Modelling ^{20}Ne–^{20}Ne collisions at the LHC

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Outline

- To investigate the origin of the collectivity in the overlap region of light colliding nuclei, the system-size scan program at the LHC was initiated.
- Xe–Xe collisions run were already finished.
- ^{16}O–^{16}O and ^{20}Ne–^{20}Ne runs are planned [1].
- As demonstrated [2], the production of spectator fragments from initial ^{16}O nuclei is sensitive to the presence of α-clustered states in ^{16}O.
- It is important to investigate whether similar effects are present in ^{20}Ne–^{20}Ne collisions.
- Spectator neutrons and protons are used to monitor the luminosity of LHC.
- Secondary nuclei with $A = 2Z$ can circulate along with the initial beams.

1) R. Alemany Fernandez, PoS **478** (2024) 0335, http://doi.org/10.22323/1.478.0335
2) A.Svetlichnyi et al., Physics, **5** (2023) 381

^{20}Ne nuclear density profiles

The exact density profile of ^{20}Ne is still under discussion:

1. Deformed Wood-Saxon non-clustered configuration has been considered [1].
2. However, significant contributions of clustered states has been considered as well (bi-pyramidal clustered configuration) [2].

1) Li, Z. H., Kuang et al., Matter density distributions of ^{20},^{22}Ne and ^{24},^{26}Mg extracted through proton elastic scattering at 0.8 GeV. Phys. Rev. C 107, 064310 (2023).
2) Bijker, R., Iachello, F. Cluster structure of ^{20}Ne: Evidence for D3h symmetry. Nucl. Phys. A 1006, 122077 (2021).

1. Deformed Wood-Saxon configuration

- 2pF model was used to describe nuclear matter density:

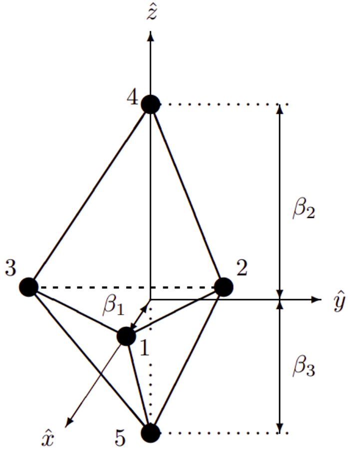
$$\rho(x,y,z) = \frac{\rho_0}{1+\exp\left(\frac{r-R(1+\beta_2 Y_{20}(\theta,\varphi)+\beta_4 Y_{40}(\theta,\varphi))}{a}\right)}$$

- Parameters R and a:
  — ^{20}Ne: $R = 2.422(67)$ fm, $a = 0.592(30)$ fm, $\beta_2 = 0.46$, $\beta_4 = 0.27$.
  — ^{22}Ne: $R = 2.396(170)$ fm, $a = 0.598(66)$ fm, $\beta_2 = 0.42$, $\beta_4 = 0.27$.

Li, Z. H., Kuang et al., Matter density distributions of ^{20,22}Ne and ^{24,26}Mg extracted through proton elastic scattering at 0.8 GeV. Phys. Rev. C 107, 064310 (2023).

2. Bi-pyramidal cluster configuration

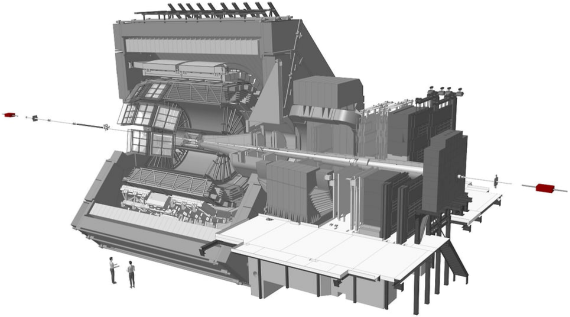
- Clustered state can be described using the bi-pyramidal configuration.
- The parameters $\beta_1 = 2.00$ fm, $\beta_2 = \beta_3 = 2.51$ fm were tuned to describe R, a of the nuclei.
- Alpha clusters are represented using the following harmonic oscilator density distribution:
  - $\rho(r) \propto r^2 \left(1 + a\left(\frac{r^2}{R^2}\right)\right) \exp\left(-\frac{r^2}{R^2}\right)$
  - $R = 1.68$ fm, $a = 0.544$ fm.



Bijker, R., Iachello, F. Cluster structure of ^{20}Ne: Evidence for D3h symmetry. Nucl. Phys. A 1006, 122077 (2021).

Role of spectators in system-size scan

- ALICE collaboration used Zero Degree Calorimeters to determine collision centrality and monitor collider luminosity by detecting forward neutrons [1].



- Can the same methods be applied to Ne–Ne collisions?

1) B. Abelev et al. (ALICE Collaboration), "Phys. Rev. C.,"vol. 88, p. 044909, 2013.

Our Abrasion-Ablation Monte Carlo for Colliders model

Simulation stages in AAMCC [1]:

- The Glauber Monte Carlo model simulates nucleus-nucleus collisions [2], where spectator matter (prefragment) is formed by non-participating nucleons.
- The excitation energy of the prefragment can be estimated as follows:
  - The Ericson formula based on the particle-hole model [3].
  - The ALADIN parabolic approximation [4] for light and heavy nuclei.
  - A hybrid method: Ericson formula for peripheral collisions and ALADIN otherwise.
- MST clustering with accounting for Coulomb repulsion [5]
- Deexcitation follows Geant4 decay models [6]:
  - Fermi break-up model.
  - Statistical Multifragmentation Model (SMM).
  - Weisskopf-Ewing evaporation model.

1) R. Nepeivoda et al., "Pre-Equilibrium Clustering in Production of Spectator Fragments in Collisions of Relativistic Nuclei,"Particles, vol. 5, pp. 40-51, 2022.

2) S. Loizides, J. Kamin, D. d'Enterria, "Phys. Rev. C,"vol. 97, p. 054910, 2018.

3) T. Ericson, "Advances in Physics,"vol. 9, p. 737, 1960.

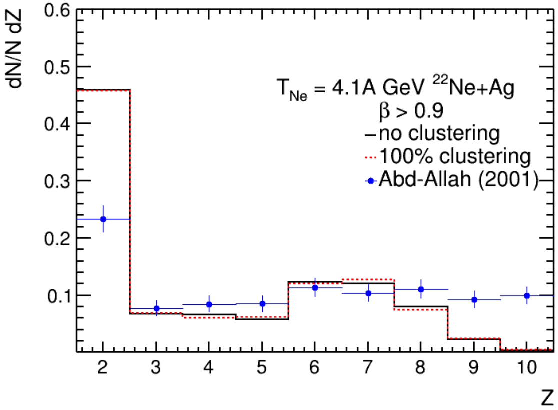
4) A. Botvina et al., "Nuclear Physics A,"vol. 584, 1995.

5) E. Vasyagina et al., PEPAN Lett., in print

6) J. Alison et al., "Nucl. Inst. A,"vol. 835, p. 186, 2016.

Model validation with experimental data

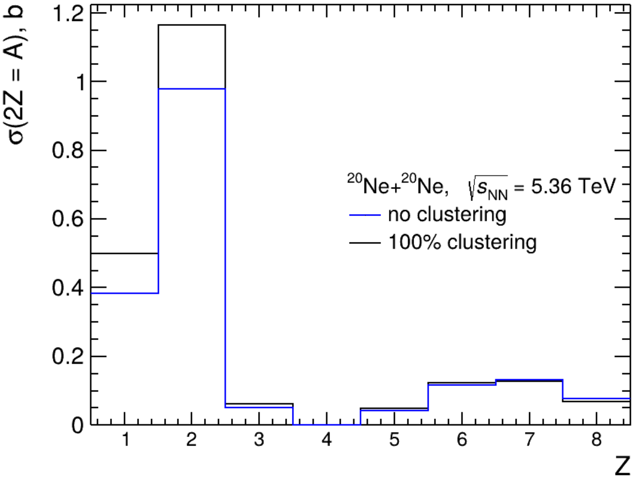
- The considered nuclear density profiles of ^{20}Ne, ^{22}Ne were incorporated in AAMCC to model the ^{22}Ne+Ag 4.1A GeV collisions.
- The calculated multiplicity distribution of spectator fragments agrees well in general with experimental data [1].
- The underestimation of the $Z = 9, 10$ fragments can be attributed to electromagnetic dissociation of ^{22}Ne.
- Here, the impact of the clusterization in ^{22}Ne is insignificant.



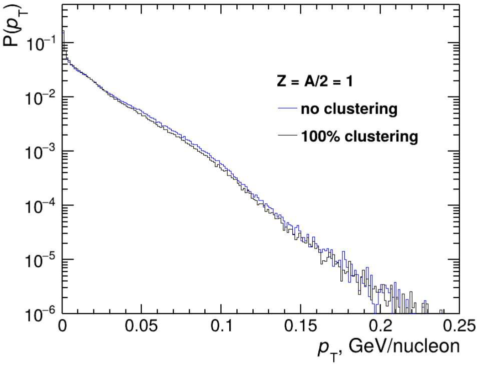
1) Abd-Allah, N. N., Mohery, M. Multiplicity of secondary particles and fragmentation in nuclear interactions of ^{22}Ne and ^{32}S nuclei with emulsion at (4.1–4.5) A GeV/c. Czechoslovak J. Phys. 51, 1189–1204 (2001).

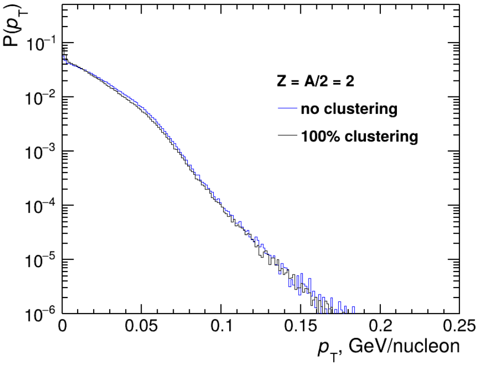
Modelling ^{20}Ne–^{20}Ne collisions at $\sqrt{s_{NN}} = 5.36$ TeV at the LHC

- The production of spectator fragments with $2Z = A$ demonstrates:
  - — sensitivity to the clusterization in ^{20}Ne for hydrogen and helium fragments.
  - — more helium fragments with clustered configuration in ^{20}Ne.



Transverse momentum distribution with $2Z = A$.

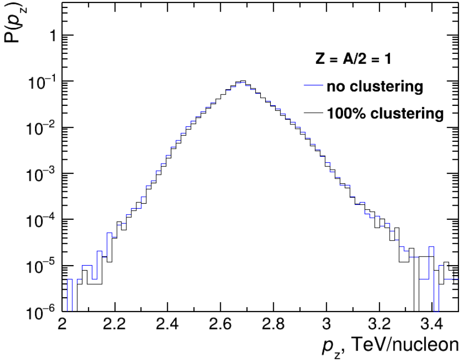


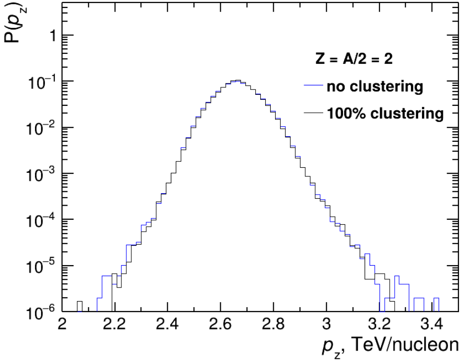


The effect of the presence of α−clusters in ^{20}Ne on the p_T distributions is negligible.

Modelling ^{20}Ne–^{20}Ne collisions at $\sqrt{s_{NN}} = 5.36$ TeV at the LHC

Longitudinal momentum distribution with $2Z = A$.

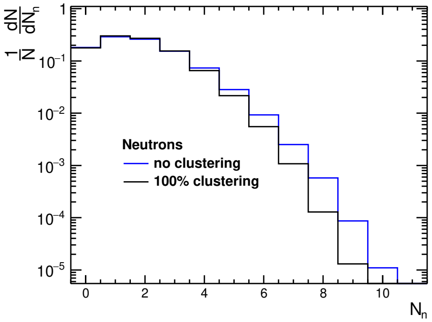


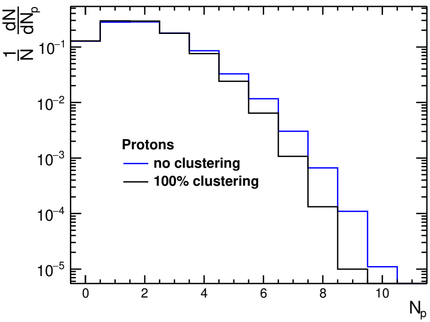


The effect of the presence of $\alpha-$clusters in ^{20}Ne on the p_z distributions is negligible.

Modelling ^{20}Ne–^{20}Ne collisions at $\sqrt{s_{NN}} = 5.36$ TeV at the LHC

The production of neutrons and protons.

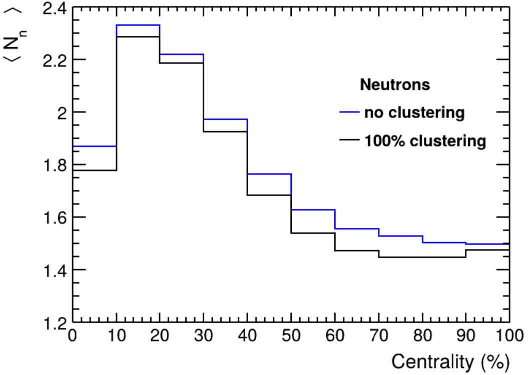


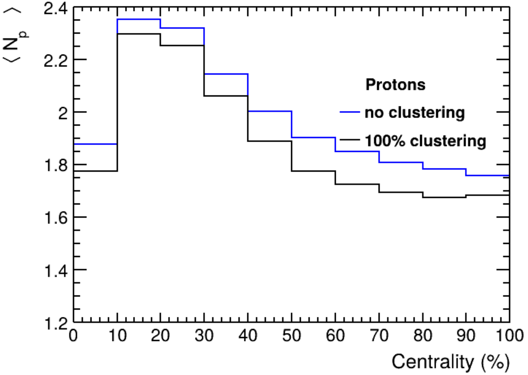


- A small fraction of events contains neither protons nor neutrons.
- The number of events with large multiplicity of protons and neutrons depends on alpha clustering in ^{20}Ne.

Modelling ^{20}Ne–^{20}Ne collisions at $\sqrt{s_{NN}} = 5.36$ TeV at the LHC

Average number of protons and neutrons in the events in given centrality bins.





More protons than neutrons in peripheral events because neutrons remain bound in fragments.

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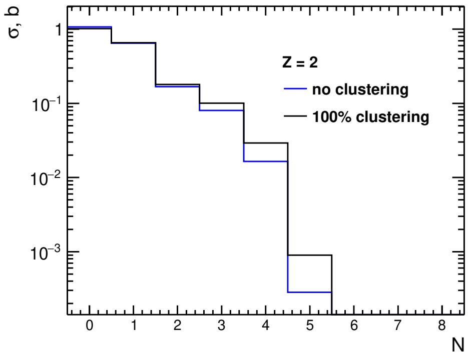
Production of helium fragments.



More alpha particles are produced in collisions of clustered ^{20}Ne.

Conclusion

- The impact of the $\alpha-$clusterization in ^{22}Ne on the production of spectator fragments with given Z in nuclear emulsion is insignificant due to the presence of two valence neutrons.
- The yields of spectator fragments from ^{20}Ne–^{20}Ne collisions at the LHC, in particular, hydrogen and helium, are sensitive to the presense of $\alpha-$clusters.
- However, the impact of $\alpha-$clusterization on the p_T and p_Z distributions is insignificant for deutrons and $\alpha-$particles.
- About 25 % of events contain no spectator neutrons. This may affect the performance of neutron ZDC at the LHC.