Challenge of nuclear transmutation in heavy-ion colliders

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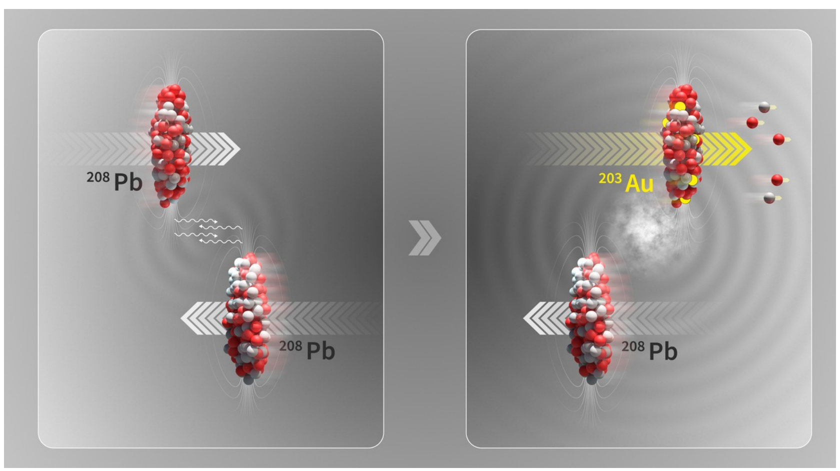


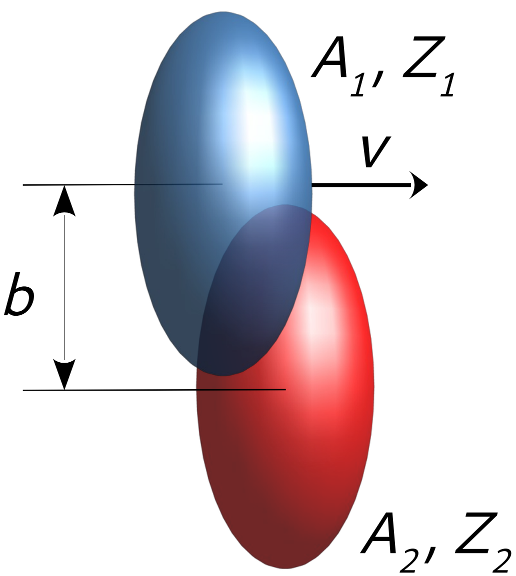
Outline

- Introduction. Fragmentation of beam nuclei and its modeling:
  - How secondary nuclei are produced in heavy-ion colliders?
  - What happens when the nuclei are emitted forward and their charge-to-mass ratio (Z/A) is close to Z/A of beam nuclei?
- Transmutation of ^{208}Pb at the LHC:
  - Recent measurements of proton emission in ultraperipheral collisions by ALICE
  - Electromagnetic dissociation (EMD) of ^{208}Pb as an "alchemy" at the LHC
- Projections to ^{124}Xe-^{124}Xe at NICA:
  - EMD remains important, its impact on NICA components to be estimated
- ^{16}O-^{16}O and ^{20}Ne-^{20}Ne at the LHC:
  - Certain nuclei, like ^{4}He and ^{12}C, are produced in hadronic collisions. They can circulate in the accelerator and collide with beam nuclei
  - EMD contribution is small
- Summary

Interactions of nuclei

hadronic

with overlap of nuclear densities $b<R_1+R_2$

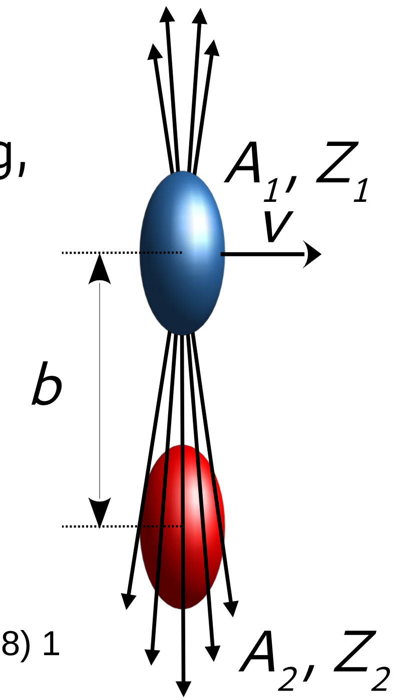


- Nuclear matter remains relatively cold beyond the nuclear overlap.
- It is represented by forward spectator nucleons and nuclear fragments.
- Heavy spectator nuclei are infrequent (only in grazing collisions)

electromagnetic

without overlap of nuclear densities – ultraperipheral collisions (UPC) leading, in particular, to electromagnetic dissociation (EMD)

$b>R_1+R_2$



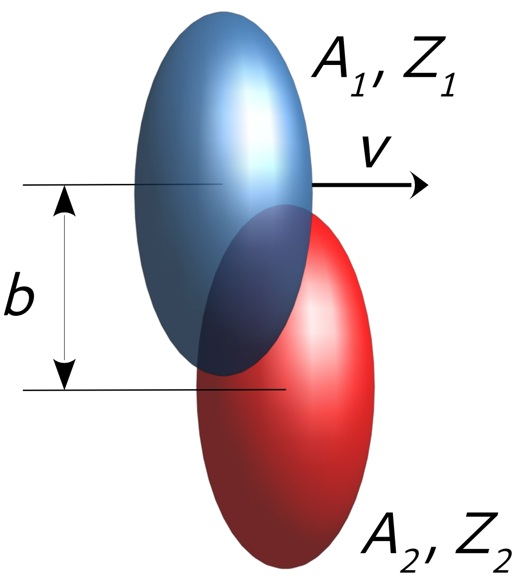
More on UPC physics:
A.J. Baltz, Phys. Rep. 458 (2008) 1

- Nuclei are excited by Lorentz-conracted Coulomb fields, mainly giant dipole resonances (GDR)
- Only few nucleons are emitted leaving a single residual nucleus in EMD

Interactions of nuclei

hadronic

with overlap of nuclear densities $b<R_1+R_2$



- Nuclear matter remains relatively cold beyond the nuclear overlap.
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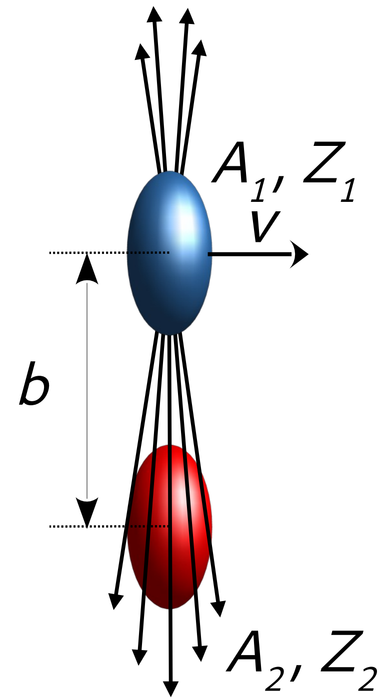
electromagnetic

without overlap of nuclear densities $b>R_1+R_2$

	total cross sections (b)	
	hadronic	EMD
^{208}Pb–^{208}Pb $\sqrt{s_{NN}} = 5.36$ TeV	7.6	206.5
^{124}Xe–^{124}Xe $\sqrt{s_{NN}} = 9.5$ GeV	6	5.3
^{20}Ne–^{20}Ne $\sqrt{s_{NN}} = 5.36$ TeV	1.7	~ 0.3
^{16}O–^{16}O $\sqrt{s_{NN}} = 5.36$ TeV	1.3	0.12



- Nuclei are excited by Lorentz-conracted Coulomb fields, mainly giant dipole resonances (GDR)
- Only few nucleons are emitted leaving a single residual nucleus in EMD

Fragmentation models

hadronic — AAMC²

Abrasion-**A**blation **M**onte **C**arlo for **C**olliders
AAMCC-MST version[1]:

- Glauber MC model[2] to identify nucleons which do not participate in collisions (spectator prefragment).
- Hybrid calculation of prefragment excitation energy:
  - Ericson formula based on the particle-hole model[3] for peripheral collisions;
  - ALADIN parabolic approximation[4] otherwise.
- Minimum Spanning Tree (MST) clustering of prefragment[1] with Coulomb repulsion[5]
- Geant4 (v 10.4)decay models[6] to decay prefragments:
  - Fermi break-up model.
  - Statistical Multifragmentation Model (SMM).
  - Weisskopf-Ewing evaporation model.

1) R. Nepeivoda et al., Particles 5 (2022) 40
2) C. Loizides et al., PRC 97 (2018) 054910
3) T. Ericson, Adv. Phys. 9 (1960) 425
4) A.S. Botvina et al., NPA 584 (1995) 737
5) E. Vasyagina et al., PEPAN Lett. 2025, in print
6) J. Alison et al., NIMA 835 (2016) 186

electromagnetic — RELDIS

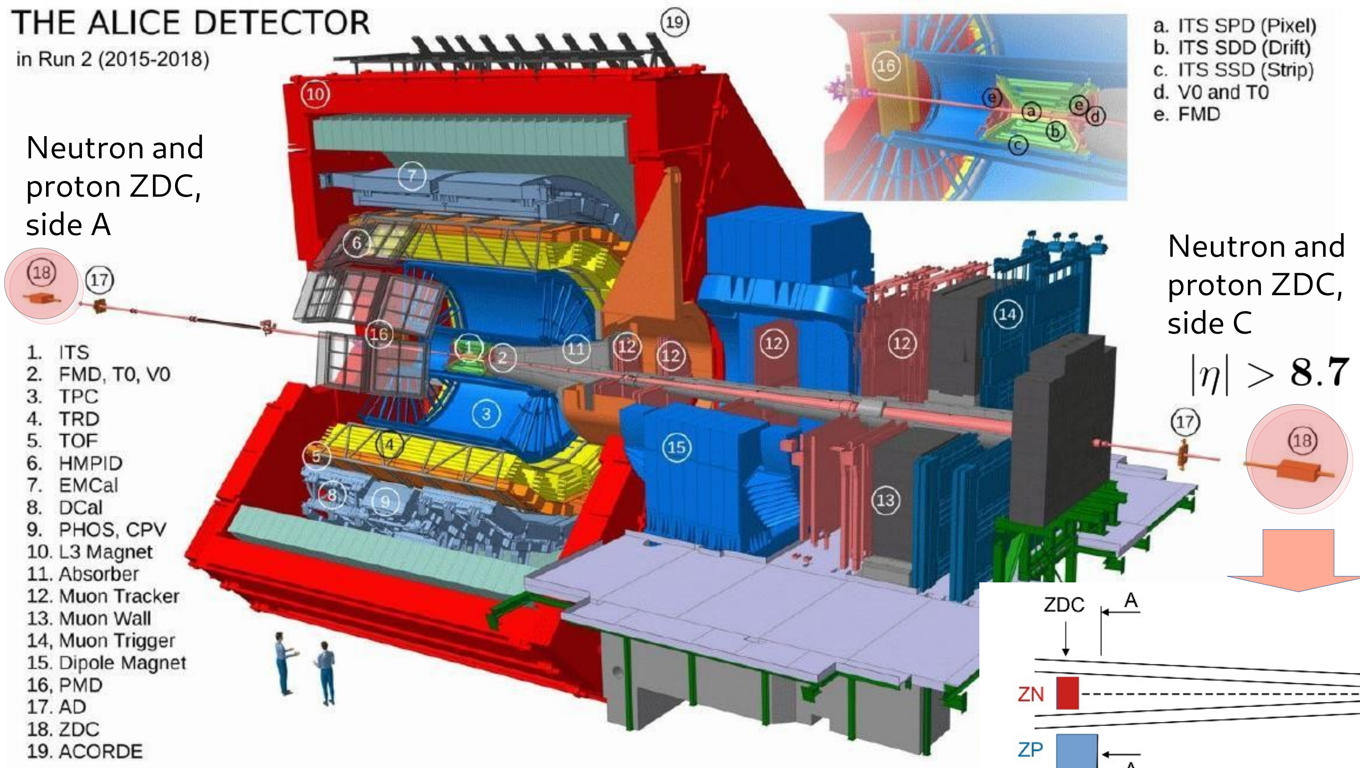
Relativistic **EL**ectromagnetic **DIS**sociation [7]

- Weizsäcker-Williams method of equivalent photons [8]
- Modeling of exchange of a single or a pair of photons in a UPC event
- Total photoabsorption cross sections based on GDR data[9] and on "the universal curve" [10] at higher photon energies
- Intranuclear cascade model of photoabsorption with subsequent decays of residual nuclei by Fermi break-up, SMM, evaporation models

7) I.P., Phys.Part.Nucl. 42 (2011) 215
8) A.J. Baltz, Phys. Rep. 458 (2008) 1
9) B.L. Berman, S.C. Fultz, Rev. Mod. Phys. 47 (1975) 713
10) I.P., Eur.Phys.J.A 24 (2005) 69

ALICE detects forward neutrons and protons

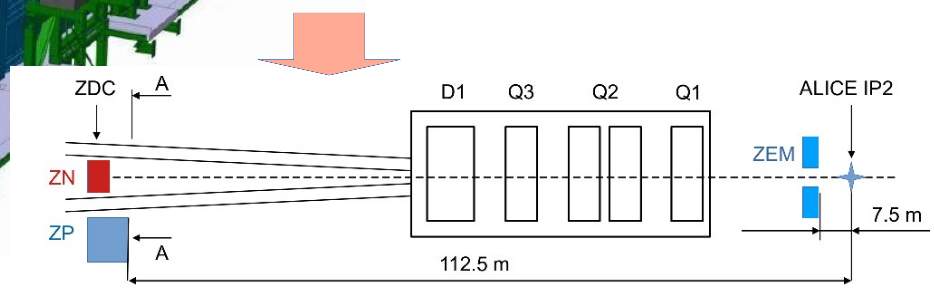
- Zero Degree Calorimeters (ZDC) are used to detect forward neutrons and protons on both sides of the interaction point (IP2) at the LHC tunnel, at 112.5 m from IP2



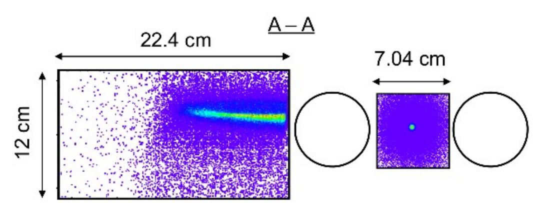
Neutron ZDCs are used:

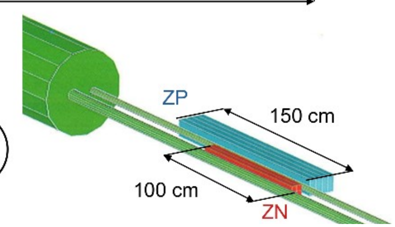
- to determine collision centrality [1)]
- to monitor collider luminosity [2)].

[1)] ALICE Collab., Phys. Rev. C 88 (2013) 044909
[2)] ALICE Collab., 2024 JINST 19 (2024) P02039



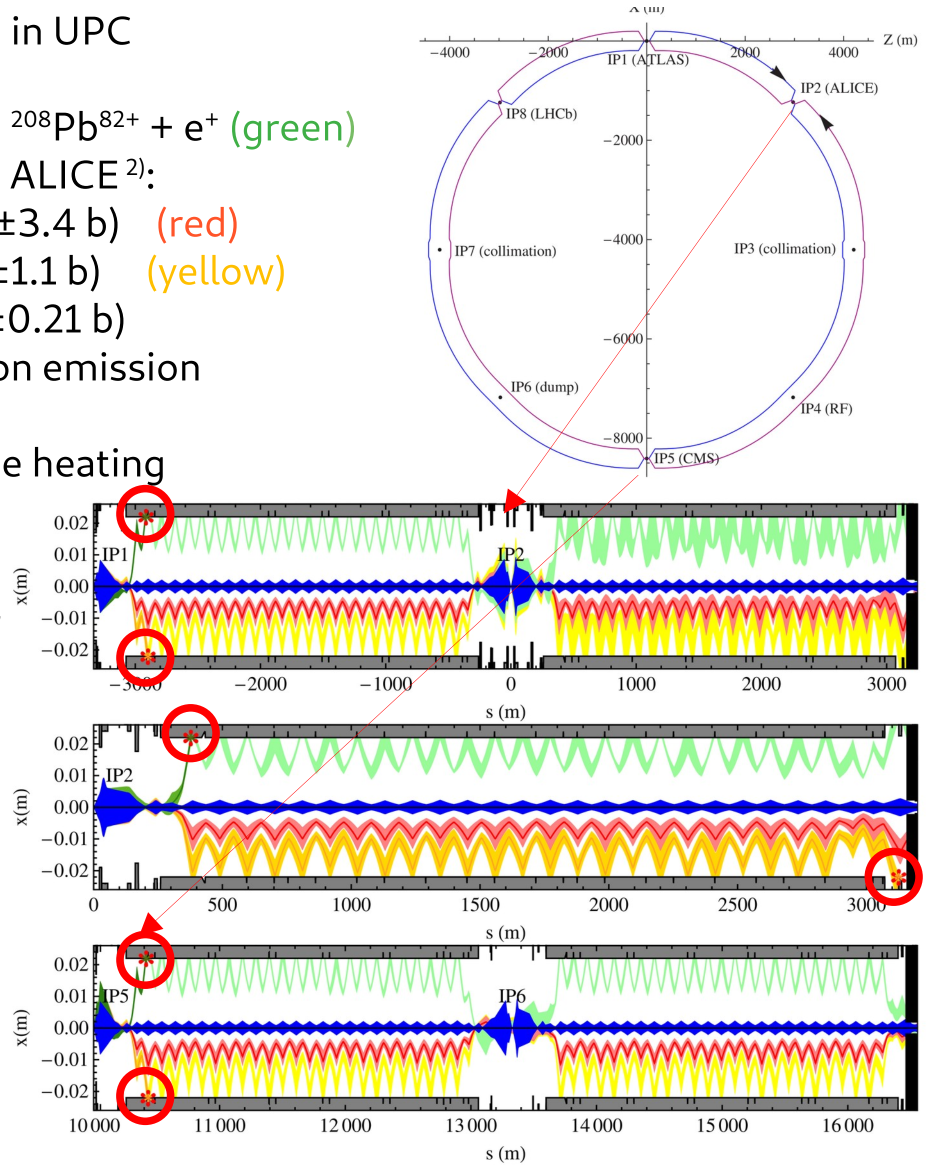
ALICE ZDC:
G. Puddu et al., Nucl. Instr. Meth. A **581** (2007) 397
R. Gemme et al., Nucl. Phys. B **197** (2009) 211





Propagation of secondary nuclei/ions in colliders

- Bound-free e^+e^- pair production (BFPP)[1)] (~281 b) in UPC at the LHC:
  - $^{208}Pb^{82+} + {}^{208}Pb^{82+} \rightarrow \mathbf{({}^{208}Pb+e^-{}_{1s,2s,2p(1/2)2p(2/3),3s})^{81+}} + {}^{208}Pb^{82+} + e^+$ (green)
- Electromagnetic dissociation (EMD), measured by ALICE [2)]:
  - $^{208}Pb^{82+} + {}^{208}Pb^{82+} \rightarrow {}^{208}Pb^{82+} + \mathbf{{}^{207}Pb^{82+}} + n$ (91.8±3.4 b) (red)
    - $\rightarrow {}^{208}Pb^{82+} + \mathbf{{}^{206}Pb^{82+}} + 2n$ (20.7±1.1 b) (yellow)
    - $\rightarrow {}^{208}Pb^{82+} + \mathbf{{}^{205}Pb^{82+}} + 3n$ (6.17±0.21 b)
    - → also **Tl, Hg, Au …** due to proton emission

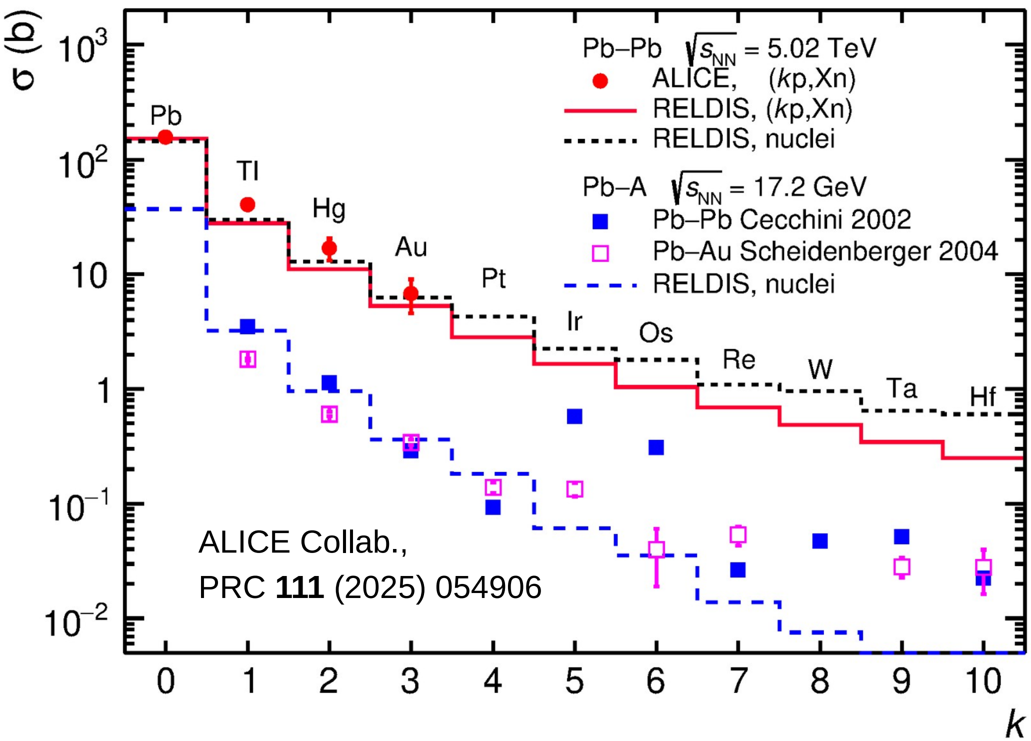


- Well before the LHC operation, localized beampipe heating due to BFPP and EMD has been predicted[3)].
- Detailed modeling of trajectories in the LHC[4)].
- Quenches of main dipole magnets were observed,
- alleviated by orbit bumping and collimators[5)].
- Large cross section (~60 b, both beams) estimated for BFPP of $^{209}Bi^{83+}$ at NICA[6)].
- Secondary nuclei with altered magnetic rigidity impact various collider components, see figure[4)].

- [1)] H. Meier et al., PRA 63 (2001) 032713
- [2)] ALICE Collab., PRC 107 (2023) 064902
- [3)] S.R. Klein, NIMA 459 (2001) 51
- [4)] R. Bruce et al., Phys. Rev. Accel. Beams 12 (2009) 071002
- [5)] M. Schaumann et al., Phys. Rev. Accel. Beams
- 23 (2020) 121003
- [6)] D. A. Bauer et al., EPJA 65 (2020) 200

Production of various elements in EMD of ^{208}Pb

- Estimated from proton emission cross sections in ultraperipheral ^{208}Pb-^{208}Pb measured at the LHC in Run 2
- Obtained by subtracting hadronic contribution from charge-changing cross sections measured at the CERN SPS for ^{208}Pb projectiles in 2002-2004



It is known that gold isotopes are produced in nuclear reactions induced by low-energy neutrons, protons, deuterons and photons on Hg, Au, and Pt targets (see Ref. [40] for a review). Gold isotopes were also produced in the fragmentation of target ^{209}Bi nuclei induced by high-energy beams of ^{12}C and ^{20}Ne [41], and in the fragmentation of uranium nuclei induced by high-energy protons [42]. However, according to the Experimental Nuclear Reaction Data database [43], no data were reported specifically for the photonuclear reactions Pb$*$ $(\gamma, *)$Au$*$. In the present work we report for the first time the production of gold in the photoabsorption by lead nuclei, purely in ultraperipheral ^{208}Pb - ^{208}Pb collisions, with unusually large cross section comparable to the total hadronic ^{208}Pb - ^{208}Pb cross section. It can be estimated that a total of some 2.9×10^{-11} g of various gold isotopes were produced from both LHC beams according to the total integrated luminosity at all four interaction points during Run 2 (2015–2018) of the LHC. The Pb-Pb data analyzed in the present paper were collected in 2018. The transmutation of lead into gold is the dream of medieval alchemists which comes true at the LHC.

- RELDIS predicts the production of a single heavy residual nucleus in EMD
- Production of protons at the LHC and Tl, Hg, Au, Pt at the CERN SPS is described well by the model

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NEWS 09 May 2025

Physicists turn lead into gold — for a fraction of a second

Colliding beams of lead create fast-moving, short-lived gold ions. Understanding the process could help to refine particle-accelerator experiments.

By Elizabeth Gibney

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Alchemists' Dream Realized As Lead Turned Into Gold at Large Hadron Collider

Published May 09, 2025 at 12:15 PM EDT | Updated May 12, 2025 at 7:02 AM EDT

STUTTGARTER ZEITUNG

Traum der Alchimisten: Forscher machen aus Blei echtes Gold

Stuttgarter Zeitung, 09 May 2025

Wovon Alchemisten for Jahrhunderten träumten, scheint wahr geworden zu sein: Am Kernforschungszentrum Cern ist Gold aus Blei...

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Alchemists rejoice as Cern turns lead into gold — for a flash

Scientists created gold atoms for fractions of a second by making lead particles collide at almost the speed of light

От свинца к золоту

Как электромагнитные поля в БАК меняют состав ядер

Международная коллаборация ALICE, работающая на Большом адронном коллайдере (БАК), впервые зафиксировала превращение сталкивающихся в коллайдере ядер свинца в золото в результате их непрямого электромагнитного взаимодействия. Результаты исследования опубликованы в журнале Physical Review C.

kommersant
https://www.kommersant.ru

n-tv

Physiker verwandeln Blei in Gold

N-TV, 09 May 2025

"Alchemisten-Traum" wird wahr Physiker verwandeln Blei in Gold 09.05.2025, 11:32 Uhr Vor Jahrhunderten träumten Alchemisten von...

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CERN scientists turn lead into gold (briefly)

How CERN turned lead into gold (very briefly) in the Large Hadron Collider

GEORGE PETRAS, STEPHEN J. BEARD — USA TODAY

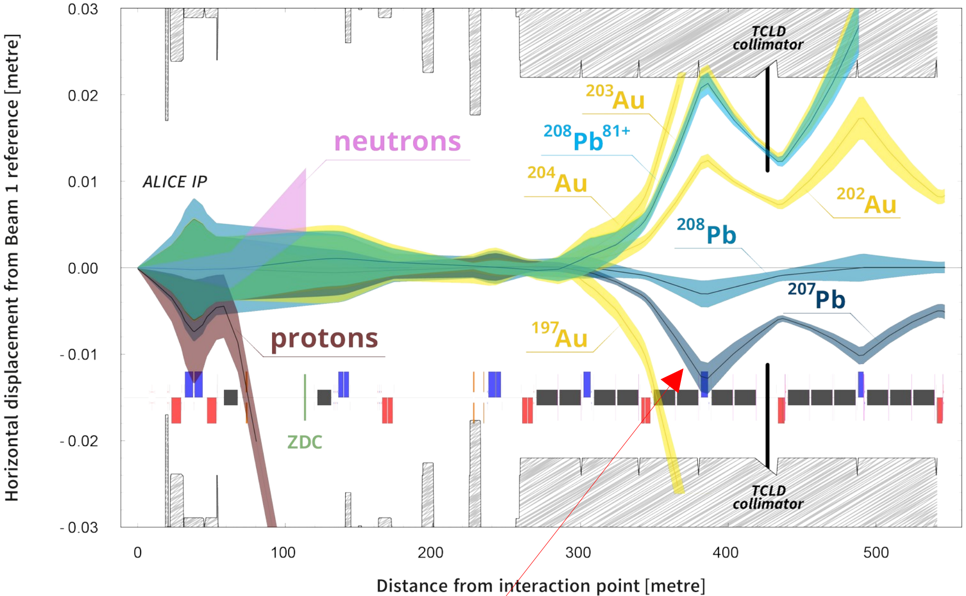
PHYS.ORG

ALICE detects the conversion of lead into gold at the Large Hadron Collider

Phys.org, 08 May 2025

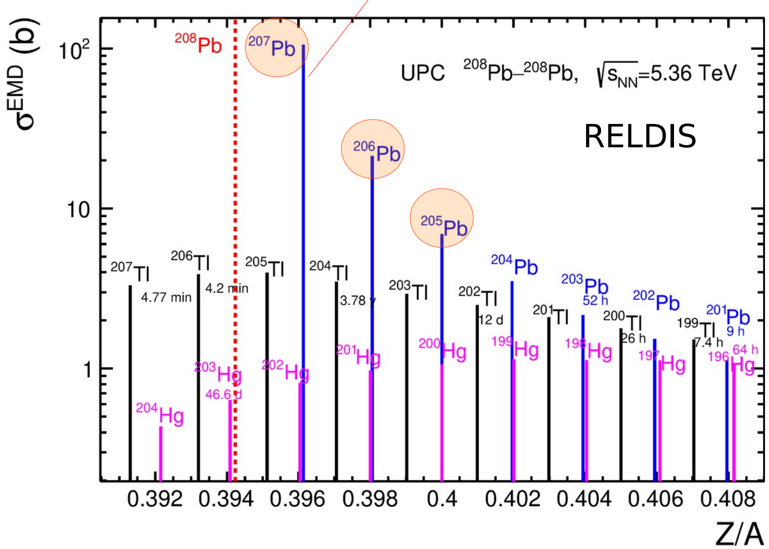
In a paper published in Physical Review C, the ALICE collaboration reports measurements that quantify the transmutation of lead...

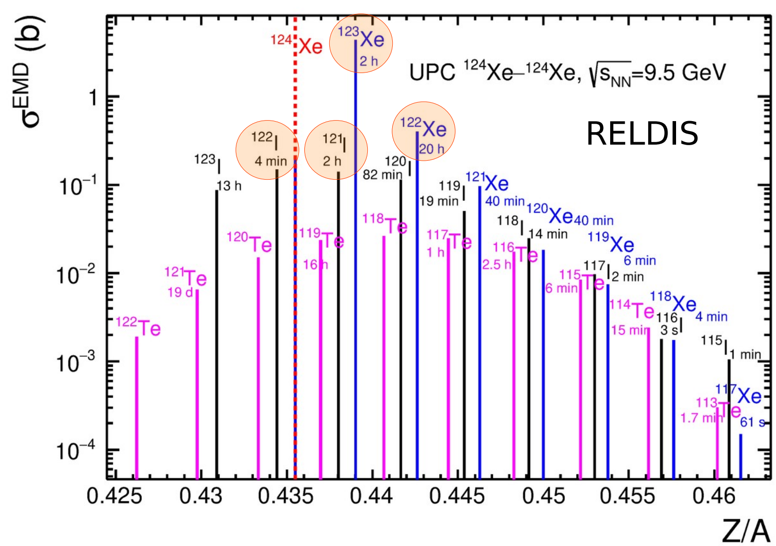
Secondary nuclei: EMD of ^{208}Pb at the LHC and ^{124}Xe at NICA



- Trajectories of secondary ions were thoroughly modeled at the LHC
- Extra measures were taken to avoid quenching of superconducting magnets[1)]
  [1)] R. Bruce et al., Phys. Rev. ST Accel. Beams **12** (2009) 071002

- $^{122,123}Xe$ and $^{121,122}I$ are produced most frequently at NICA.
- Their impact on NICA components is not yet studied (heating, impact on beam monitors/detectors, background?)





First-ever p-^{16}O, ^{16}O-^{16}O, ^{20}Ne-^{20}Ne collisions at the LHC

- **CERN press release:** "The Large Hadron Collider gets a breath of fresh air as it collides beams of protons and oxygen ions for the very first time… From 29 June to 9 July, 2025 the LHC will switch to a special operations: two days of proton–oxygen ion collisions, followed by two days of oxygen–oxygen collisions and one day of neon–neon collisions."
  1 July, 2025 | By Anaïs Schaeffer
  https://home.cern/news/news/accelerators/first-ever-collisions-oxygen-lhc

- **Fun fact:** After several hours in the accelerator, the oxygen beams might have to be ejected because of "beam pollution". "This is a problem that we don't face with proton beams, but with oxygen we experience what's called the transmutation effect," explains Roderik Bruce, an LHC ion specialist. "Each collision creates secondary particles of the same charge-to-mass ratio as oxygen ions, polluting the beam and potentially making it complicated to analyse collisions. So, at some point, we might need to eject the beam and inject a new beam of pure oxygen…"

- **The first estimate, 1-10% pollution:** A. Svetlichnyi et al., "Clustering in Oxygen Nuclei and Spectator Fragments in ^{16}O–^{16}O Collisions at the LHC", Physics 5 (2023) 381

- **A recent study:** G. Nijs, W. van der Schee, "Transmutation of ^{16}O and ^{20}Ne at the Large Hadron Collider", arXiv:2507.01659 [nucl-th], 2 Jul 2025

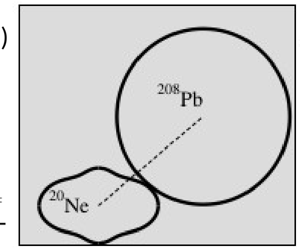
Fragmentation of self-conjugate deformed ^{20}Ne nuclei

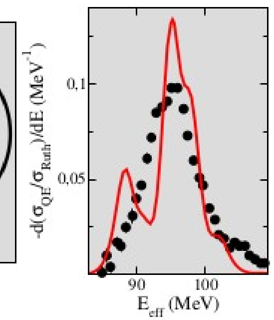
- ^{20}Ne is a self-conjugate nucleus in the isospin space: N=Z (2Z=A)
- Two options to account for its deformation in Glauber MC/AAMCC models :

I. A deformed shape of ^{20}Ne represented by deformed Woods-Saxon[1)]

$$\rho(x,y,z) = \frac{\rho_0}{1+\exp\lfloor(r-R(1+\beta_2 Y_{20}+\beta_4 Y_{40}))/a\rfloor}$$

$$Y_{20}(x,y,z) = \sqrt{\frac{5}{\pi}}\frac{2z^2-x^2-y^2}{4r^2}, \quad Y_{40}(x,y,z) = \frac{3}{\sqrt{\pi}}\frac{35z^4-30z^2r^2+3r^4}{16r^4}$$





Shape is reflected in quasielastic barrier distribution[3)]

with the following radii, diffuseness parameters[2)] and deformation parameters.

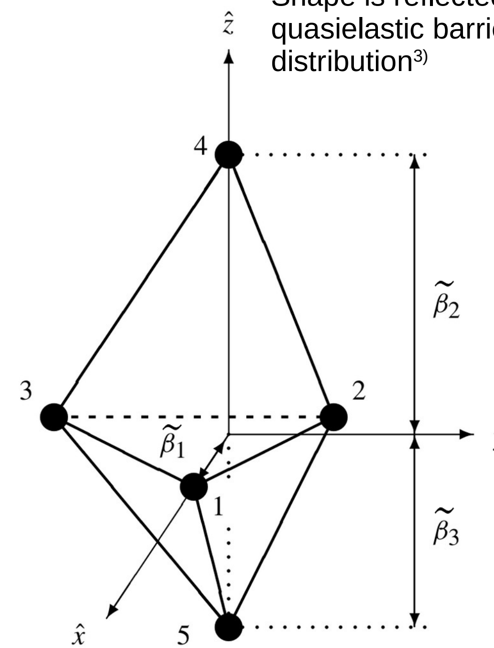
^{20}Ne: $R = 2.422$ fm, $a = 0.592$ fm, $\beta_2 = 0.46$, $\beta_4 = 0.27$

^{22}Ne: $R = 2.396$ fm, $a = 0.598$ fm, $\beta_2 = 0.42$, $\beta_4 = 0.27$

II. α-clustering effects are also expected leading to a clustered bi-pyramid shape[4)] with $\tilde{\beta}_1 = 2$ fm, $\tilde{\beta}_2 = \tilde{\beta}_3 = 2.51$ fm tuned to describe R and a given above.

In its turn, α-clusters are described by harmonic oscillator density distribution: $\rho(r) \propto r^2\left(1 + a_\alpha \frac{r^2}{R_\alpha^2}\right)\exp(-\frac{r}{R_\alpha^2})$

$R_\alpha = 1.68$ fm, $a_= 0.544$ fm.



[1)] Suitable for Glauber MC: Q.Y. Shou et al., PLB 749 (2015) 215

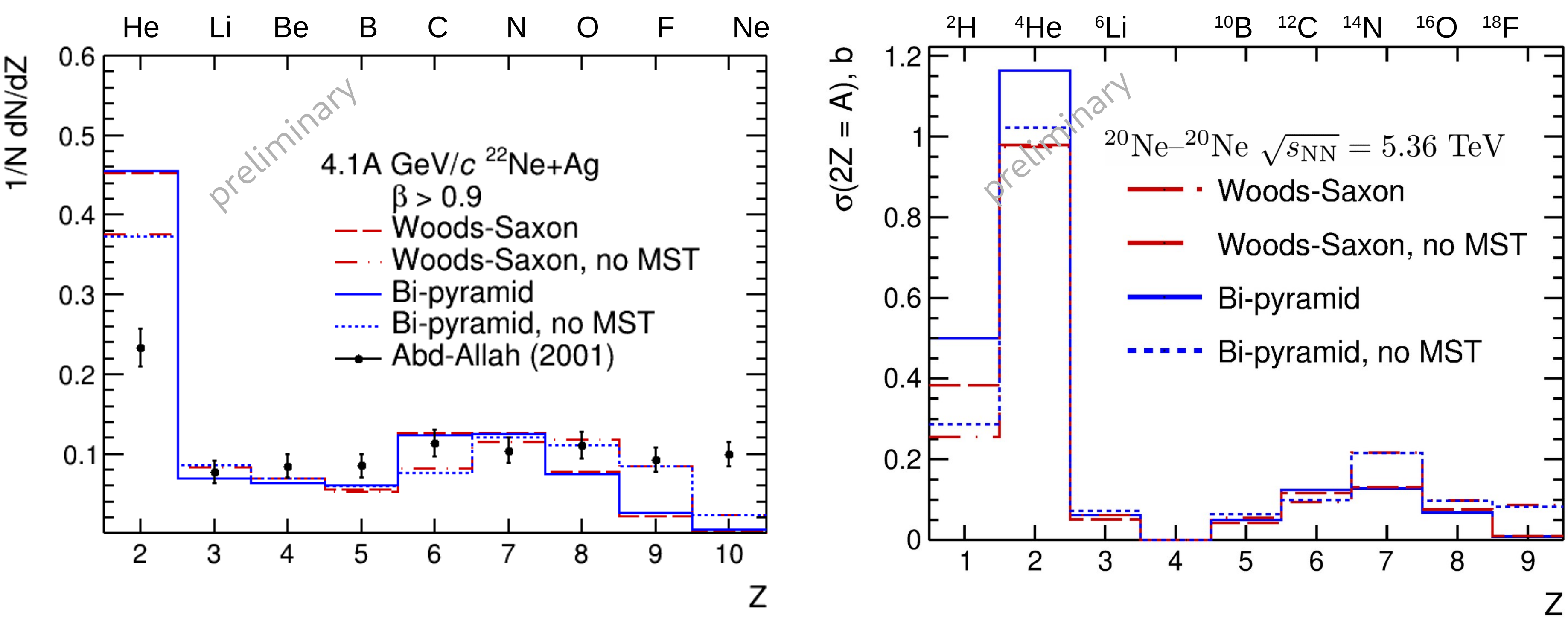
[2)] Extracted from data on proton elastic scattering: Z.H. Li et al., PRC 107 (2023) 064310

[3)] N. Rowley, J.Phys.Conf.Ser. 381 (2012) 012086

[4)] R.Bijker, F. Iachello, NPA 1006 (2021) 122077

Neon fragmentation at Dubna Synchrophasotron and LHC

- Ne-Ne collisions were not studied in experiments.
- However, there were measurements in Dubna with 4.1A GeV/c ^{22}Ne fragmenting in nuclear emulsion, in particular, on Ag(Br)
- Charge distributions of secondary nuclei from ^{22}Ne can be used to test AAMCC-MST

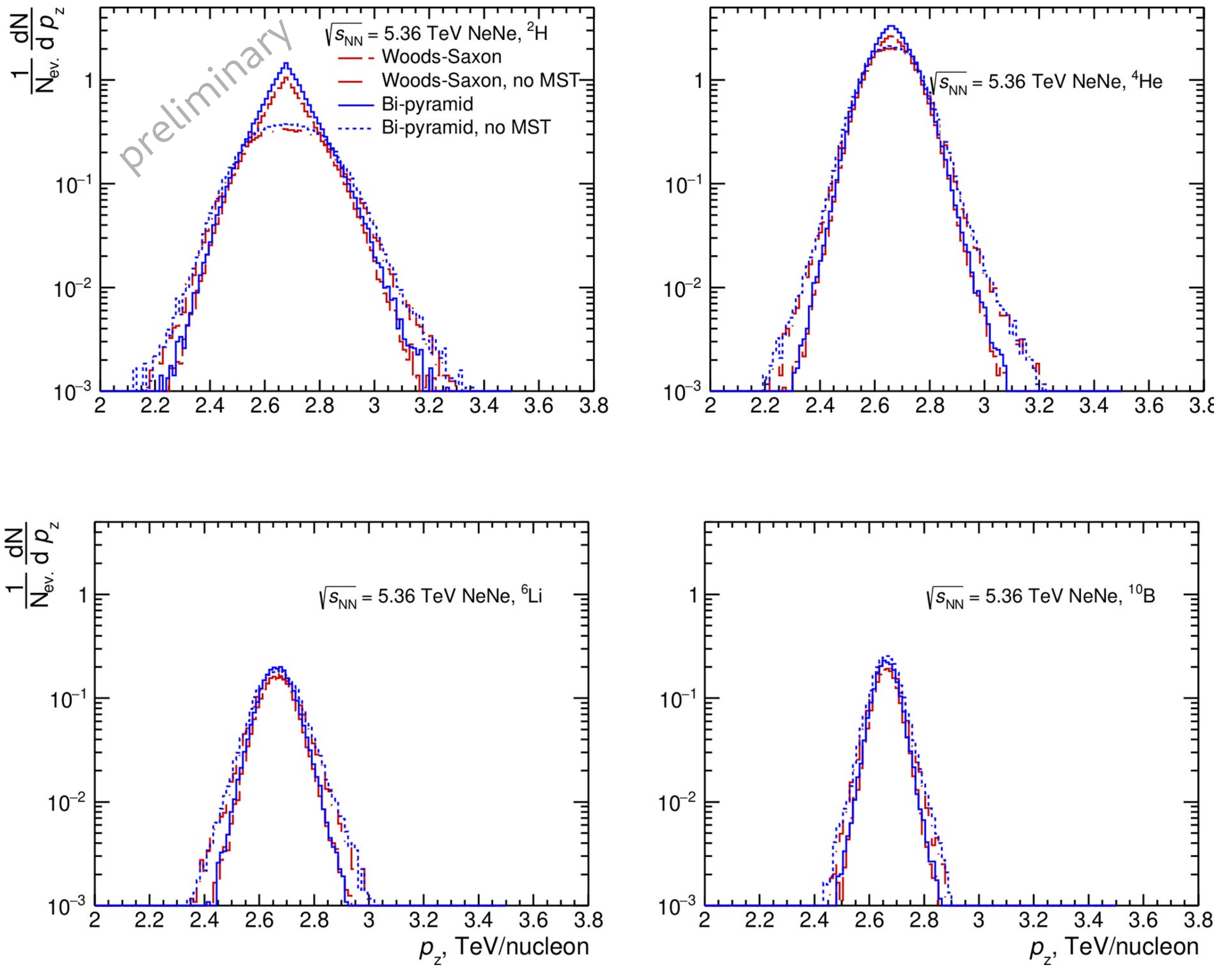


- Results with bi-pyramid+2n ^{22}Ne without MST are closer to data, but He yield is not well described.
- Not very sensitive to the presence of α-clusterization, but depend on preequilibrium MST-clustering.
- Note the absence of ^{8}Be among 2Z=A products at the LHC.

Data from N.N. Abd-Allah, M. Mohery, Czech. J. Phys. 51 (2001) 1189

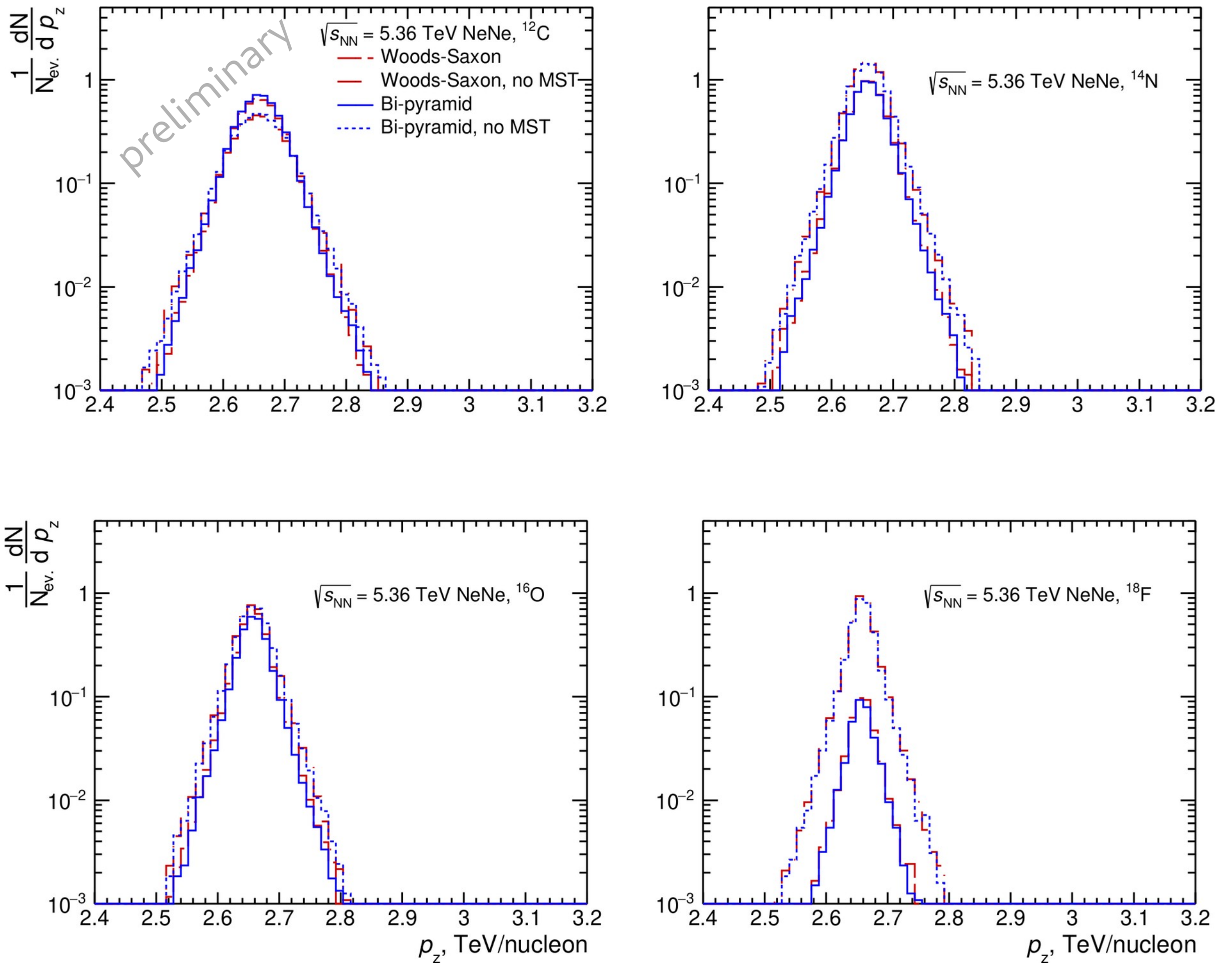
Transverse momentum distributions of ^{2}H, ^{4}He, ^{6}Li, ^{10}B calculated with AAMCC

- Can be used in modeling their propagation in the LHC with beam optics software.
- Species with p_z far from the nominal beam momentum are typically intercepted by collimators



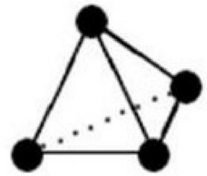
Transverse momentum distributions of ^{12}C, ^{14}N, ^{16}O, ^{18}F calculated with AAMCC

- Can be used in modeling their propagation in the LHC with beam optics software.
- Species with p_z far from the nominal beam momentum are typically intercepted by collimators



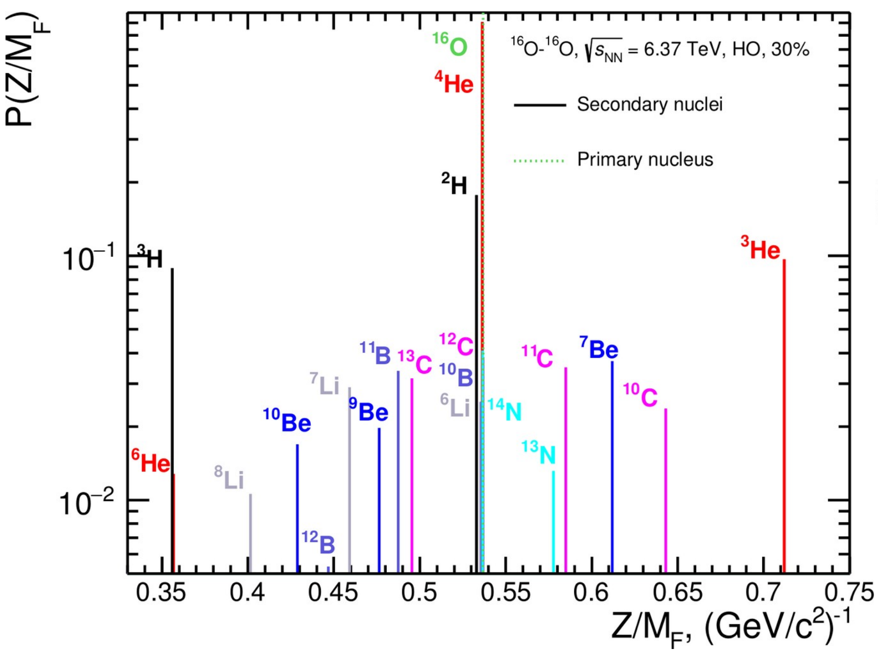
If the beam cleaning is not successful, ^4He-^{20}Ne, ^{14}N-^{20}Ne, ... collisions can take place!

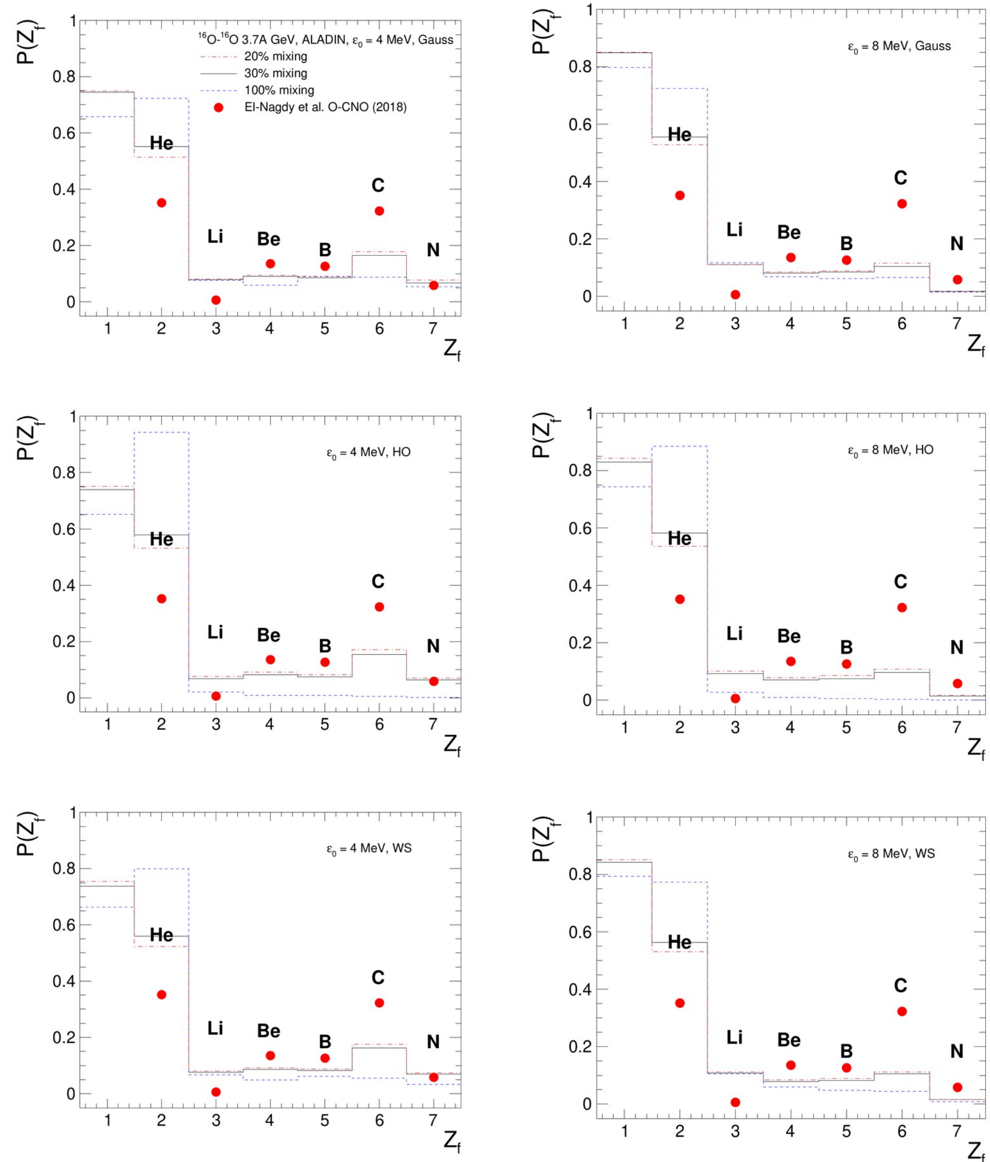
^{16}O-^{16}O at the LHC



- Tetrahedron shape of ^{16}O
- Essential α-clustering effects are expected in fragmentation
- 30% contribution of clustered states was found realistic on the basis of comparison with data
- ^{4}He are produced most frequently at the LHC

A. Svetlichnyi et al., Physics 5 (2023) 381





AAMCC-MST parameters were tuned with data on fragmentation of 3.7A GeV ^{16}O on CNO
A.Svetlichnyi et al., Phys. At. Nucl. 85 (2022) 958

Summary table: impact of secondary nuclei from nucleus-nucleus collisions in colliders

process	^{208}Pb-^{208}Pb $\sqrt{s_{NN}}$=5.36 TeV	^{129}Xe-^{129}Xe $\sqrt{s_{NN}}$=9.2 GeV	^{20}Ne-^{20}Ne $\sqrt{s_{NN}}$=5.36 TeV	^{16}O-^{16}O $\sqrt{s_{NN}}$=5.36 TeV
EMD	large cross sections, ^{207,206,206}Pb can hit LHC components	EMD cs ~ hadronic cs, possible impact from ^{121,122}I and ^{122,123}Xe [2)]	no impact [3)]	no impact [3)]
hadronic fragmentation	no impact [1)]	some fragments can be detected in forward detectors	^{2}H, ^{4}He, ^{6}Li, ^{10}B, ^{12}C, ^{14}N, ^{16}O, ^{18}F can circulate and collide with ^{20}Ne	^{2}H, ^{4}He, ^{6}Li, ^{10}B, ^{12}C can circulate and collide with ^{16}O

[1)] Relatively small cross sections, various spectator nuclei are produced, but are not transported along with beam nuclei

[2)] Further studies by accelerator experts are necessary in addition to the impact from BFPP

[3)] Relatively small cross sections, very few 2Z=A nuclei

Conclusions

- Collisions of relativistic beam nuclei in heavy-ion colliders lead to their transmutation to other elements

- AAMCC and RELDIS models calculate the yields

- Such phenomena are very interesting as a connection between nuclear structure and high-energy physics

- They affect the collider operation (collisions of heavy nuclei) or data taking (collisions of light nuclei)

- Thank you for your attention!