Simulation of nuclear ion-ion reactions with the CRISP code

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Overview

Introduction

Ion nuclear reactions:

- Heavy ion reactions
- Light ion reactions
- Energy dependence

CRISP code

- MCMC
- MCEF
- Multimodal fission

Intranuclear Cascade

Initial interaction

- Proton.
- Deuteron (deprecated).
- Photon.
- Hyperon.
- Ion (Implemented within this work).
- Neutrino.
- Ultraperiferic interactions.

Objectives

Main objective

- Simulate ion–ion nuclear reactions using the CRISP code

Specific objectives

- Study nuclear reactions induced by protons
- Implementation of ion–ion nuclear reactions
- Compare observables for different steps of the nuclear reactions with experimental dates.

Proton reactions

Nuclear cascade implementation (proton)

- Target preparation
- Point of interaction of the proton with the nuclear surface
- Proton event generator
- Cascade execution

Nuclear cascade implementation (ion)

- Target and projectile preparation
- Point of contact of the two nuclei (Coulomb dispersion)
- Ion event generator with cascade execution.
- Cascade execution

Target preparation

- Square potential (effective mass)

$$E = \sqrt{p^2 + m_0^2} - V_0 = \sqrt{p^2 + m_{eff}^2} \tag{1}$$

$$m_{eff} = 0.95 m_0$$

- Fermi energy and moment for protons and neutrons:

$$Ef_{n,p} = \frac{\hbar^2}{2 m_n r_0^2} (\frac{9\pi}{4})^{2/3} (\frac{N, Z}{A})^{2/3} \tag{2}$$

$$Pf = \sqrt{Ef(Ef + 2m_{eff})} \tag{3}$$

Target preparation

- Quantum numbers

$$n^2 = n_x^2 + n_y^2 + n_z^2 \quad (4)$$

$$N_n = 6, 6, 12, 6, 18, 12, 18, 30, 18, 24, 12, 30, 18, 48....$$

- Moments for protons:

$$\vec{P} = \frac{p + P_{fn} - P_{fp}}{p}\vec{p} \quad (5)$$

$$E = \sqrt{P^2 + m_{eff}^2} \quad (6)$$

- For ion–ion is necessary to do the projectile preparation in similar way of target preparation.

Proton and ion reactions

Initial point of interaction

- For proton the entering position at the nucleus is sampled following a uniform distribution in the nuclear cross area.
- For ion-ion is calculate the initial contact point of the nucleus
- Is sampled the initial impact parameter:

$$b = (R_1 + R_2)sqrt(s) \tag{7}$$

- Is know the initial conditions:

$$r_0 = \infty,\ \theta_0 = 0,\ pr_0 = sqrt((T + m_{ion})^2 - m_{ion}^2),\ l_0 = r_0 pr_0$$

Initial point of interaction

- Coulomb dispersion $V = \frac{Z_1 Z_2 e^2}{r}$.
- Coulomb trajectory:

$$\frac{C}{r} = Acos(\theta - \theta_0) - 1 \quad (8)$$

- Contact point:

$$r = R_1 + R_2, \ \theta, \ p_r, \ l \quad (9)$$

- Ion Momentum

$$l = rpsin\phi \quad p_r = pcos\phi \quad (10)$$

$$\vec{p} = (pcos(\phi - \theta), psin(\phi - \theta), 0) \quad (11)$$

$$\vec{r} = (-rcos(\theta), rsin(\theta), 0) \quad (12)$$

- System geometric rotation

Proton and ion reactions

Lorentz transformation

- Direct transformation:

$$\vec{p} = \vec{p}' + \vec{\beta}\gamma(\frac{\gamma}{\gamma+1}\vec{\beta}\vec{p}' + \varepsilon') \qquad (13)$$

$$\varepsilon = \gamma(\varepsilon' + \beta\vec{p}') \qquad (14)$$

- Inverse transformation:

$$\vec{p}' = \vec{p} + \vec{\beta}\gamma(\frac{\gamma}{\gamma+1}\vec{\beta}\vec{p} - \varepsilon) \qquad (15)$$

$$\varepsilon' = \gamma(\varepsilon - \beta\vec{p}) \qquad (16)$$

$$\vec{\beta} = \frac{\vec{P}}{E}, \quad \gamma = \frac{E}{M}$$

Lorentz transformation

- Initial condition in the two body system:

$$P = P_1 + P_2 \tag{17}$$

$$p0 = LorentzRotation(P, P_1) = -LorentzRotation(P, P_2)$$
$$T = T_1 + T_2 = (E_1 - M_1) + (E_2 - M_2) \tag{18}$$

- After the contact point

$$P_1 = inverseLorentzR(p, P) \quad P_2 = inverseLorentzR(-p, P) \tag{19}$$

- Inverse Kinematic

Initial interaction

- The proton is put in the nuclear surface and the following function is call:

$$GeneratingSingleNucleon$$

$$ptar_x^2 = p_x^2 + m_0^2 - m_{eff}^2 \tag{20}$$

- For ion is necessary to calculate the incident point and the time for each incident nucleon in the nuclear surface
- Nucleon momentum in the lab and target system:

$$plab_i = inverseLorentzR(P_1, pion_i) \tag{21}$$

$$ptar_i = LorentzR(P_2, plab_i) \tag{22}$$

$$\vec{r}_{tari} = \vec{R} + \vec{r}_{ioni} \tag{23}$$

Proton and ion reactions

Initial interaction

- Intersection points:

$$\vec{r} = \vec{r}_0 + \vec{v}t \quad (24)$$

$$x^2 + y^2 + z^2 = R^2 \quad (25)$$

$$v_0^2 t^2 + 2\vec{r}_0 \vec{v}_0 t + r_0^2 - R_2 \quad (26)$$

- For the first interaction

$$GeneratingSingleNucleon$$

- The other interactions are simulated with a cascade execution with the temporal stopping criteria
- For the last cascade execution is incorpored the energetic stopping criteria

Proton and ion reactions

Final information

- Target:

$$\vec{P}_f = \vec{P}_2 + \sum_i \vec{p}_i \tag{27}$$

$$E^* = E^* - E_{\sum} \tag{28}$$

- Projectile

$$E^* = \sum_{j=1}^{A} \varepsilon_j - \sum_{j=1}^{A} \varepsilon_i j \tag{29}$$

$$\vec{P}_f = A/A_0 \vec{P}_1 \tag{30}$$

Evaporation/Fission Model

Competition between particle evaporation and fission processes

Evaporation (Weisskopf's Model)

- Emission of neutron, proton and alphas allowed.
- Probability relative to neutrons:

$$\frac{\Gamma_p}{\Gamma_n} = (\frac{E_p^*}{E_n^*}) exp \left\{ 2(a_n)^{\frac{1}{2}} \left[(r_p E_p^*)^{\frac{1}{2}} - (E_n^*)^{\frac{1}{2}} \right], \right\}$$

$$\frac{\Gamma_\alpha}{\Gamma_n} = (\frac{2E_\alpha^*}{E_n^*}) exp \left\{ 2(a_n)^{\frac{1}{2}} \left[(r_\alpha E_\alpha^*)^{\frac{1}{2}} - (E_n^*)^{\frac{1}{2}} \right]. \right\}$$

- Level density parameters are calculated by Dostrovsky's

Evaporation/Fission Model

Competition between particle evaporation and fission processes

Fission (Bohr and Wheeler's Model)

- Probability relative to neutrons:

$$\frac{\Gamma_f}{\Gamma_n} = K_f exp\left\{2\left[(a_f E_f^*)^{\frac{1}{2}} - (a_n E_n^*)^{\frac{1}{2}}\right]\right\},$$

$$K_f = K_0 a_n \frac{\left[2(a_f E_f^*)^{\frac{1}{2}} - 1\right]}{(4A^{\frac{2}{3}} a_f E_n^*)}$$

- Fission barrier is calculated by Nix's model (drop model base)

Studied reactions

- For nuclear cascade double differential cross sections of emitted neutrons

$$^{12}C +^{12} C \;\; 290AMeV$$

- For nuclear cascade and evaporation double differential cross sections of emitted protons

$$^{40}Ne +^{238} U \;\; 250A \; MeV$$

$$^{40}Ne +^{238} U \;\; 500A \; MeV$$

$$^{18}Ar +^{20} Ca \;\; 1050A \; MeV$$

Studied reactions

- For residual fragments distribution

$$^{58}Ni +^{9} Be \;\; 140A \; MeV$$

$$^{86}Kr +^{9} Be \;\; 500A \; MeV$$

$$^{2}H +^{208} Pb \;\; 1000A \; MeV$$

$$^{1}H +^{208} Pb \;\; 1000A \; MeV$$

Double differential cross sections

$$\sigma_r = \sigma_{geom} \frac{N_{casc}}{N_{Attem}} \tag{31}$$

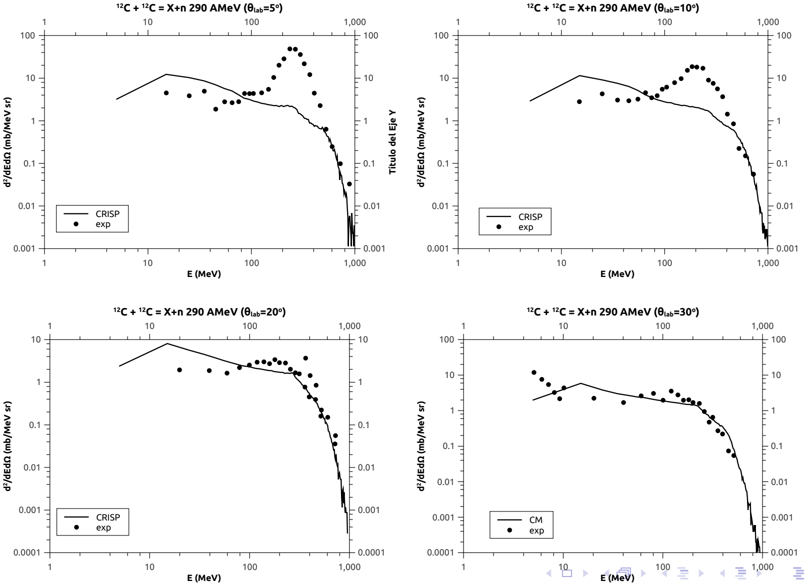
$$\sigma_{event} = \sigma_r \frac{N_{event}}{N_t} \tag{32}$$

$$\frac{d\sigma^2}{d\Omega dE} = \frac{\sigma_{geom} N_{event}}{N_{attem} \Delta\Omega\Delta E} \tag{33}$$

Fragment distribution cross sections

$$\sigma = \sigma_r P_{spall} \frac{N_{event}}{N_{total}} \tag{34}$$

Studied reactions



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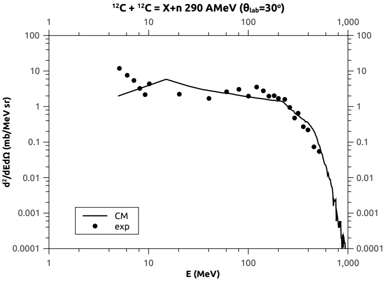

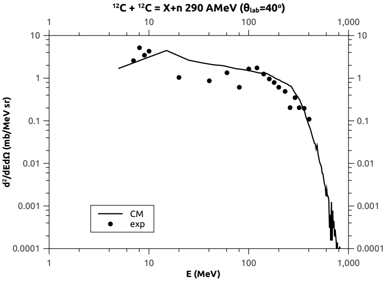

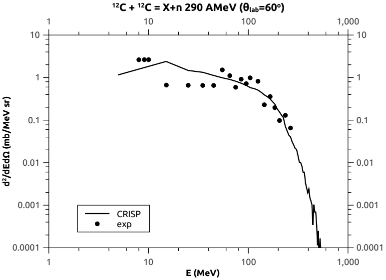

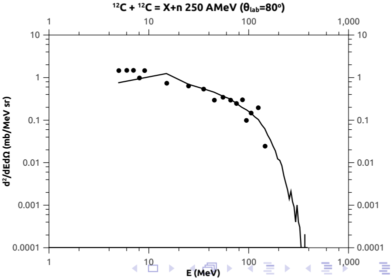

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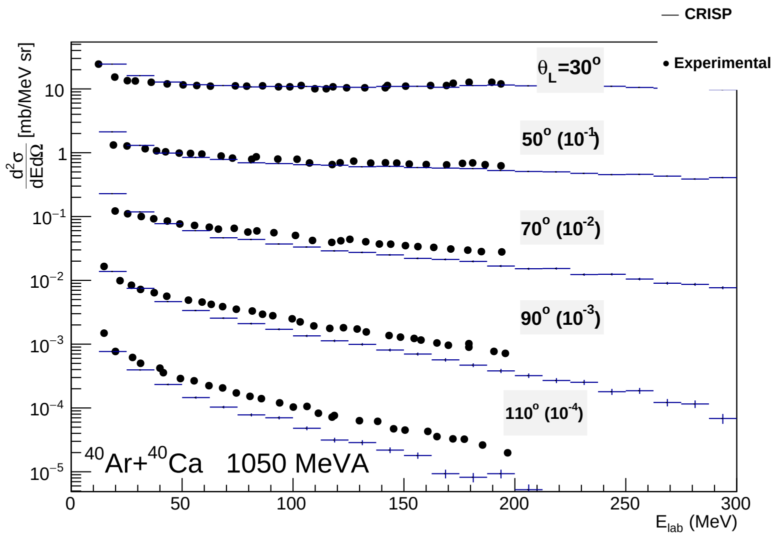

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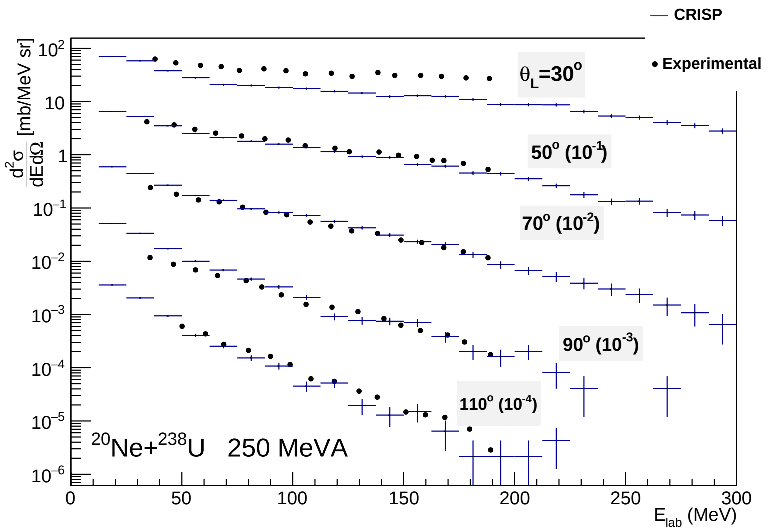

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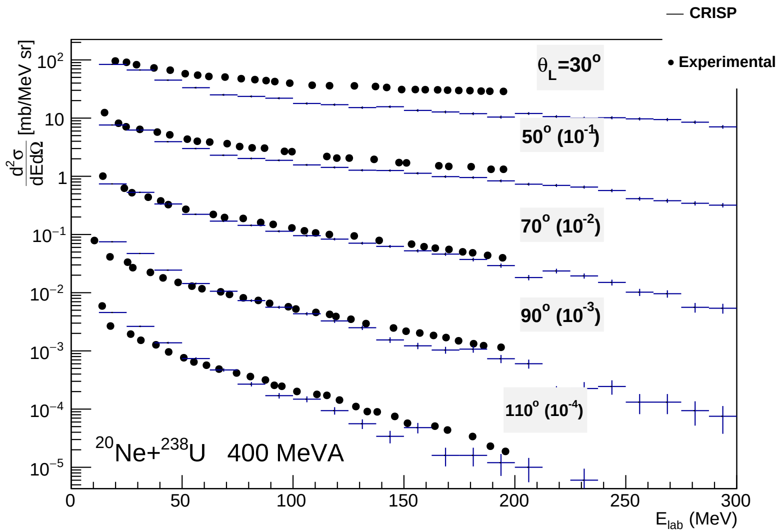

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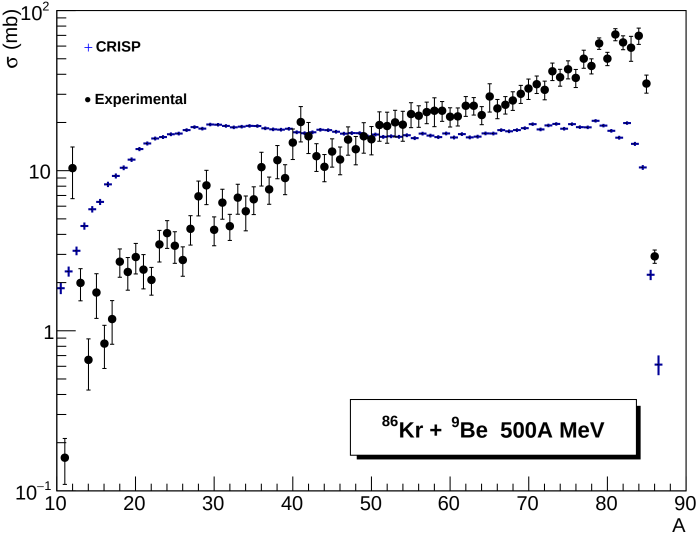

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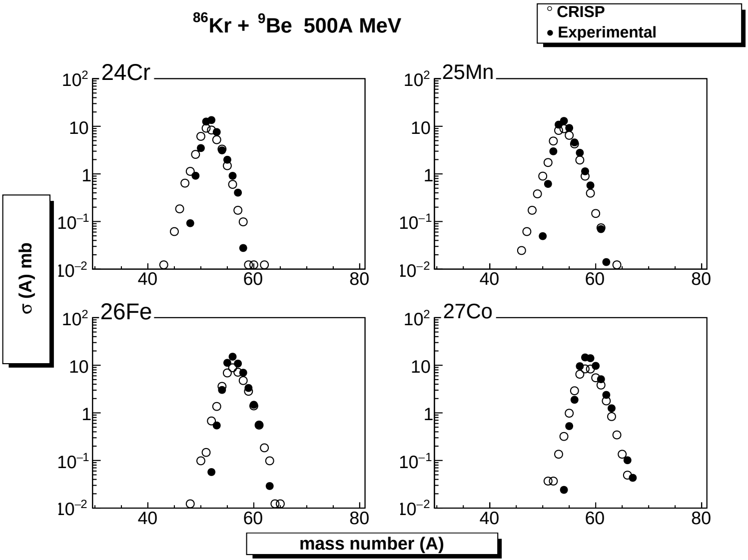

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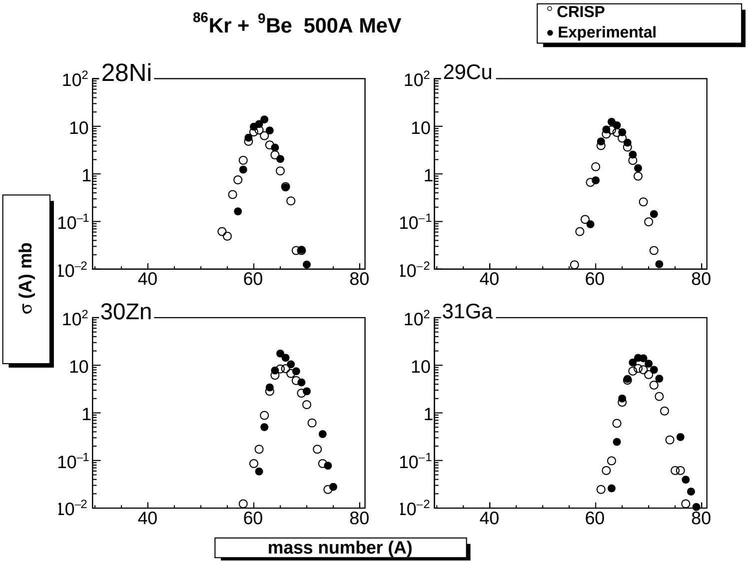

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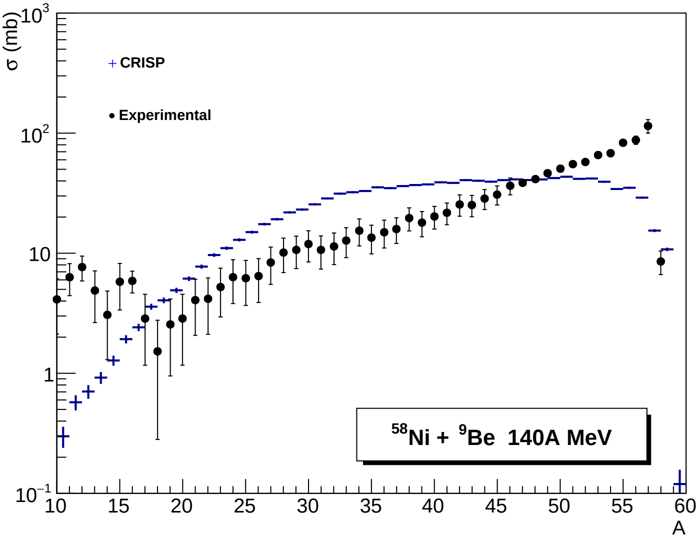

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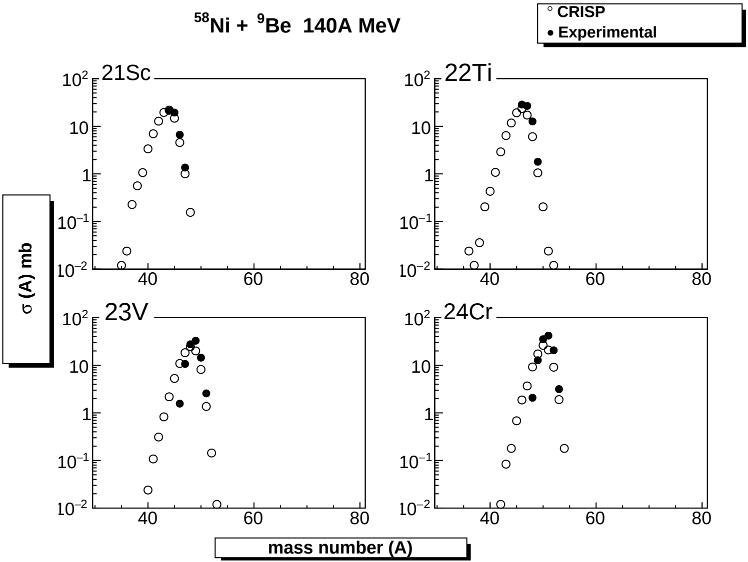

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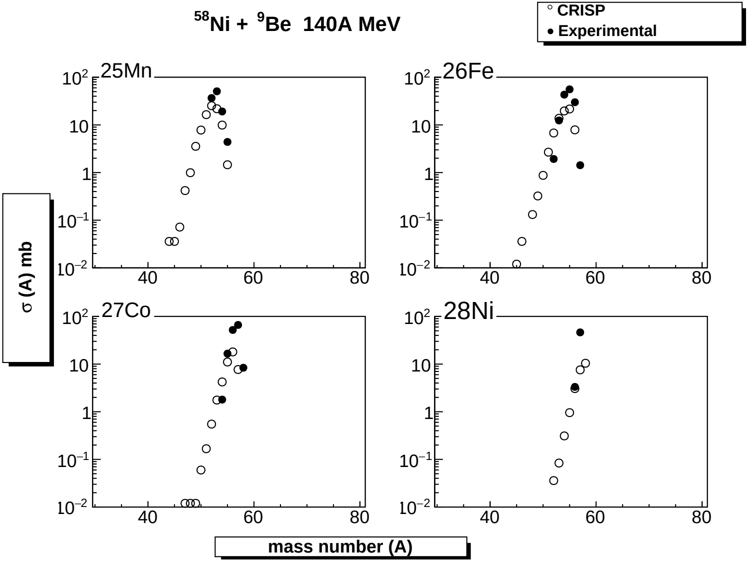

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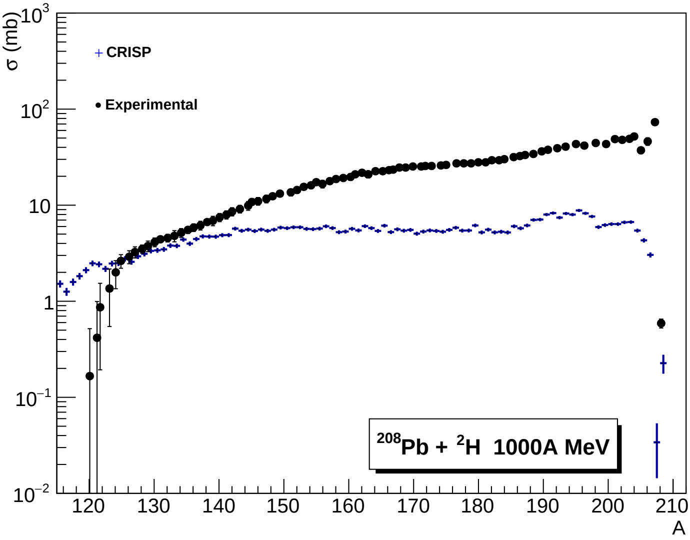

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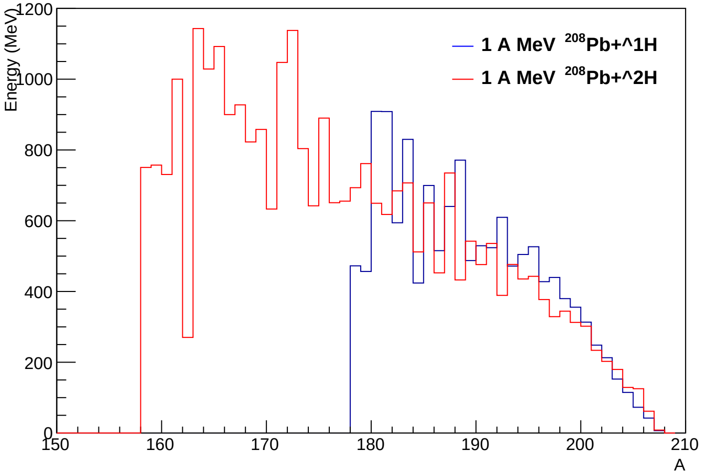

Proton and ion reactions

Table : Liège intranuclear cascade comparison

Reaction	A	Z	$E^*/nucleon$
140 A MeV $^{58}Ni +^{9} Be$ (Liège)	56.6	27.2	2.3
CRISP	53.77	26.5	3.47
500 A MeV $^{58}Ni +^{9} Be$ (Liège)	76.6	32.2	3.0
CRISP	73.52	31.44	5.18
1000 A MeV $^{208}Pb +^{2} H$ (Liège)	199.6	78.7	1.2
CRISP	193.1	79.23	2.15

Conclusions

- Comparison between proton–nuc and ion–ion reactions for cascade.
- Study different experimental excitation functions for ion–ion reactions.
- Study the mcef code for this excitation energies and others theoretical des-excitation models.