ALICE

FORWARD NEUTRONS FROM ELECTROMAGNETIC DISSOCIATION OF ^{208}PB AT THE LHC

Uliana Dmitrieva for the ALICE collaboration

uliana.dmitrieva@cern.ch

Outline

- Introduction and motivation to study EMD
- ALICE zero degree calorimeters ZDC
  - neutron ZDC: ZNC and ZNA
  - proton ZDC: ZPC and ZPA
  - electromagnetic calorimeters: ZEM
- Corrections for the efficiency of these detectors for EMD measurements
- Measured cross sections of the emission of 1, 2, 3, 4 and 5 neutrons with and without protons in EMD of ^{208}Pb
- Relation of these cross sections to the production of ^{207,206,205,204,203}Pb as secondary nuclei in colliders
- Summary

New ALICE results

ALICE Collaboration. Neutron emission in ultraperipheral Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. arXiv:2209.04250 [nucl-ex]

(submitted to Physical Review C)

- In **ultraperipheral collisions (UPC)** colliding nuclei interact electromagnetically leading to their break-up – **electromagnetic dissociation (EMD)** of nuclei
- The total cross section of EMD (~ 211 b for ^{208}Pb) at the LHC is much larger than the hadronic cross section (7.7 b)
- In most cases, EMD results in the emission of one or few nucleons with the production of a single residual nucleus
- **Emission of neutrons in EMD was measured**

Motivation

- EMD of Pb was studied [1] at $\sqrt{s_{NN}}$ = 2.76 TeV

  Now the highest collision energy of $\sqrt{s_{NN}}$ = 5.02 TeV is available

- Different EMD models can be tested/validated with these data:
  - RELDIS [2]
  - nOOn [3]

- Estimate the production of residual nuclei left after the emission of several neutrons and zero protons from ^{208}Pb in EMD:
  - ^{207}Pb, ^{206}Pb create heat load on LHC components [4], [5]
  - Data can be extrapolated to the higher collision energies

1) B. Abelev et al., Phys. Rev. Lett. 109 (2012) 252302
2) I. Pshenichnov, Phys. Part. Nucl. 42, 215 (2011)
3) M. Broz et al., Comp. Phys. Com. p. 107181 (2020)
4) R. Bruce et al., Phys. Rev. ST 12 (2009) 071002
5) P.D. Hermes et al., NIM A 819 (2016) 73

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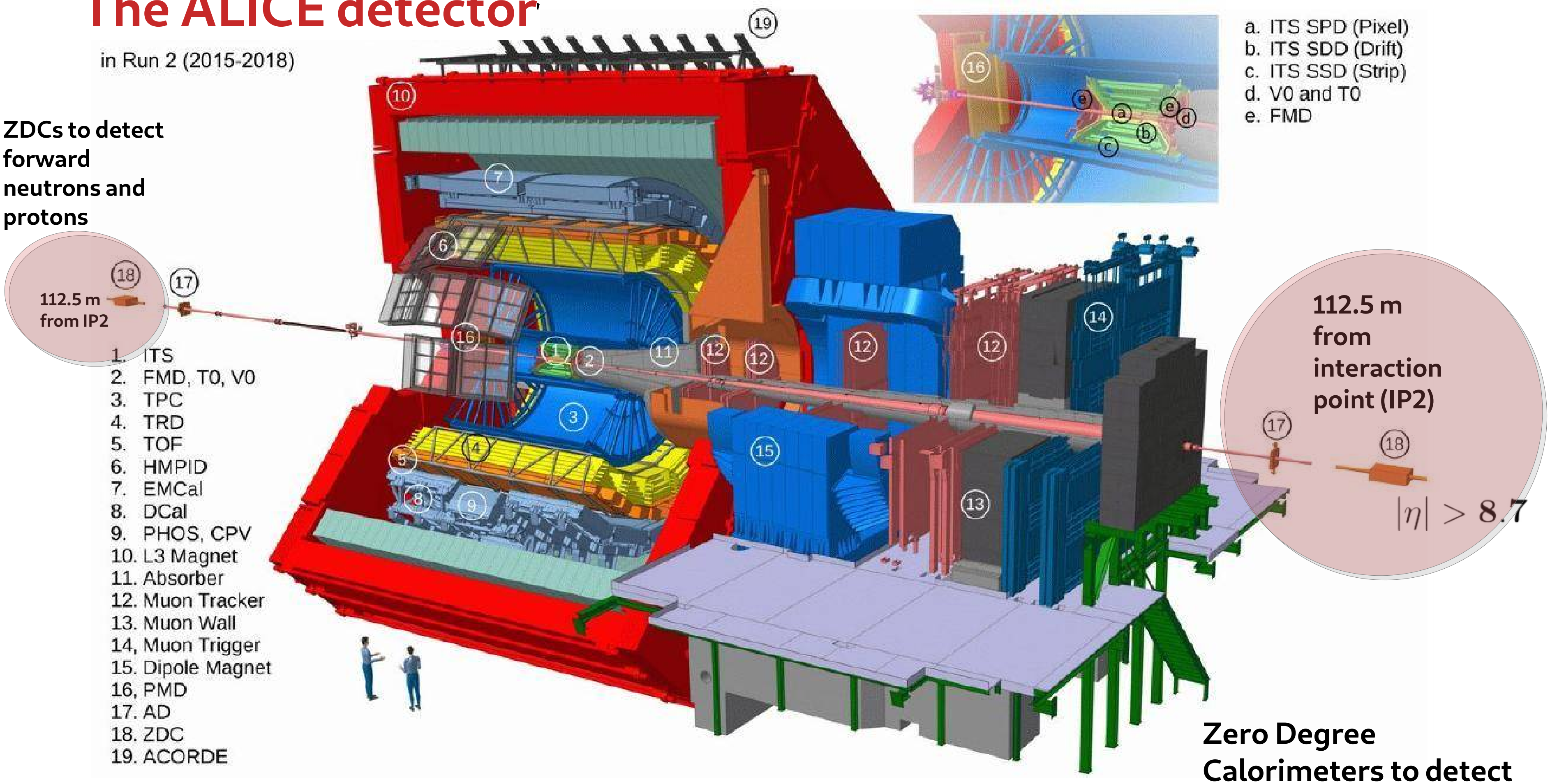
The ALICE detector

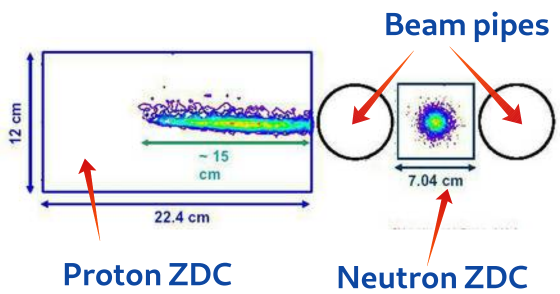
in Run 2 (2015-2018)

ZDCs to detect forward neutrons and protons



Zero Degree Calorimeters to detect forward neutrons and protons

ALICE ZDC



are placed far from the IP2 and they are partially shadowed by collimators and other collider components.

- **Nucleon losses lead to the redistribution of true high multiplicity events in favor of detected low multiplicity events**
- **Visible cross sections should be corrected for the efficiency of nucleon registration**
- **Correction factors were obtained by Monte-Carlo modeling of the transport of nucleons from EMD in the ALICE setup**

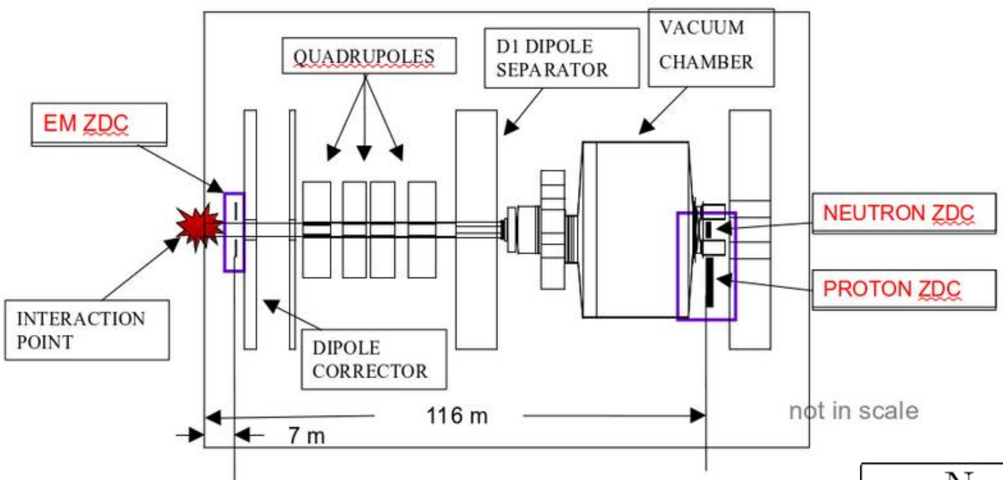
Neutron multiplicity in	Correction factor* $f_{i\mathrm{n}}$ ZNC	Correction factor* $f_{i\mathrm{n}}$ ZNA
0n	0.286 ± 0.126	0.302 ± 0.097
1n	1.064 ± 0.031	1.064 ± 0.030
2n	1.092 ± 0.024	1.010 ± 0.095
3n	1.057 ± 0.032	1.066 ± 0.018
4n	1.001 ± 0.046	0.962 ± 0.094
5n	0.907 ± 0.132	0.917 ± 0.104

Proton multiplicity	Correction factor* $f_{0\mathrm{p}}$ ZPC	Correction factor* $f_{0\mathrm{p}}$ ZPA
0p	0.848 ± 0.015	0.852 ± 0.018

*) correction factor = 1/efficiency

Selecting electromagnetic events in ALICE

M. Gallio, Joint LHC Machine-Experiment Workshop, 25 January 2007



ZDCs are supplemented by two ZEM calorimeters at 7 m only on the side A: $4.8 < \eta < 5.7$

- **ZEMs are sensitive to > 92 % of hadronic events**
- **No signals in ZEMs in > 99 % of EMD events**

Neutron multiplicity *in*	efficiency of ZEM veto ε_i (%)	
	Side C	Side A
1n	99.875 ± 0.005	99.902 ± 0.005
2n	99.766 ± 0.014	99.819 ± 0.013
3n	99.457 ± 0.039	99.349 ± 0.042
4n	99.479 ± 0.043	99.321 ± 0.049
5n	99.368 ± 0.050	99.025 ± 0.064
total 1n–5n	99.802 ± 0.005	99.806 ± 0.005
total Xn	96.722 ± 0.017	96.117 ± 0.019

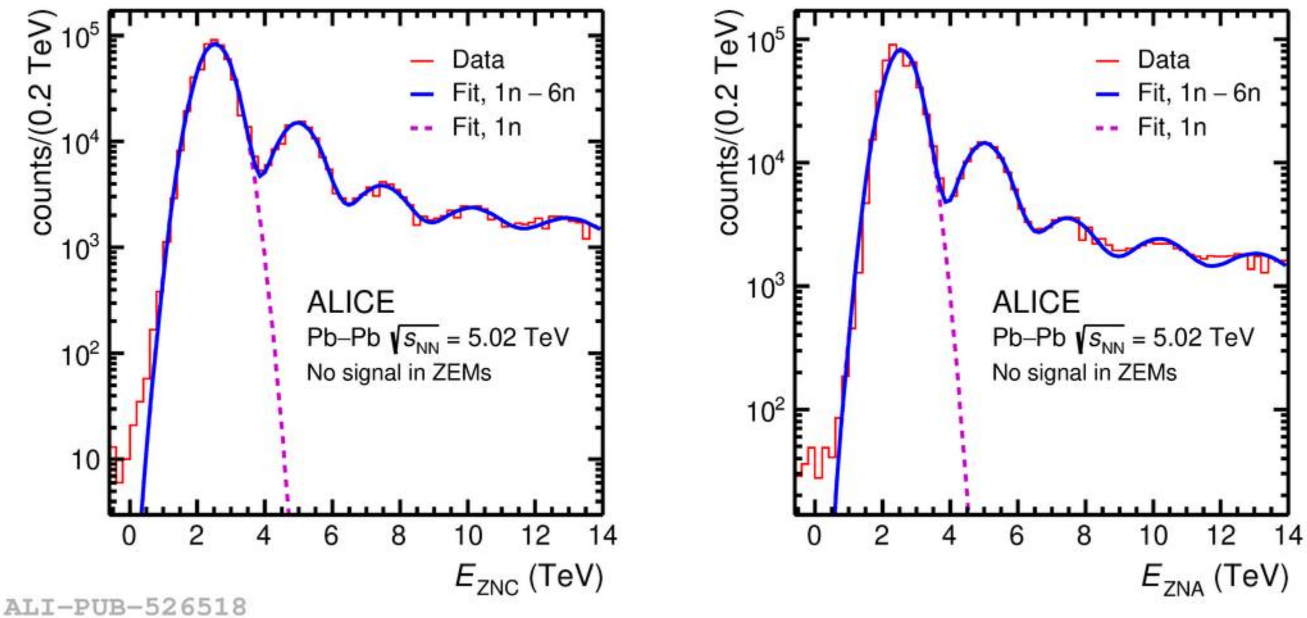
ZDC energy spectra

ZDC spectra are described by the sum of Gaussians:

$$F(E) = \sum_{i=1}^{6} f_i(E) = $$

$$= \sum_{i=1}^{6} \frac{\mathrm{n}_i}{\sqrt{2\pi}\sigma_i} \mathrm{e}^{-\frac{(E-\mu_i)^2}{2\sigma_i^2}}$$

with n_i – number of events of corresponding neutron multiplicity *i.*



The cross section of neutron emission can be calculated for each channel:

for EMD with $\sigma(in) = \sigma_{\mathrm{ZED}} \frac{n_i}{N_{\mathrm{tot}}} \frac{f_{in}}{\varepsilon_i}$

and without protons $\sigma(in, 0\mathrm{p}) = \sigma_{\mathrm{ZED}} \frac{n_i}{N_{\mathrm{tot}}} \frac{f_{in} f_{0\mathrm{p}}}{\varepsilon_i}$, where

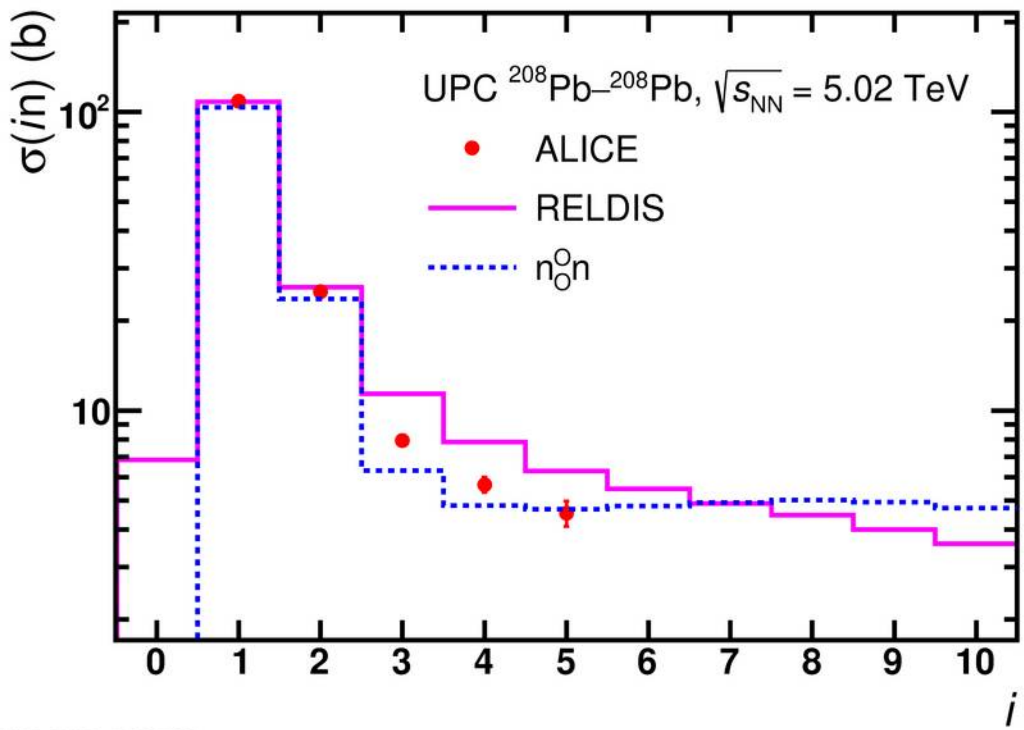
N_{tot} – the total number of events tagged by ZED-trigger,

$\sigma_{\mathrm{ZED}}{}^{*}$ – visible cross section of ZED-trigger.

**) ALICE Collaboration, "ALICE luminosity determination for Pb−Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV", arXiv:2204.10148 [nucl-ex]*

Neutron emission with arbitrary number of protons

- One and two neutrons (1n and 2n) are emitted most frequently in UPC of ^{208}Pb
- These cross sections are well described by RELDIS and n$^{\text{O}}_{\text{O}}$n models
- 3n and 4n measured cross sections are underestimated by n$^{\text{O}}_{\text{O}}$n and overestimated by RELDIS



ALI-PUB-526522

- Measured cross sections can be used to improve EMD models

Neutron emission without protons

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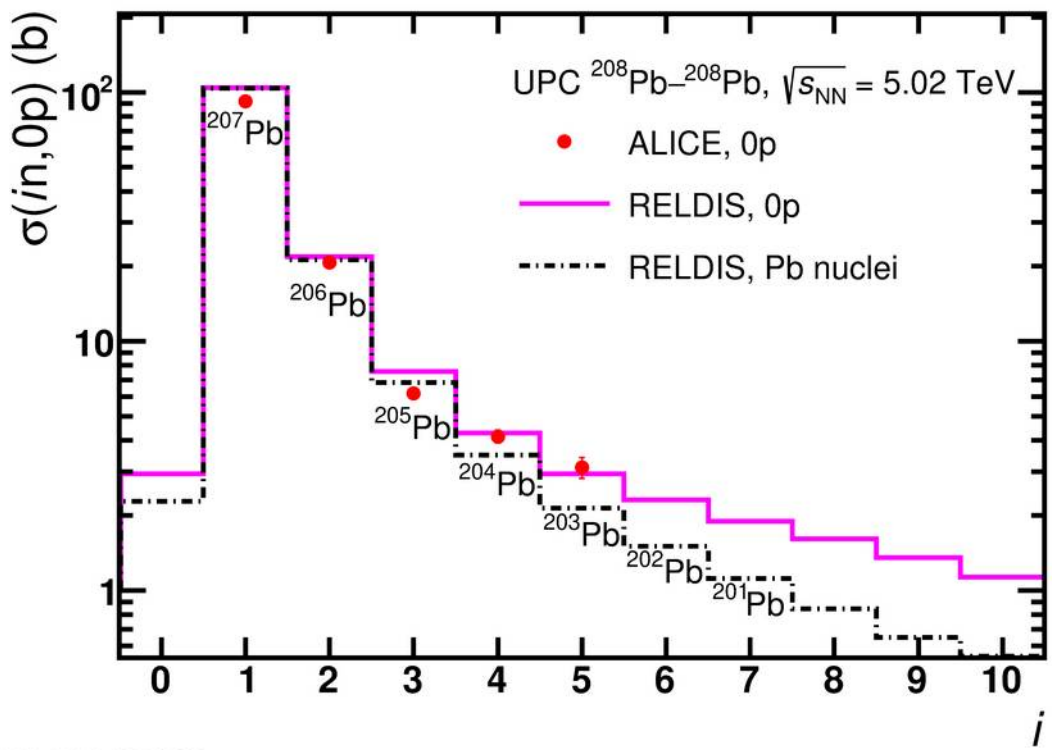
- Measured 1n, 2n and 3n cross sections agree with RELDIS.



ALI-PUB-526526

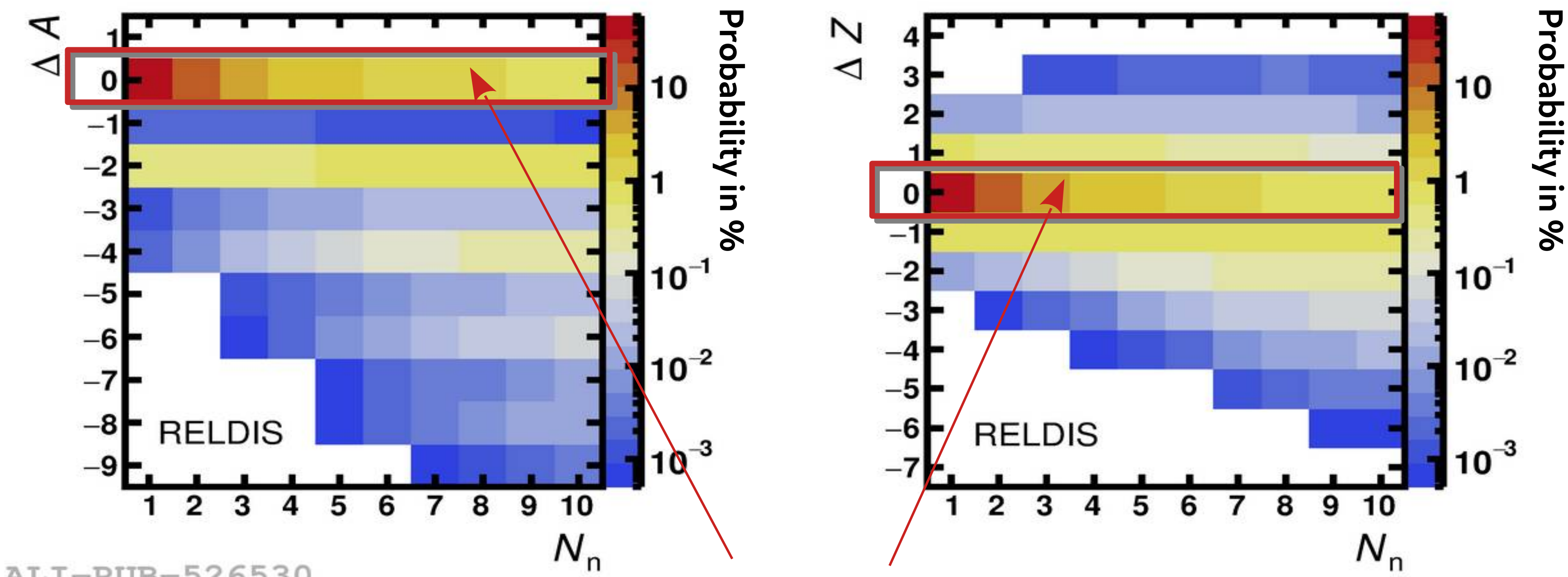
- According to RELDIS, the cross sections to produce ^{207}Pb, ^{206}Pb, ^{205}Pb are well approximated by 1n, 2n and 3n cross sections without proton emission.

EMD: single residue with several nucleons

$\Delta A = A_{res} + N_n + N_p - 208$

$\Delta Z = Z_{res} + N_p - 82$

Z_{res} and A_{res} – the charge and mass of the heaviest residual nucleus
N_n and N_p – the numbers of emitted neutrons and protons



$\Delta A = 0$ and $\Delta Z = 0$ in most cases

⇒ the properties of residual nuclei can be estimated by detecting forward neutrons and protons

Summary

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- The cross sections of emission of given numbers of neutrons in UPC of ^{208}Pb nuclei at $\sqrt{s_{NN}}$ = 5.02 TeV were measured with ALICE neutron zero degree calorimeters
- The cross sections for the emission of 1, 2, 3, 4 and 5 forward neutrons in UPC, not accompanied by protons were measured for the first time. They mostly correspond to the production of ^{207,206,205,204,203}Pb, respectively
- The predictions from the available models describe the measured cross sections
- The obtained cross sections can be used for evaluating the impact of secondary nuclei on the LHC components, in particular, on superconducting magnets, and also provide useful input for the design of the Future Circular Collider (FCC-hh)

THANK YOU FOR YOUR ATTENTION!

Backup slides

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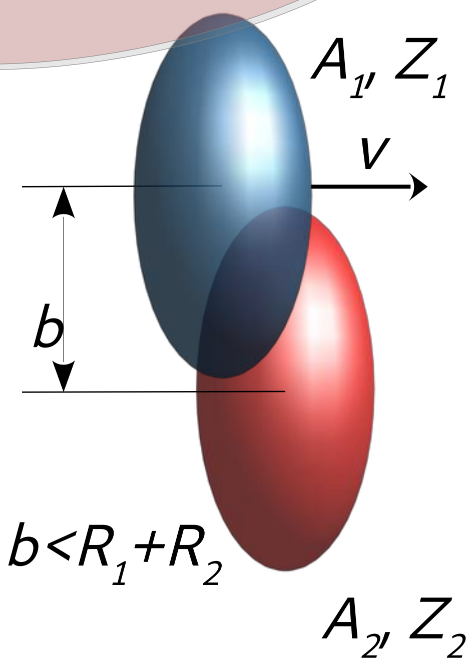
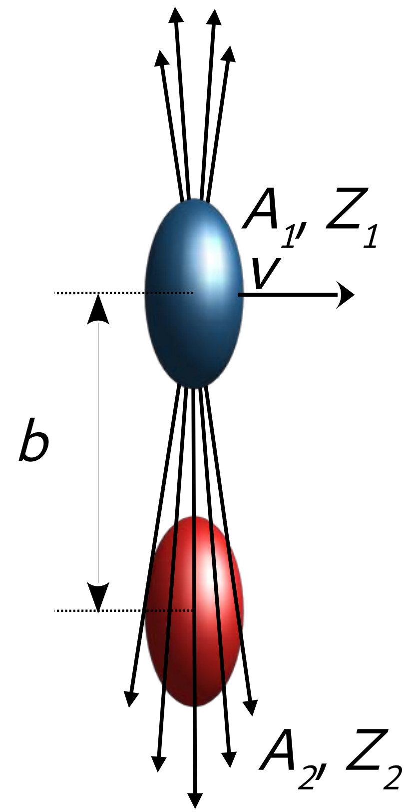
Hadronic and electromagnetic interactions of nuclei

with overlap of nuclei densities



without overlap of nuclei densities



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Ultraperipheral collisions

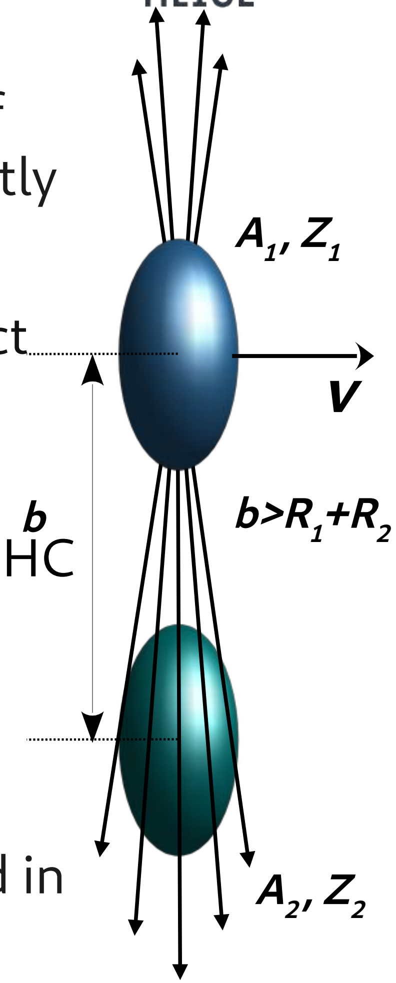
- Hadronic interactions of nuclei with significant overlap of nuclear densities and multiple particle production are mostly studied at RHIC and at the LHC.

- In **ultraperipheral collisions (UPC)** colliding nuclei interact electromagnetically leading to their break-up – **electromagnetic dissociation (EMD)** of nuclei.

- The total cross section of EMD (~ 211 b for ^{208}Pb) at the LHC is much larger than the hadronic cross section (7.7 b).

- In most cases, EMD results in the emission of one or few nucleons with the production of a single residual nucleus.

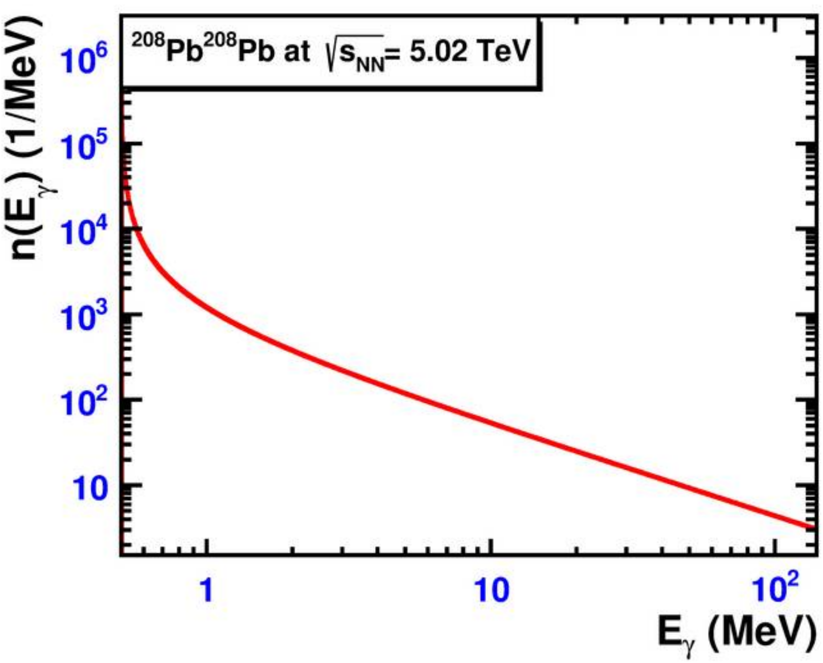
- As expected,various heavy secondary nuclei are produced in EMD at the LHC. These nuclei are not detectable, but they can pass through the collimator system and impact collider elements.

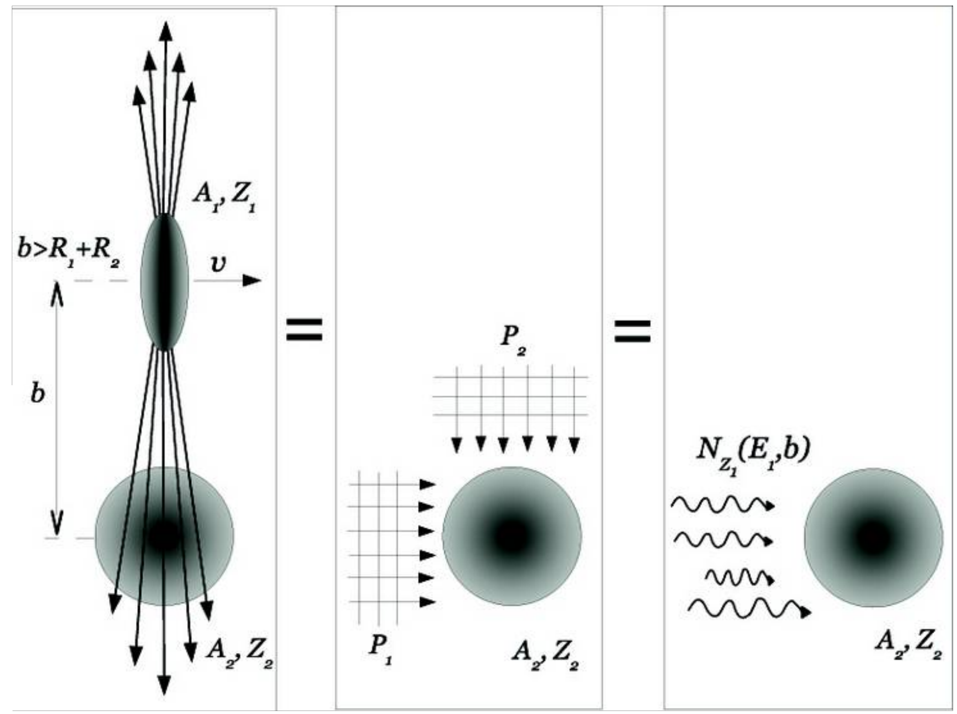


A. J. Baltz, Phys Rep 458, 1 – 171 (2008)
R. Bruce et al., Phys Rev ST Accel Beams 12, 071002 (2009)

Weizsäcker–Williams method

The impact of the Coulomb field of the nucleus A_1 to A_2 can be represented by the absorption of one or more equivalent photons by the target nucleus A_2.

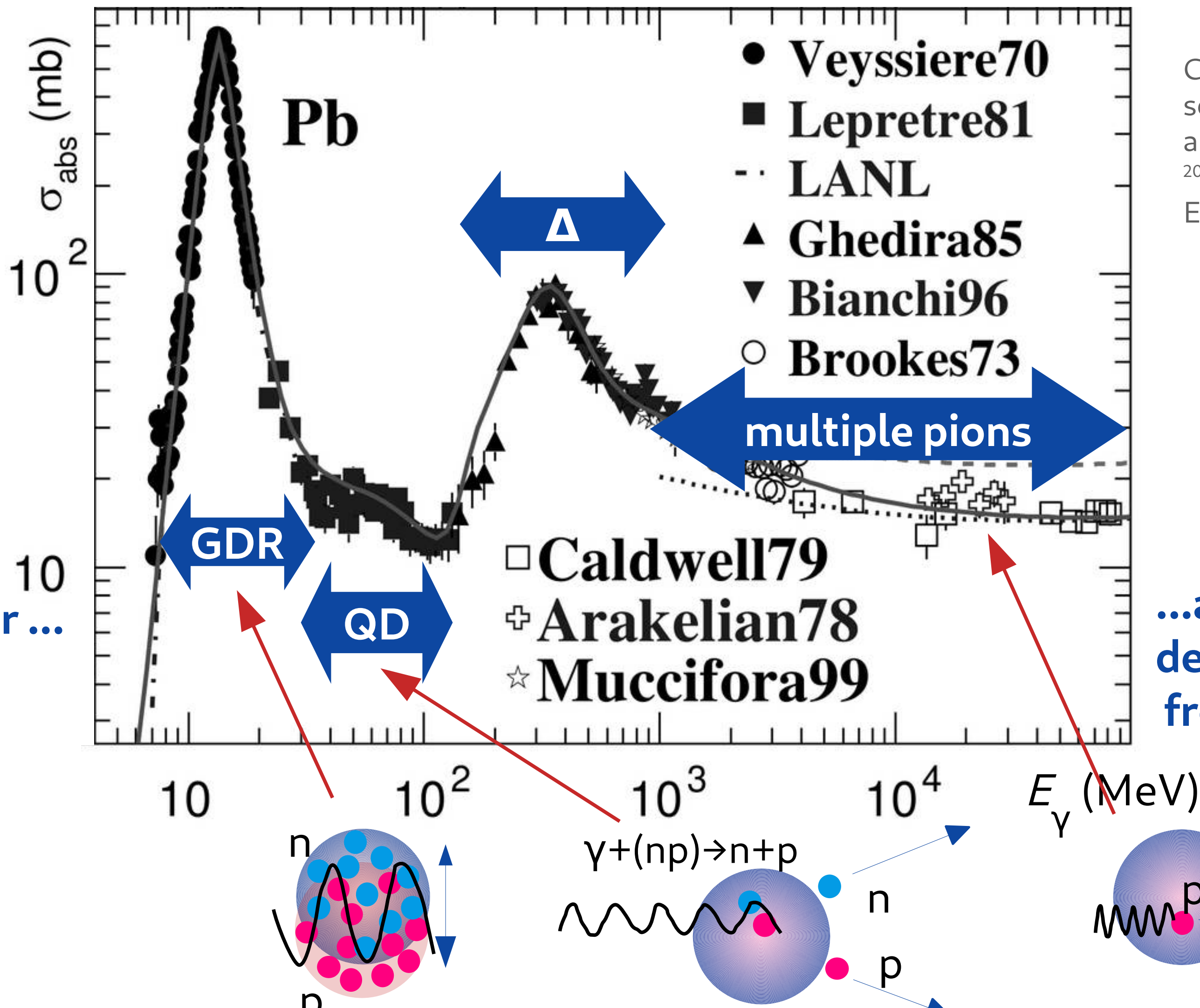




The impact of the Coulomb field of the nucleus A_1 to A_2 can be represented by the absorption of one or more equivalent photons by the target nucleus A_2.

Various processes of photoabsorbtion with the emission of nucleons

Nuclear …

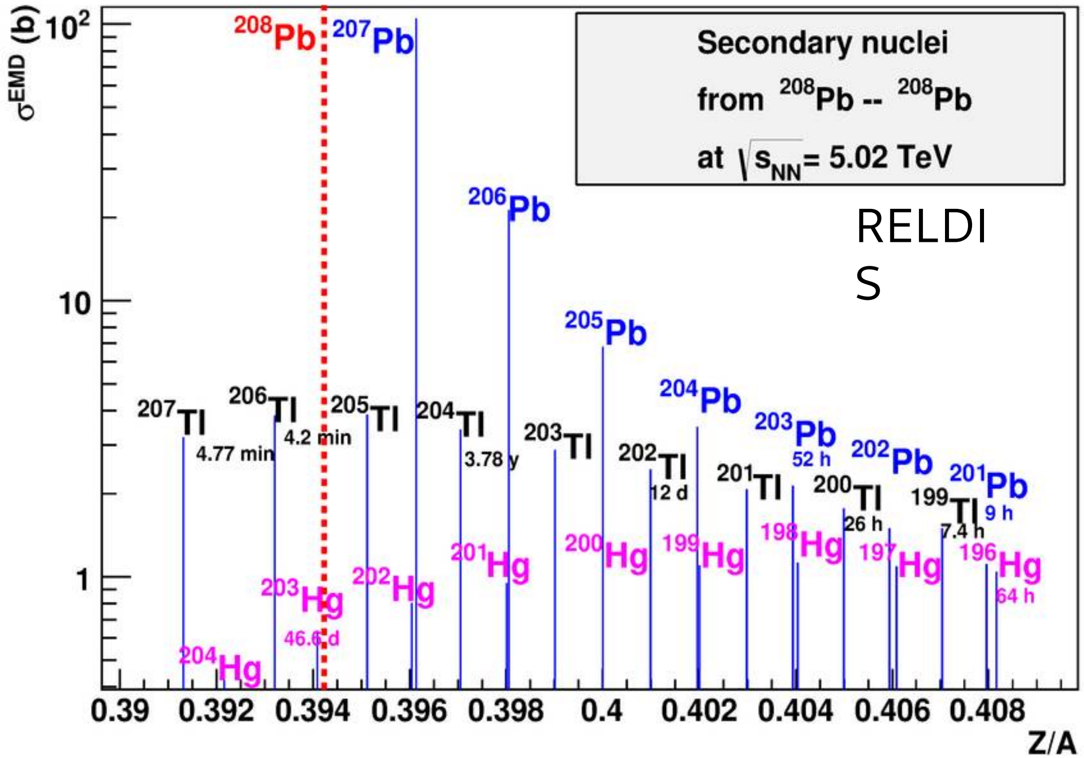


…and hadronic degrees of freedom

Compilation of cross section data and approximation for ^{208}Pb from M.V. Kossov, EPJA 14 (2002) 377

Production of Pb, Tl and Hg isotopes

Z/A ratio characterizes the proximity of the trajectories of secondary nuclei in the magnetic field of the LHC to the beam.



RELDIS

ALICE measurements

ZN	$\sigma(in)$ (b)		$\sigma(in)$ (b)	$\sigma^{\mathrm{RELDIS}}(in)$ (b)	$\sigma^{\mathrm{n_{O}^{O}n}}(in)$ (b)
	Side C	Side A			
1n	$109.7 \pm 0.1 \pm 4.0$	$107.2 \pm 0.1 \pm 4.0$	$108.4 \pm 0.1 \pm 3.7$	108.0 ± 5.4	103.7 ± 2.1
2n	$25.8 \pm 0.1 \pm 0.8$	$24.1 \pm 0.1 \pm 2.3$	$25.0 \pm 0.1 \pm 1.3$	25.9 ± 1.3	23.6 ± 0.5
3n	$7.97 \pm 0.07 \pm 0.32$	$7.94 \pm 0.04 \pm 0.24$	$7.95 \pm 0.04 \pm 0.23$	11.4 ± 0.6	6.3 ± 0.1
4n	$5.73 \pm 0.04 \pm 0.30$	$5.56 \pm 0.04 \pm 0.56$	$5.65 \pm 0.03 \pm 0.33$	7.8 ± 0.4	4.8 ± 0.1
5n	$4.61 \pm 0.04 \pm 0.68$	$4.47 \pm 0.04 \pm 0.52$	$4.54 \pm 0.03 \pm 0.44$	6.3 ± 0.3	4.7 ± 0.1
1n–5n			$151.5 \pm 0.2 \pm 4.6$	159.8 ± 5.6	143.1 ± 2.2

ZN	ZP	$\sigma(in, 0p)$ (b)		$\sigma(in, 0p)$ (b)	$\sigma^{\mathrm{RELDIS}}(in, 0p)$ (b)
		Side C	Side A		
1n	0p	$92.6 \pm 0.1 \pm 3.8$	$90.9 \pm 0.1 \pm 3.9$	$91.8 \pm 0.1 \pm 3.3$	104.1 ± 5.2
2n		$21.4 \pm 0.1 \pm 0.8$	$20.0 \pm 0.1 \pm 2.0$	$20.7 \pm 0.1 \pm 1.1$	21.9 ± 1.1
3n		$6.14 \pm 0.07 \pm 0.27$	$6.21 \pm 0.04 \pm 0.23$	$6.17 \pm 0.04 \pm 0.20$	7.59 ± 0.38
4n		$4.21 \pm 0.04 \pm 0.23$	$4.08 \pm 0.04 \pm 0.42$	$4.15 \pm 0.03 \pm 0.25$	4.29 ± 0.22
5n		$3.16 \pm 0.04 \pm 0.47$	$3.08 \pm 0.03 \pm 0.36$	$3.12 \pm 0.03 \pm 0.30$	2.95 ± 0.15
1n–5n				$126.0 \pm 0.2 \pm 4.0$	140.8 ± 5.3

Good agreement between C and A sides for both kinds of cross sections

ALICE Collabaration., Neutron emission in ultraperipheral Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV.
arXiv:2209.04250 [nucl-ex]

Probabilistic model to account for ZDC acceptance

The numbers of detected events n_i and those calculated by RELDIS N_i for a given multiplicity *i* are connected by means of a triangular transformation matrix P:

$$\begin{pmatrix} n_0 \\ n_1 \\ n_2 \\ n_3 \\ n_4 \\ n_5 \end{pmatrix} = \begin{pmatrix} p_{00} & p_{01} & p_{02} & p_{03} & p_{04} & p_{05} \\ 0 & p_{11} & p_{12} & p_{13} & p_{14} & p_{15} \\ 0 & 0 & p_{22} & p_{23} & p_{24} & p_{25} \\ 0 & 0 & 0 & p_{33} & p_{34} & p_{35} \\ 0 & 0 & 0 & 0 & p_{44} & p_{45} \\ 0 & 0 & 0 & 0 & 0 & p_{55} \end{pmatrix} \begin{pmatrix} N_0 \\ N_1 \\ N_2 \\ N_3 \\ N_4 \\ N_5 \end{pmatrix} = P \begin{pmatrix} N_0 \\ N_1 \\ N_2 \\ N_3 \\ N_4 \\ N_5 \end{pmatrix}$$

with $p_{nk} = \binom{n}{k} p^k (1-p)^{n-k}$, where p – probability to detect a nucleon.

U. Dmitrieva, I. Pshenichnov, NIM **A 906** (2018) 114 https://doi.org/10.1016/j.nima.2018.07.072