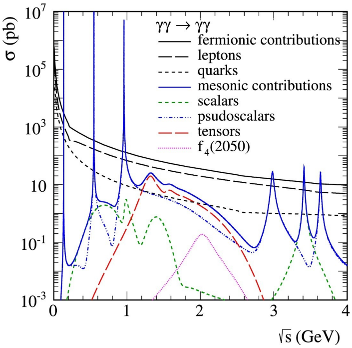


b)

Two-dimensional distribution of elementary cross section in diphoton mass and $z = \cos\theta$ for: a) box contribution, b) VDM-Regge contribution.



Main contribution to the $\gamma\gamma \rightarrow \gamma\gamma$ process from mesonic resonances in the low mass region coming from pseudoscalars: π, η and η'.

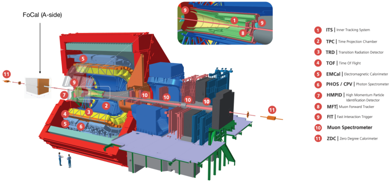


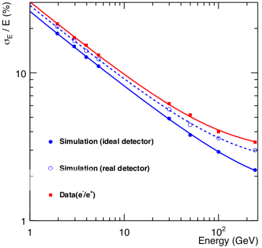
Elementary cross section for different $\gamma\gamma \rightarrow \gamma\gamma$ processes.

Forward Calorimeter (FoCal) ALICE

- Acceptance:
  $3.4 < y_\gamma < 5.8$
  $p_t^\gamma > 200$ MeV
- Position resolution:
  $\sigma_x = \sigma_y = 1$ mm
- Energy resolution:

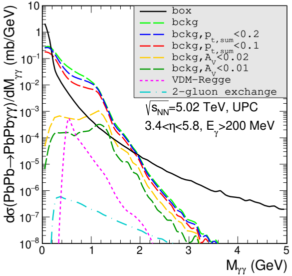
$$\frac{\sigma_E}{E} = \frac{28.5\%}{\sqrt{E(GeV)}} + \frac{6.3\%}{E(GeV)} + 2.95\%$$



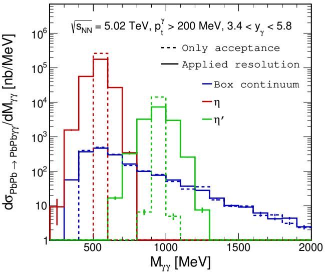


A.P. de Haas et al. (ALICE Collaboration), *The FoCal prototype — an extremely fine-grained electromagnetic calorimeter using CMOS pixel sensors*, JINST 13 P01014, 2018.

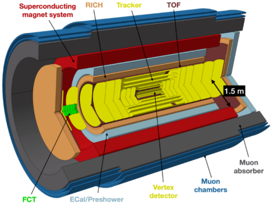
C. Loizides, *The Forward Calorimeter project in ALICE*, EF06 meeting 2020, https://indico.fnal.gov/event/44126/contributions/191953/attachments/132434/162766/20200805_focal_snowmass.pdf



Invariant mass distribution for the nuclear process. Predictions are made for the future FoCal acceptance $E_{t,\gamma} > 200$ MeV and $3.4 < y_\gamma < 5.8$.



Results of combined theoretical results for light-by-light scattering and Monte Carlo simulation of energy and position resolution for diphoton invariant mass for FoCal detector.



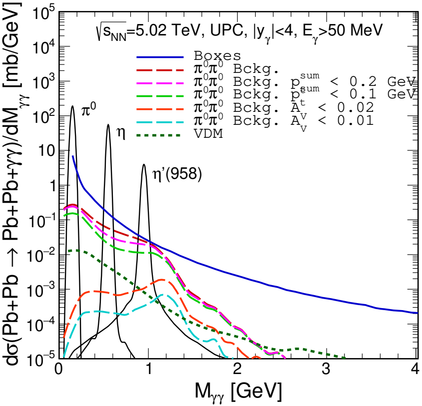
ALICE 3 - a next-generation heavy-ion detector for the LHC Runs 5-6.

$p_{t,min}$[GeV]	$p_{t,max}$ [GeV]	y_{min}	y_{max}
0.001	0.1	3	5
0.2	50	-1.6	4

Assumed kinematic limits in ALICE 3 experiment for photon measurement.

L. Musa, W. Riegler, *Letter of intent for ALICE 3: A next generation heavy-ion experiment at the LHC*, arXiv:2211.02491, 2022.

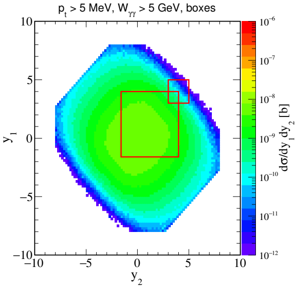
UPC Results for ALICE 3

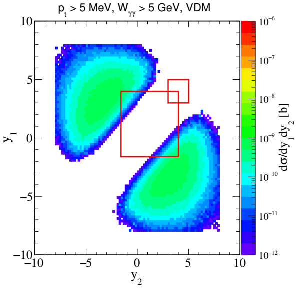


Differential cross section as function of diphoton invariant mass for future ALICE 3 experiment.

UPC Results for ALICE 3

The differential cross-section for the VDM-Regge process in UPC, Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

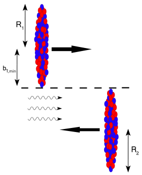


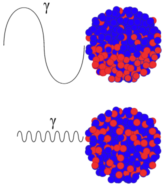


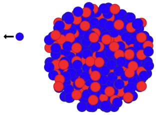
The red frames mark the acceptance range of the ALICE 3 detectors.

Wide rapidity range is key to the experimental observation of VDM.

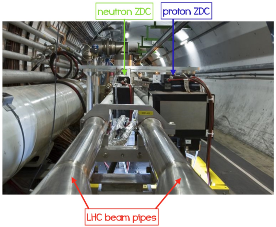
Particle evaporation





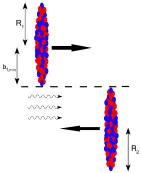


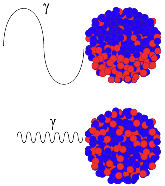
- Photons from ultrarelativistic nucleus are absorbed by the second ion.
- Photoabsorption leads to the de-excitation of the nucleus primarily through photons and neutrons. Emission of charged particles such as protons, deuterons, and α particles is also possible.
- Due to high Lorentz boost, emitted particles are measured in Zero Degree Calorimeters (ZDC).

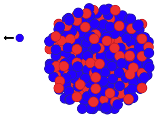


Zero Degree Calorimeters for ALICE experiment.

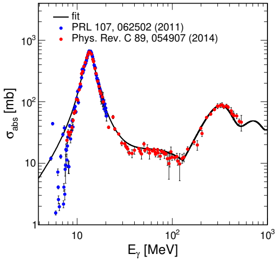
Photoabsorption





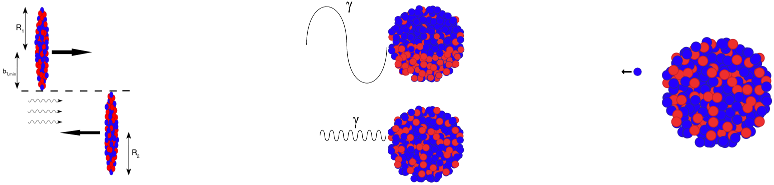


- The interaction of a photon with the nucleus is described by the photoabsorption cross section.
- The dependence of energy on the cross section has been established through experimental measurements.



Photoabsorption cross section for ^{208}Pb. Theoretical models were used to describe data.

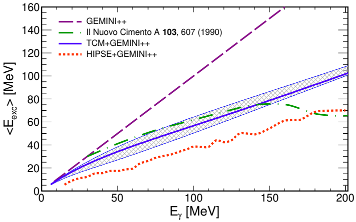
Neutron emission



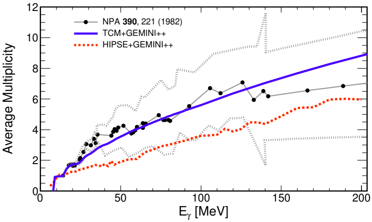
- De-excitation of the nucleus was calculated from different nuclear models:
  - GEMINI++
  - EMPIRE
- The excitation energy depends on the manner of the nucleus excitation. Therefore, the photon energy, and consequently the probabilities of particle emissions, must be adjusted. To investigate this, we tested two models:
  - HIPSE
  - our Two-Component Model (TCM), which is based on the function:

$$P_k(\omega) = e^{-\omega/E_0} \cdot \delta(E^* - \omega) + (1 - e^{-\omega/E_0})\frac{1}{\omega}$$

Neutron emission

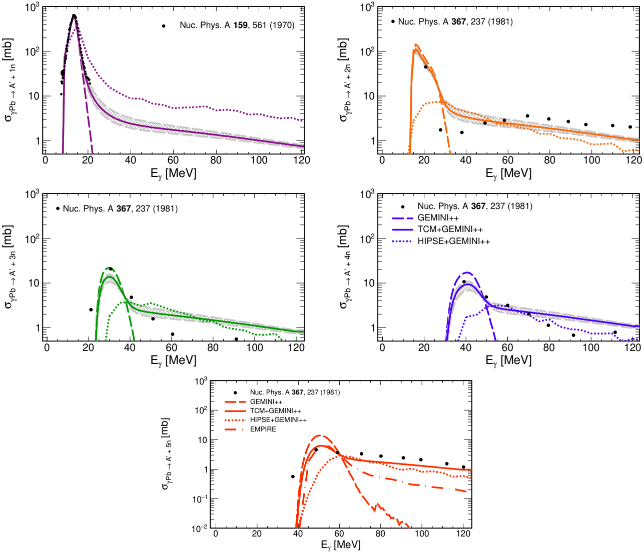


Mean excitation energy as function of absorbed photon energy.

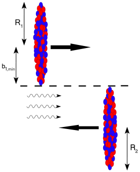


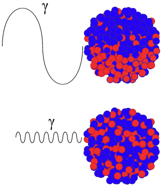
Multiplicity of neutron emission as function of absorbed photon energy.

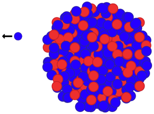
Nucleus de-excitation channels



Equivalent Photon Approximation

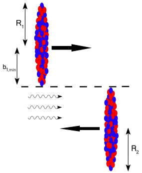


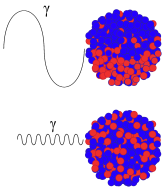


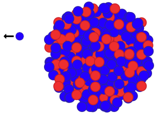


$$\sigma_{A_1A_2 \xrightarrow{1\gamma} X_1X_2+kn} = \int\int db d\omega \cdot 2\pi b \cdot e^{-m(b)} N(\omega, b)\sigma_{abs}(\omega) P_k(\omega)$$

$$m(b) = \int d\omega \cdot N(b,\omega)\sigma_{abs}(\omega)$$



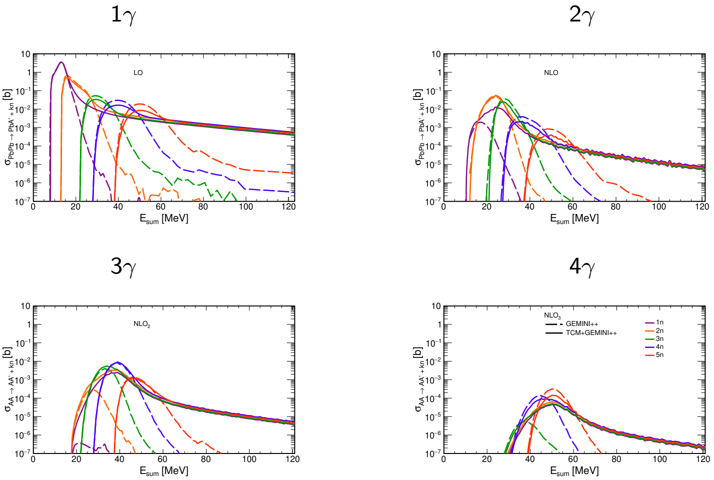




$$\sigma_{A_1 A_2 \xrightarrow{1\gamma} X_1 X_2 + kn} = \int\int db\,d\omega \cdot 2\pi b \cdot e^{-m(b)} N(\omega, b) \sigma_{abs}(\omega) P_k(\omega)$$

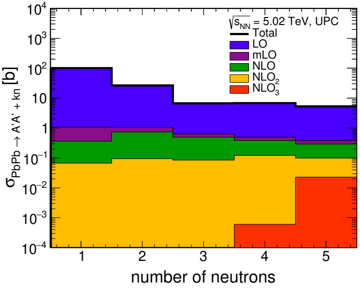
$$\sigma_{A_1 A_2 \xrightarrow{j\gamma} X_1 X_2 + kn} = \int d\omega_1 \cdots \int d\omega_j \int 2\pi b\,db \cdot \frac{e^{-m(b)}}{j!} \left(\prod_{i=1}^{j} N(\omega_i, b) \sigma_{abs}(\omega_i) \right) P_k(\Sigma_i^j(\omega_i))$$

Absorption of multiple photons



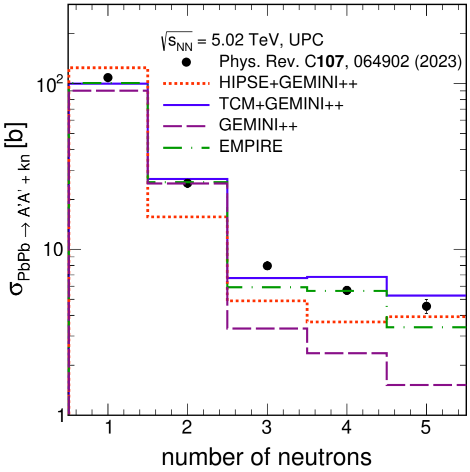
Neutrons emission cross sections as function of sum energy.

- The primary contribution resulting from the absorption of a single photon.
- The mutual excitation of nuclei affects the outcome similarly to the photoabsorption of one photon by a single nucleus.



Results of TCM for different components of total cross section.

Total cross section



Comparison of models to ALICE data.

- Ultrarelativistic, ultraperipheral collisions of heavy ions allow observations of photon-induced processes hitherto not accessible.
- Light-by-light scattering is a fundamental prediction of QED.
- Future experiments such as ATLAS, FoCal and ALICE 3 will improve statistics and extend the kinematic ranges of measurements, allowing theoretical predictions to be tested.
- We also collaborate with LHCb, looking to validate models of high-energy physics and nuclear physics experimentally.
- The work will culminate in a combination of measuring photons from light-by-light scattering with simultaneous measurement of evaporated neutrons.

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