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Numerical study of neutron and nuclear fragment production using UrQMD model supplemented by statistical multi-fragmentation model.

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1. Introduction

-UrQMD model is widely used in modern high energy experiments.

$$\frac{df_i(x,p)}{dt} \equiv \frac{\partial p}{\partial t}\frac{\partial f_i(x,p)}{\partial p} + \frac{\partial x}{\partial t}\frac{\partial f_i(x,p)}{\partial x} + \frac{\partial f_i(x,p)}{\partial t} = Stf_i(x,p)$$

- $f_i(x,p)$ are phase space densities of the particle species $i = N, \Delta, \Lambda$
- x, p are position and momentum of a particle.
- $Stf_i(x,p)$ denotes the collision term.

(See Ref: https://github.com/keweiyao/urqmd-afterburner)

- Cross-sections of various meson-meson, meson-baryon, and baryon-baryon interactions are implemented in the model.

❖ **At small energies there are:**

$N + N \to \Delta N, \Delta\Delta, N * N, \ldots;\ M + N \to \Delta^0, \Lambda, \ldots$

- Potential interactions between baryons are considered: Yukawa, Columb, Pauli Potentials.

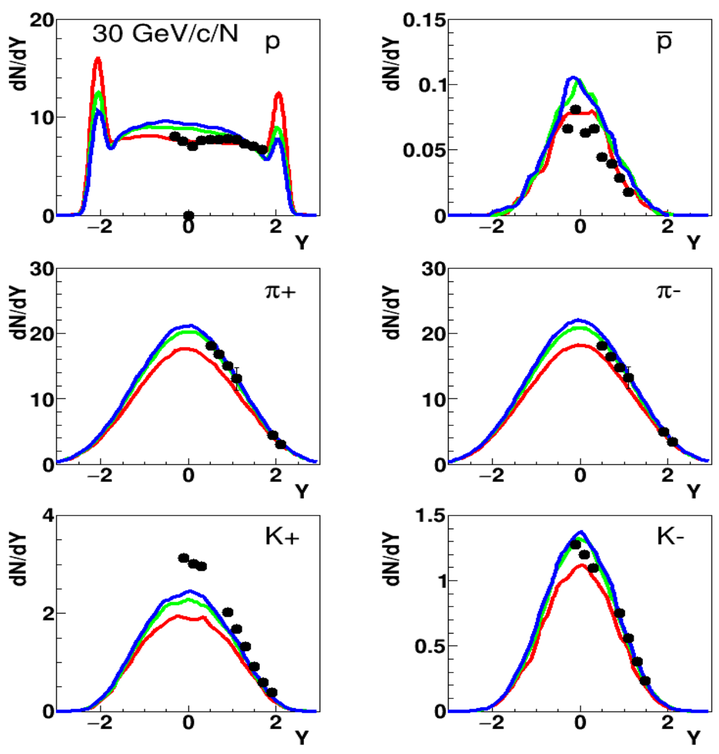
❖ **At high energies:**

- $Q\bar{Q}$ string creation is similar to FRITIOF model.
- String fragmention and formation time of particles
- Production of various resonances (ρ, ω, η, Δ, Λ, Ξ and others) is included
- However, a creation of nuclear residuals is **NOT** implemented in the code

Our goal was to *predict* and *analyse* data for the NICA (BM@N and MPD) experiments.

2. UrQMD prediction for NA61

$\pi^{\pm}, K^{\pm}, p, \bar{p}$ production in NA61/SHINE experiment (Ar+Sc interactions) according to UrQMD model version 3.4 .



Centralities c are setting up from:

$$\sigma^{exp.} = c \times \sigma^{inel.} = \pi B_{max}^2$$

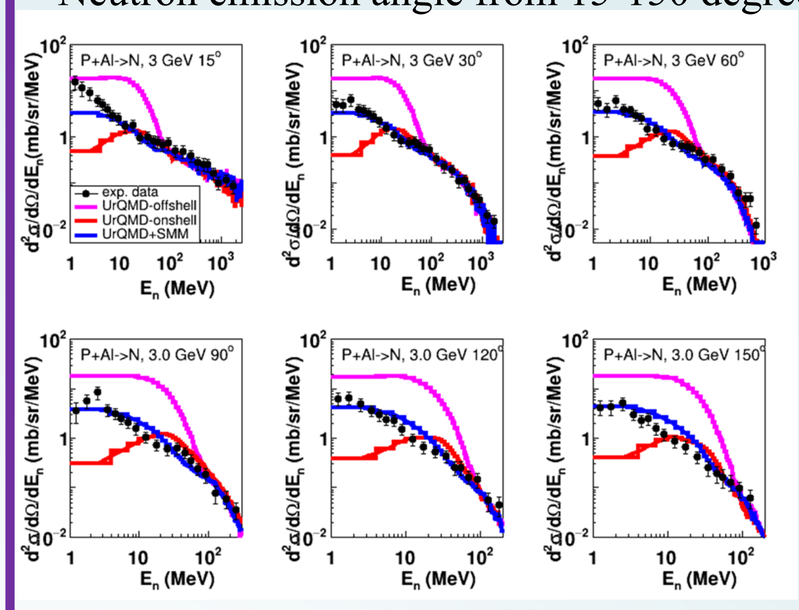
UrQMD c=10%
UrQMD c=2.5%
UrQMD c=0%
Exp. data (NA61/SHINE)

NA61/SHINE Collaboration., Adhikary, H., Adrich, P. *et al. Eur. Phys. J. C* **84**, 416 (2024)

Similar results were *obtained* at **P_{lab}=13,19,75,150GeV/c**

3. Neutron production

Neutron emission angle from 15-150 degrees



There is a *good agreement* between the modified model and exp. data at large En (blue line). On-shell neutrons (red histograms). Offshell neutrons –magenta lines.

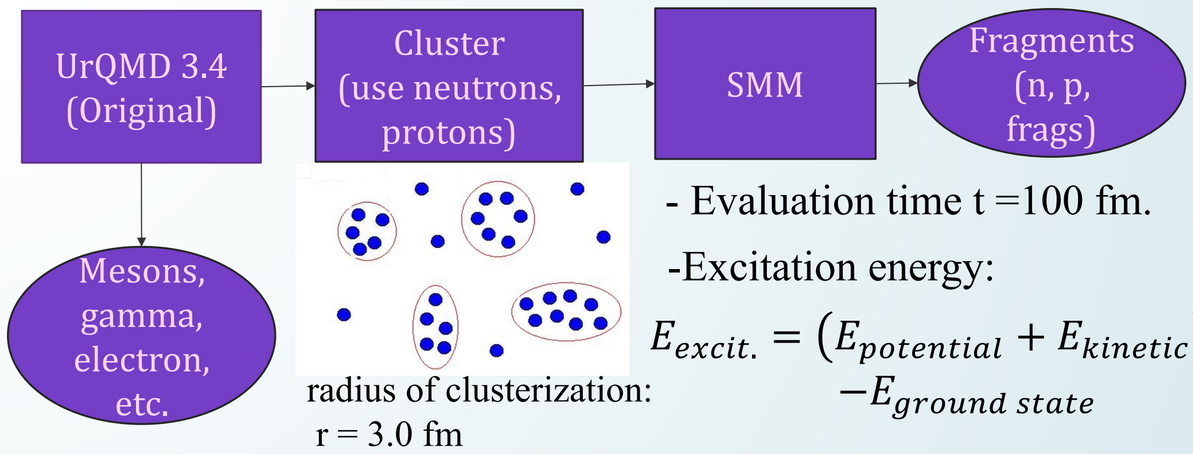
At all angles and small kinetic energies, UrQMD+SMM *underestimates* the neutron multiplicities.

Similar results are *obtained* for **p+Fe, p+Pb** interactions at E_n=3 GeV

(Exp. Data: K. Ishibashi et al., J.Nucl. Sci. Tech., Vol.34, N6 (1997) P. 529)

4. UrQMD+SMM Model

Coupling of UrQMD and SMM model - potential mode of UrQMD is used (Option: eos=1 Skyrm energy; Coulomb energy) + clusterization and SMM.



radius of clusterization: r = 3.0 fm

- Evaluation time t =100 fm.

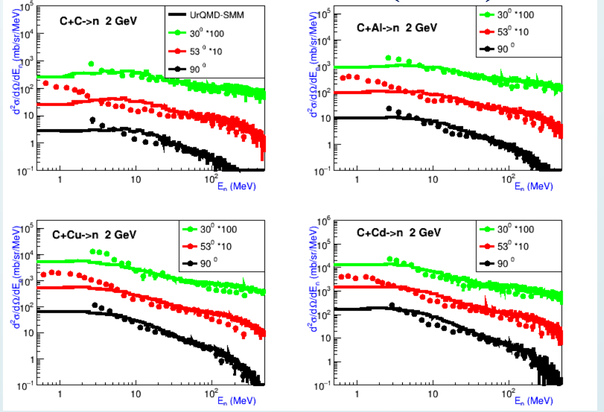
-Excitation energy:

$$E_{excit.} = (E_{potential} + E_{kinetic}) - E_{ground\ state}$$

5. Nucleus-nucleus interactions

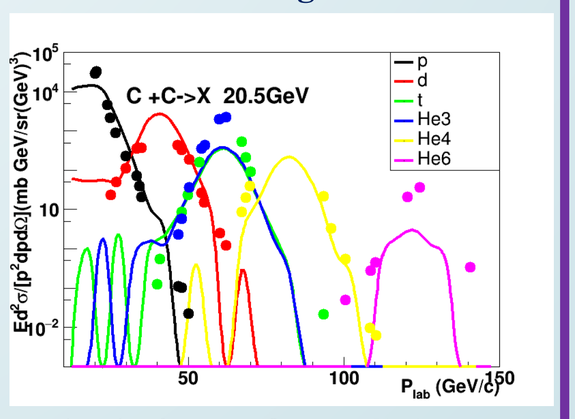
(Exp. Data: V. I. Yurevich, R.M. Yakovlev, V. G. Lyapin (JINR) Physics of Atomic Nuclei, 2006, Vol. 69, No. 9, P. 1496)

Neutron Data (JINR)



(Exp. Data: Afonin, A. G., et al. *Nuclear Physics A* 997 (2020): 121718)

Nuclear Fragments Data



At the request of the **BM@N** exp., the calculations of **Xe+Cs/I** interactions (10000 Events) at P_{lab} = 4.64 GeV/c have been done. Now, mass production (10^6 Events) of **Xe+W, Xe+Xe** interactions at E_{kin}=3.3 GeV has been performed for the **NICA/MPD** experiment.

6. Conclusion

-The **UrQMD 3.4** model has been coupled with **clustering model (Minimal Spanning Tree)** and **Statistical Multi- fragmentation Model**. As shown, the **UrQMD+SMM** model reproduces quite well neutron and fragment productions in proton-nucleus and nucleus-nucleus collisions. The combined model can be applied for NICA and RHIC experiments. This work was published in Physics of Particles and Nuclei journal (Galoyan, A.S., Le, T.Q., *et al.,* Coupling of UrQMD 3.4 and SMM Models for Simulation of Neutron and Nuclear Fragment Productions in Nucleus–Nucleus Interactions. *Phys. Part. Nuclei* **56**, 1433–1438 (2025).