Cumulative production of nucleons by heavy baryonic resonances in proton-nucleus collisions

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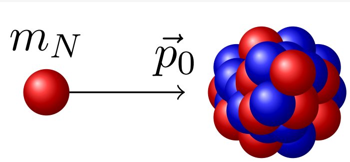
Outline

1. Introduction
2. Backward nucleon maximal energy in p+A collisions from energy -momentum conservation
   - $n = 2$
   - $n \geq 3$
3. UrQMD simulations
4. Summary and plans

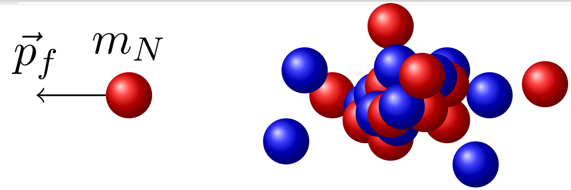
Introduction

Cumulative effect

- It is a creation of particle in p+A collision with energy outside the kinematical boundary of p+p interactions at the same beam energy.
- Discovered in 1971 in Dubna (Baldin, Leksin).



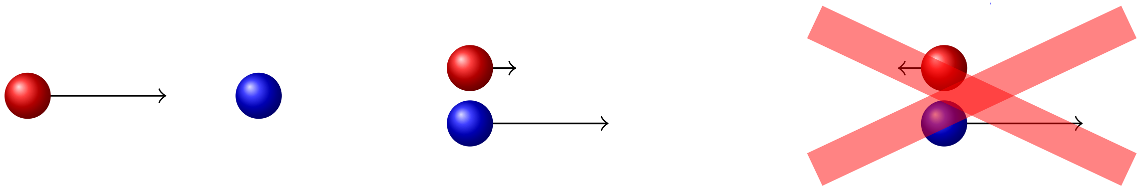
(a) Initial state.



(b) Final state.

A. Motornenko, M. I. Gorenstein, Journal of Physics G (2017)

Ways of production or backward nucleons



(c) Initial state. (d) Final state. (e) Final state.

Figure: Nucleon production in $N + N \rightarrow N + N$ reaction.

(a) Nucleon collision with moving nuclear nucleon.

(b) Nucleon collision with coupled nuclear nucleons.

Figure: Other reactions.

Backward nucleon production due to 2 successive collisions

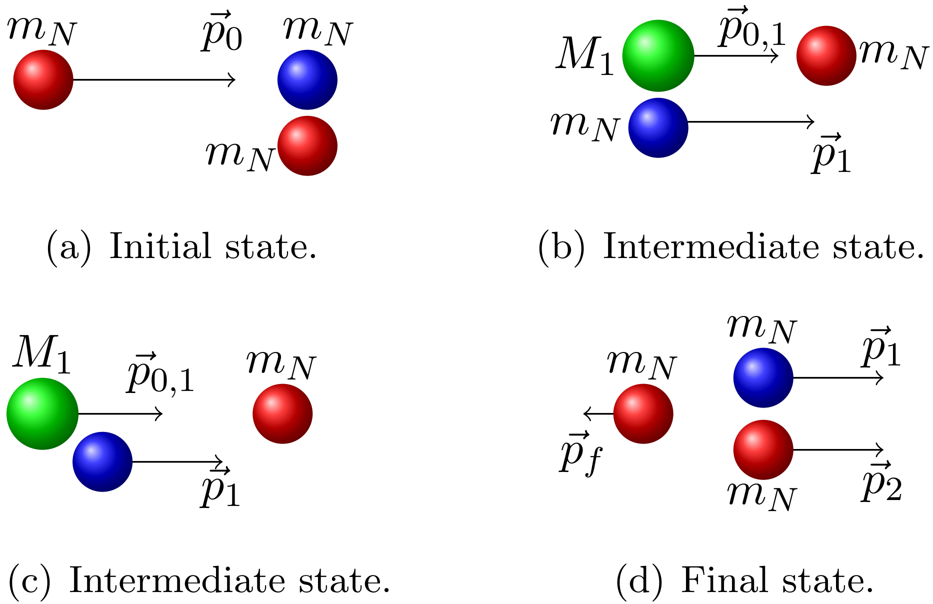


Figure: Nucleon production in $N + 2N \to 3N$ reaction.

Laws of energy momentum conservation for n = 2

$$\begin{cases} \sqrt{p_0^2 + m_N^2} + 2m_N = \sqrt{p_f^2 + m_N^2} + \sqrt{p_1^2 + m_N^2} + \sqrt{p_2^2 + m_N^2} \\ p_0 = p_1 + p_2 - p_f. \end{cases}$$

$$\sqrt{p_0^2 + m_N^2} + 2m_N = \sqrt{p_f^2 + m_N^2} + \sqrt{p_2^2 + m_N^2} + \sqrt{(p_0 + p_f - p_2)^2 + m_N^2}$$

$$\frac{\partial p_f}{\partial p_2} = 0 \qquad => \qquad p_1 = p_2 = p = \frac{p_0 + p_f^*}{2}$$

$$E_f^* = 2m_N + \sqrt{p_0^2 + m_N^2} - 2\sqrt{m_N^2 + \left(\frac{p_0 + \sqrt{{E_f^*}^2 - m_N^2}}{2}\right)^2}$$

Maximal energy for n = 2

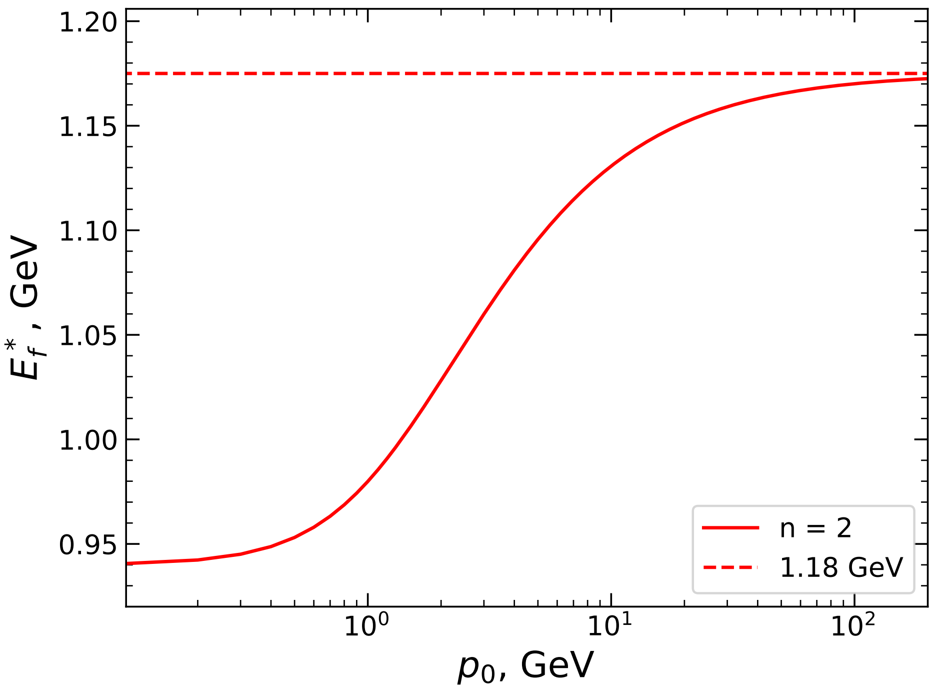


Figure: Maximal energy of nucleon emitted backward after 2 successive collisions as a function of projectile proton momentum.

Mass of resonance for n = 2

$$E_{0,1} = E_0 - E_1 - m_N, \qquad p_{0,1} = p_0 - p_1$$

$$M_1^2 = E_{0,1}^2 - p_{0,1}^2 \quad => \quad M_1^2 = (E_0 - \sqrt{p_1^2 + m_N^2} - m_N)^2 - (p_0 - p_1)^2$$

$$M_1^2 = \left(E_0 - \sqrt{\left(\frac{p_0 + p_f^*}{2}\right)^2 + m_N^2} - m_N \right)^2 - \left(p_0 - \left(\frac{p_0 + p_f^*}{2}\right)\right)^2$$

Mass of resonance for n = 2

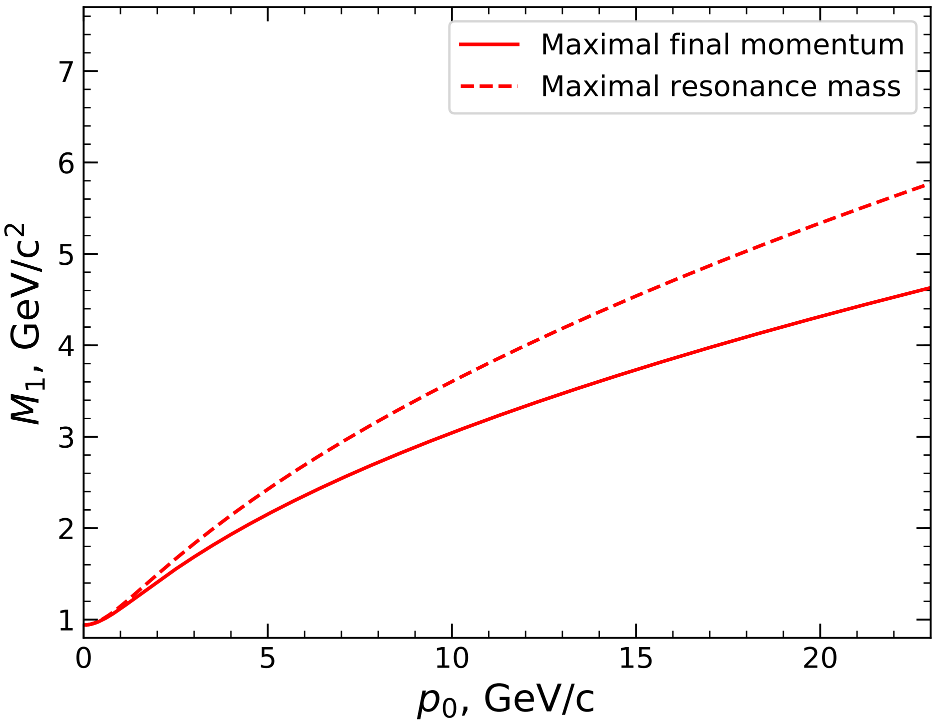


Figure: Mass or resonance after 1 collision.

Maximal energy of backward nucleon and mass of resonance for n $\geq$ 3

$$p_1 = ... = p_n = p = \frac{p_0 + p_f^*}{2}$$

$$E_f^* = nm_N + \sqrt{p_0^2 + m_N^2} - n\sqrt{m_N^2 + \left(\frac{p_0 + \sqrt{{E_f^*}^2 - m_N^2}}{n}\right)^2}$$

$$M_k^2 = \left(E_0 + km_N - k\sqrt{m_N^2 + \left(\frac{p_0 + p_f^*}{n}\right)^2}\right)^2 - \left(p_0 - k\left(\frac{p_0 + p_f^*}{n}\right)\right)^2$$

Maximal energy of backward nucleon for n $\geq$ 2

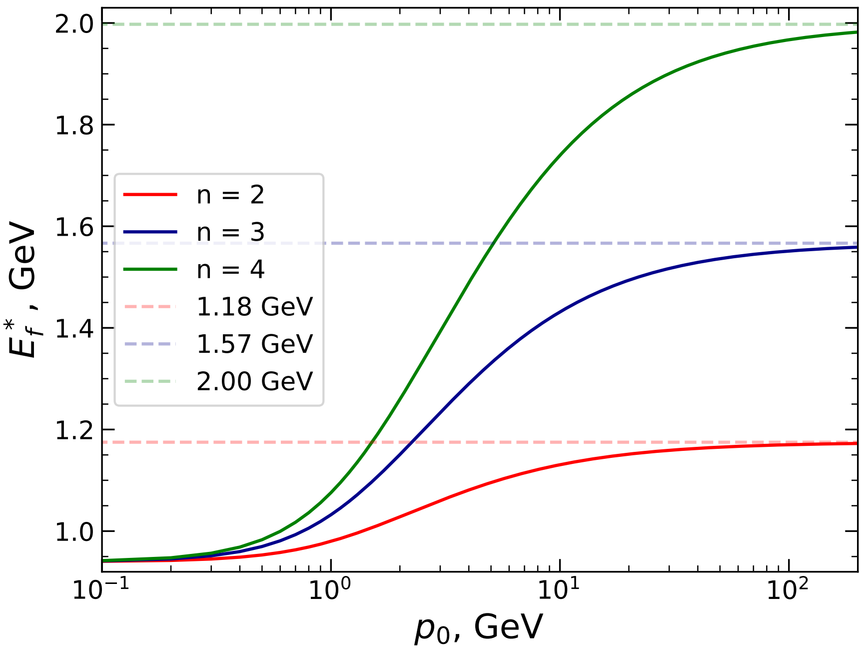


Figure: Maximal energy of backward nucleon after 2, 3 and 4 successive collisions.

Resonance mass for n = 4

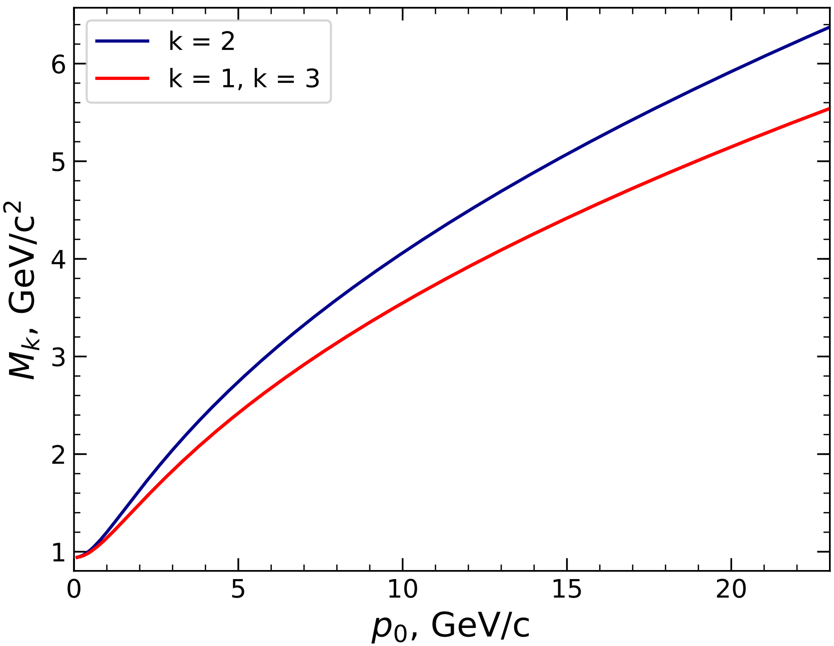


Figure: Mass or resonance after 1, 2 and 3 successive collisions in 4 collision event.

Model description

UrQMD

- UrQMD is a microscopic transport model used to simulate (ultra)relativistic heavy ion collisons in the wide range of energies developed in Goethe University Frankfurt.
- Includes resonances and strings.
- Gives information about full history of every collision.
- Gives information about sources of particles.
- References:
  S. A. Bass, M. Belkacem, M. Bleicher and others:
  Microscopic Models for Ultrarelativistic Heavy Ion Collisions Prog. Part. Nucl. Phys. 41 (1998)
  Relativistic Hadron-Hadron Collisions in the Ultra-Relativistic Quantum Molecular Dynamics Model J. Phys. G: Nucl. Part. Phys. 25 (1999)

Results

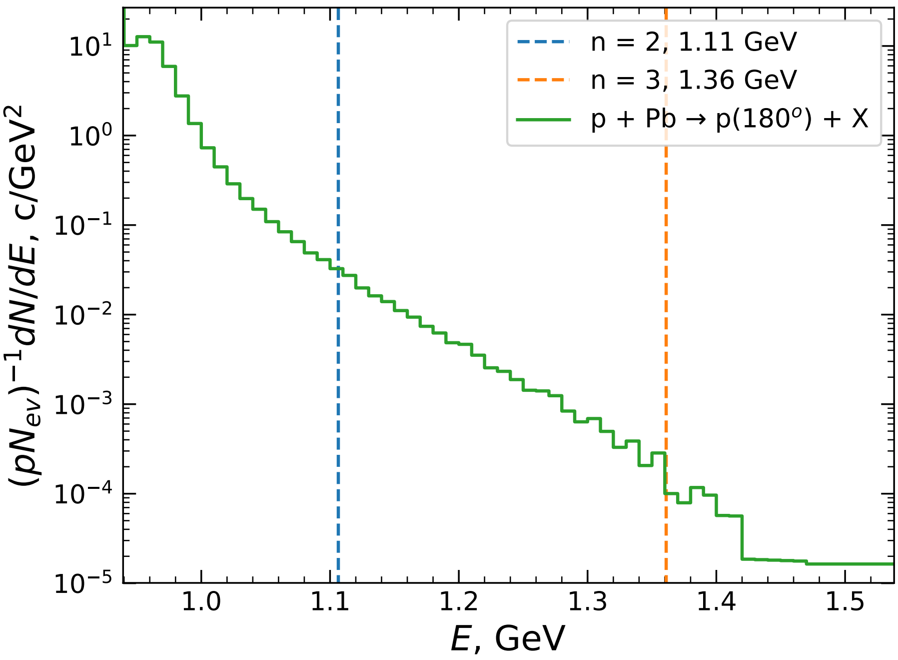


Figure: UrQMD results.

- p+Pb reactions,
- $p_{\text{lab}} = 6$ Gev/c,
- 10^7 collisions.

Results

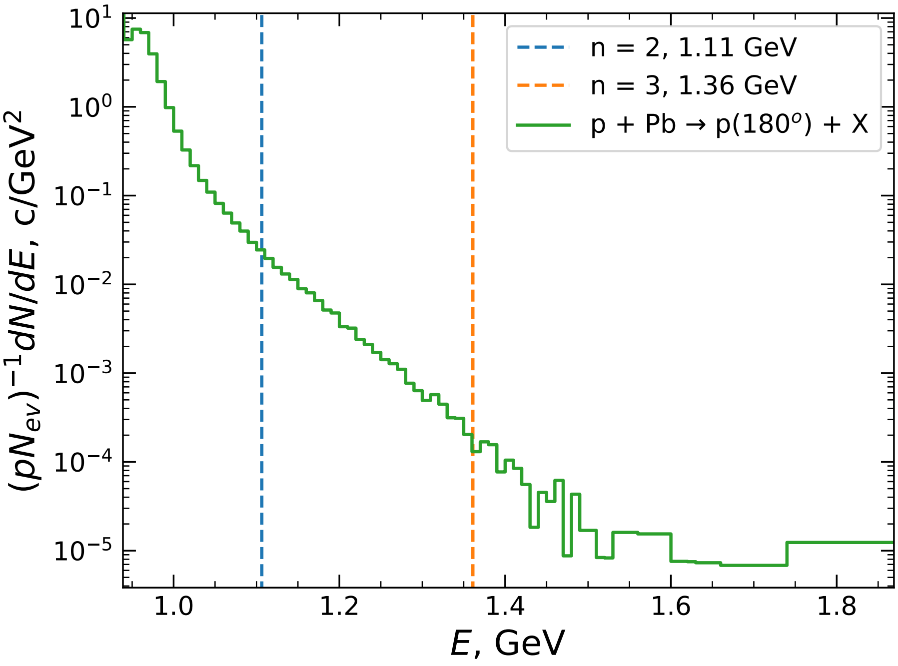


Figure: UrQMD results.

- p+Pb reactions,
- $p_{\text{lab}} = 158$ Gev/c,
- 10^7 collisions.

Results

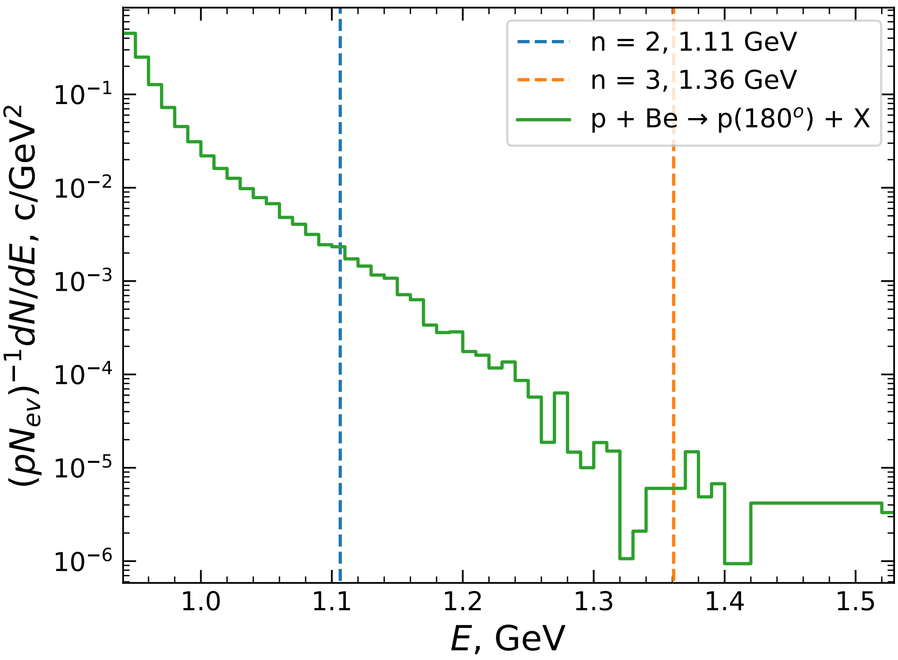


Figure: UrQMD results.

- p+Be reactions,
- $p_{\rm lab} = 6$ Gev/c,
- 10^8 collisions.

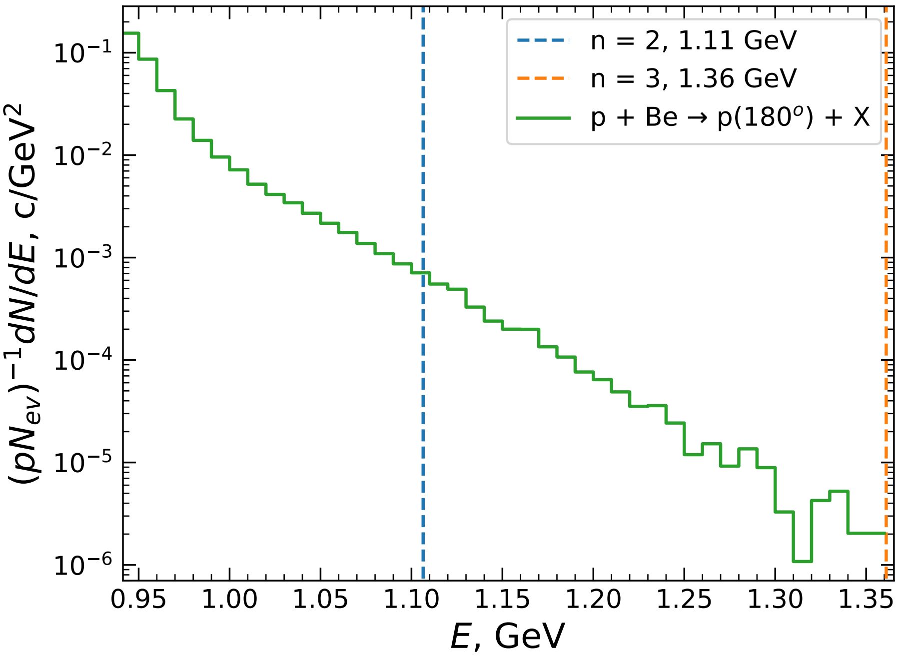


Figure: UrQMD results.

- p+Be reactions,
- $p_{\text{lab}} = 158$ Gev/c,
- 10^8 collisions.

Summary

- Production of cumulative nucleons is possible only after 2 or more successive collisions.
- Creating of backward nucleons requires existence of heavy resonances.

Further plans

- Collect more data for other nuclei in wide energy range (10 — 160 GeV).
- Select nucleons created after 2, 3 and more collisions in each data sample.
- Make similar calculations for other particles (e.g. kaons).
- We believe that heavy resonances will be discovered due to our predictions.