Measurement of neutron-induced light-ion production at 175 MeV quasi mono-energetic neutrons

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Short introduction.

Background and motivation

Light-ion production measurements at the Uppsala Neutron Beam Facility

(details on the facility/experimental set-up: poster by Shusuke Hirayama)

Experimental data and model calculations

Focus: pre-equilibrium emission of light complex particles

Part 1.

Phase space statistical approach:

Exciton model and Kalbach systematics (TALYS)

Part 2.

Microscopic simulation approach:

Quantum Molecular Dynamics (QMD),

Surface Coalescence Model (SCM)

Background and motivation

Light-ion production measurements in the 20-200 MeV region

time ↓

Three Mile Island accident (March 28, 1979)
Sweden, 1980:
decision to phase out nuclear power (now revised)
Public acceptance
Accelerator Driven Systems

The Accelerator Transmutation of Waste (Bowman, LANL 1991)
Energy Amplifier (Rubbia, CERN 1993)

- Uppsala University: Neutron beam line at the The Svedberg Laboratory

  Medley setup: neutron induced light-ion production

  Scandal setup: elastic neutron scattering

  Neutron data needs for accelerator applications:

- Accelerator-based transmutation of nuclear waste.

  Particle transport calculations.

  Shielding calculations, activity estimation, nuclear heating and radiation damage.

- Medical applications. Space dosimetry. Soft errors in microelectronics.
- Benchmark nuclear models

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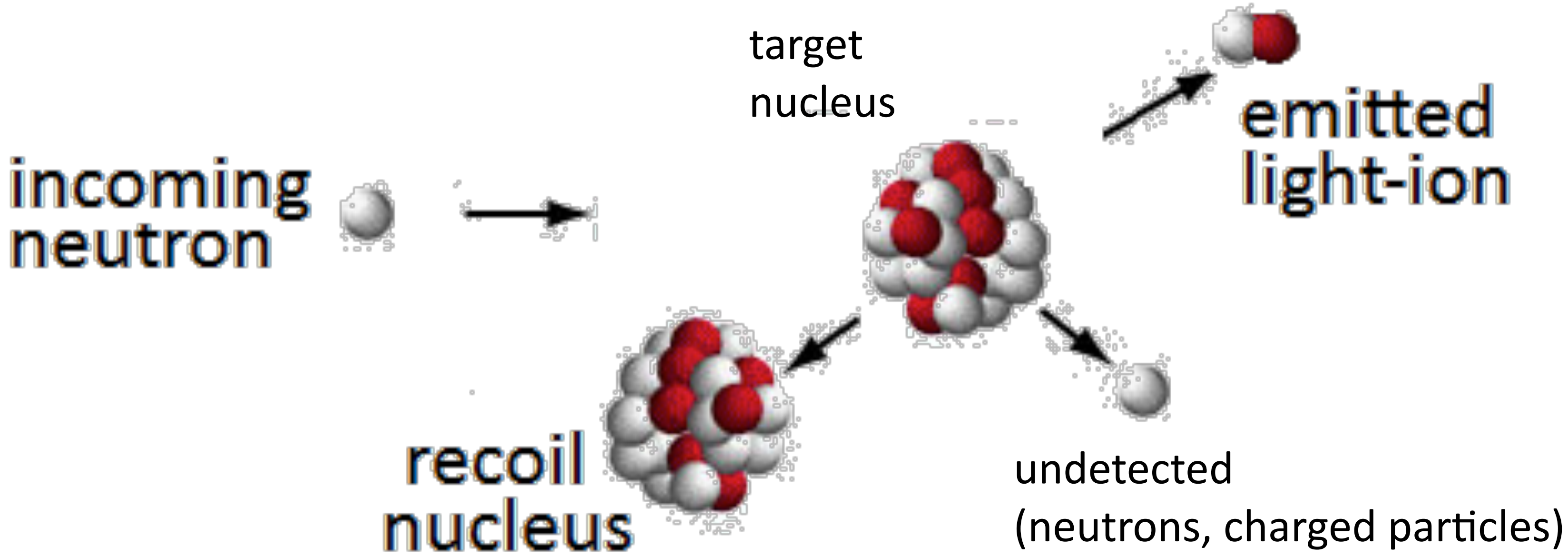
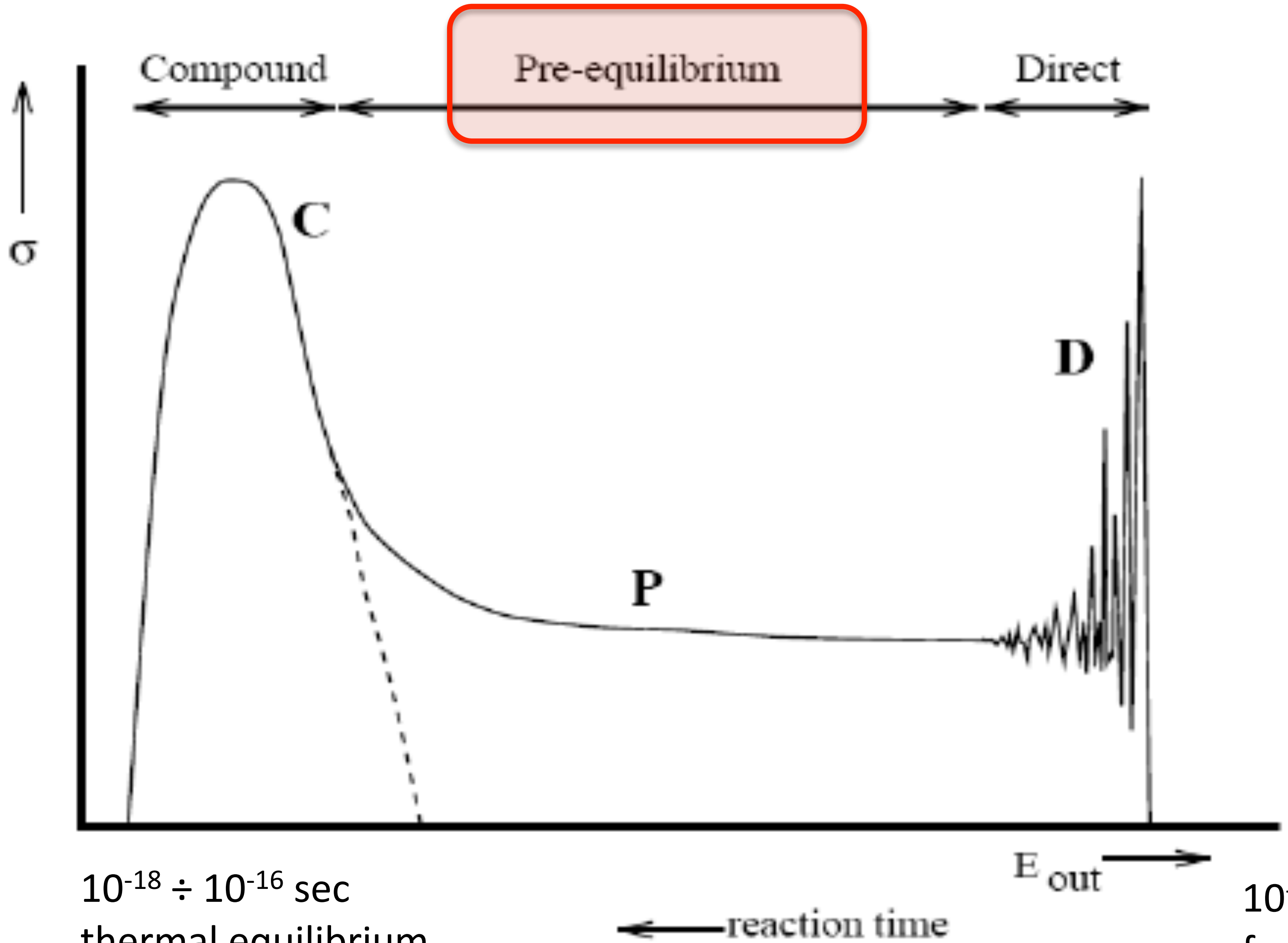

target
nucleus
emitted
light-ion
incoming
neutron
recoil
nucleus
undetected
(neutrons, charged particles)

figure from TALYS manual



$10^{-18} \div 10^{-16}$ sec
thermal equilibrium

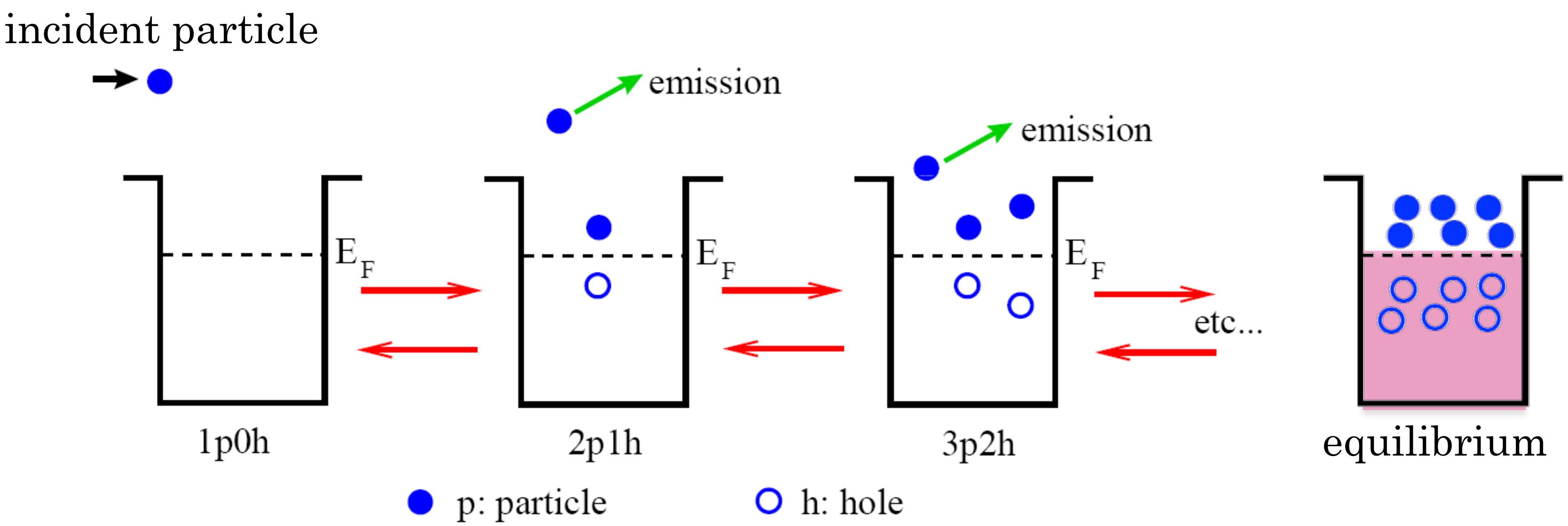
$10^{-22} \div 10^{-20}$ sec
few interactions

- **Time evolution** of the occupation probability of n-exciton state in the **energy space**

exciton = particle-hole pair

- Projectile energy gradually **redistributed** among nucleons

- Allows **emission** of particles

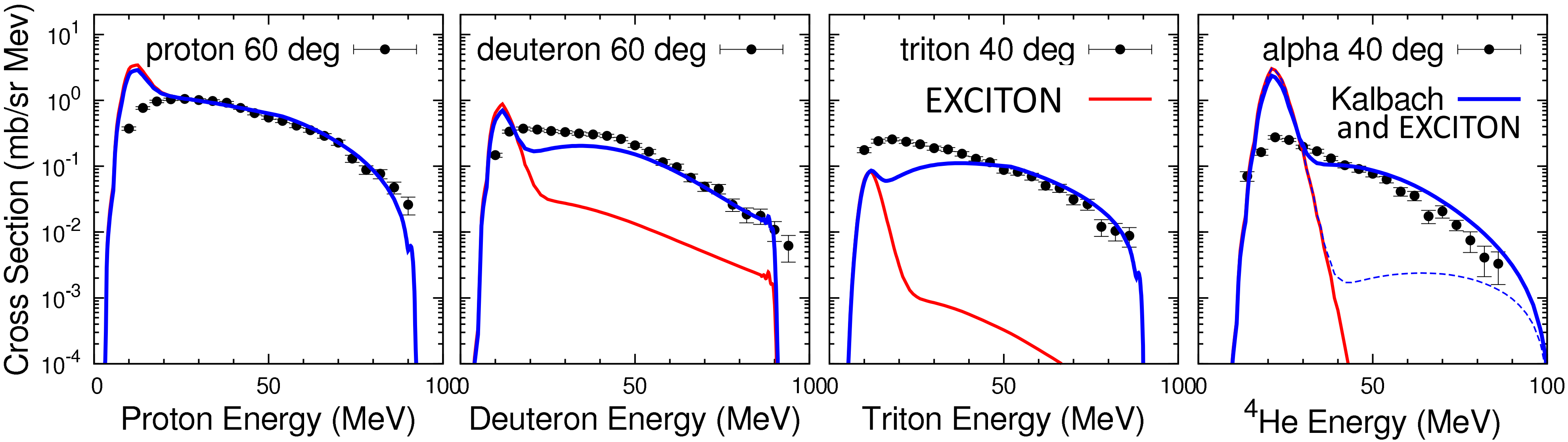


- **Direct-like reactions not included in the Exciton Model**
  nucleon transfer (NT): pick-up and stripping
  knock-out (KO) of preformed clusters

- **Kalbach phenomenological model**
  pre-equilibrium reactions with complex particle channels
  C. Kalbach, Phys. Rev. C 37, 2350 (1998) and Phys. Rev. C 71, 034606 (2005)

$$\frac{d\sigma_k^{\mathrm{PE}}}{dE_k} = \frac{d\sigma_k^{EM}}{dE_k} + \frac{d\sigma_k^{NT}}{dE_k} + \frac{d\sigma_k^{KO}}{dE_k}$$

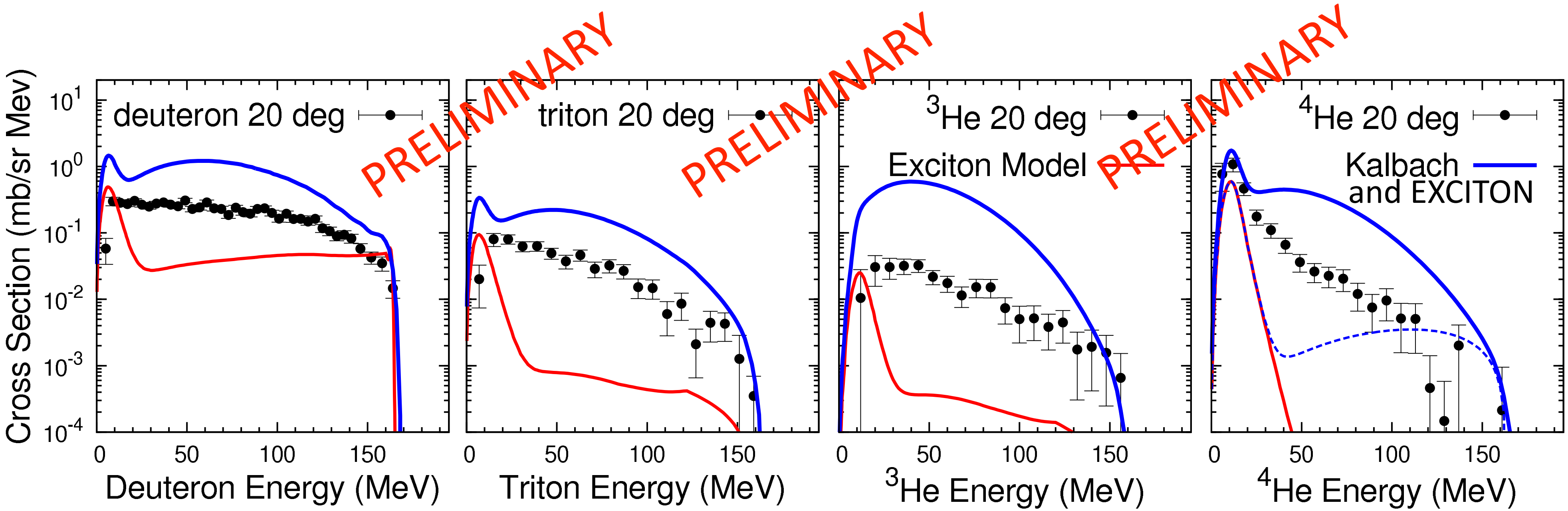
Neutron induced light-ion production from Pb at 96 MeV



Pre-equilibrium: two components exciton model complemented by Kalbach systematics

Data: Blideanu et al. (2004) – Calculations: TALYS-1.2

Neutron induced light-ion production from Fe at 175 MeV



✓ Proton production: well reproduced (not shown)

✗ Complex particles: overestimated by Exciton Model + Kalbach

Data: present experiment (2009) – Calculations: TALYS-1.2

PHYSICAL REVIEW C **71**, 034606 (2005)

Preequilibrium reactions with complex particle channels

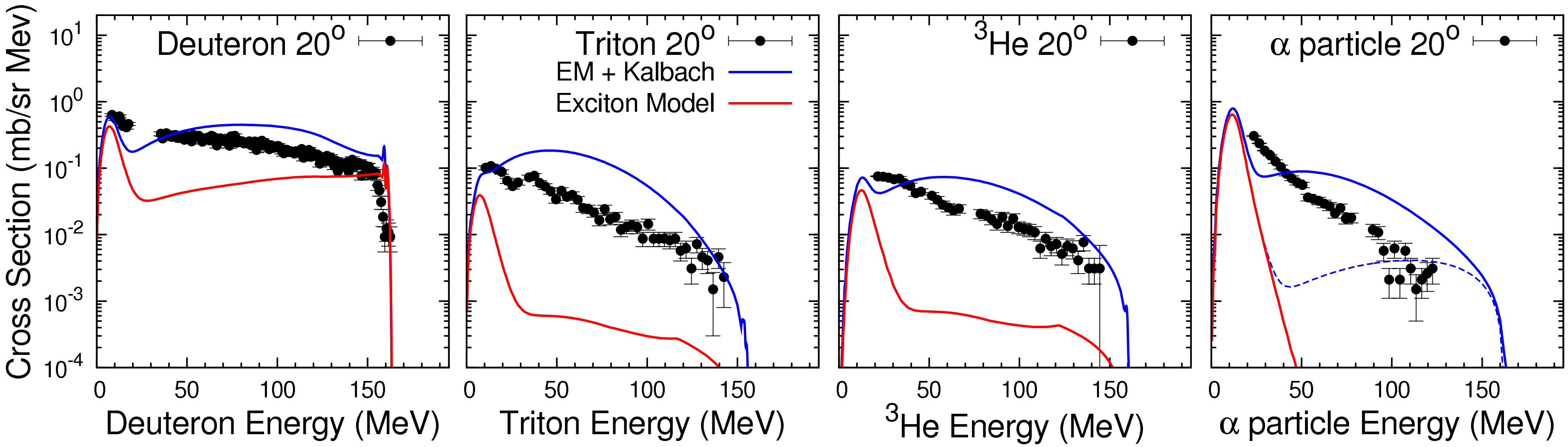
Neutron induced reactions ≤ 63 MeV

C. Kalbach
Physics Department, Duke University, Durham, North Carolina 27708-0305
(Received 10 November 2004; published 22 March 2005)

Investigations of nucleon induced reactions at incident energies of 14–90 MeV resulting in the emission of complex particles ($A = 2$–4) have provided insights which complement those previously obtained from (N, xN) reactions. The description of the preequilibrium energy spectra required modifications to an earlier phenomenological model for direct pickup reactions. This model supplements the usual exciton preequilibrium model. Work on complex particle induced reactions confirms some of these results, extends them to include stripping and exchange reactions, and provides evidence for a projectile dependence of the average effective matrix elements for the residual interactions in the exciton model. A full description of reactions with complex projectiles will require the inclusion of a realistic breakup component and the resulting reduction of the cross section available for the exciton model calculations. Reactions with complex particles in the entrance and/or exit channels have provided indirect evidence for the amount of surface peaking of the initial target-projectile interaction. A summary of additional data needed to help resolve remaining questions is presented.

DOI: 10.1103/PhysRevC.71.034606 PACS number(s): 24.60.Gv, 24.10.Pa

Proton induced light-ion production from Ni at 175 MeV

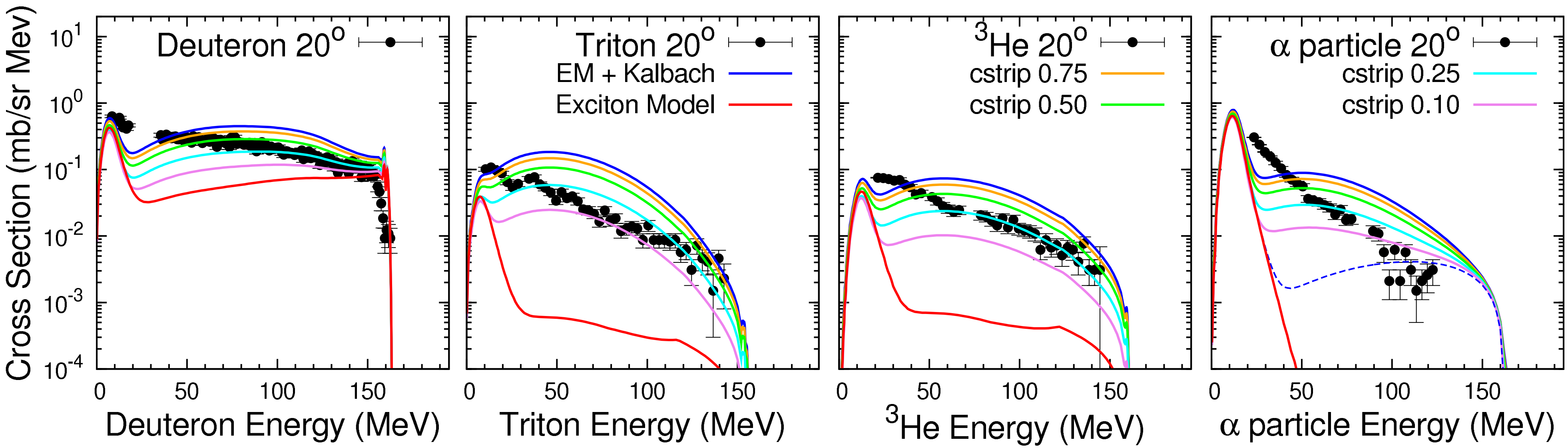


Pre-equilibrium DDX = Exciton Model DDX + Nucleon Transfer DDX + Knock Out DDX

Kalbach systematics

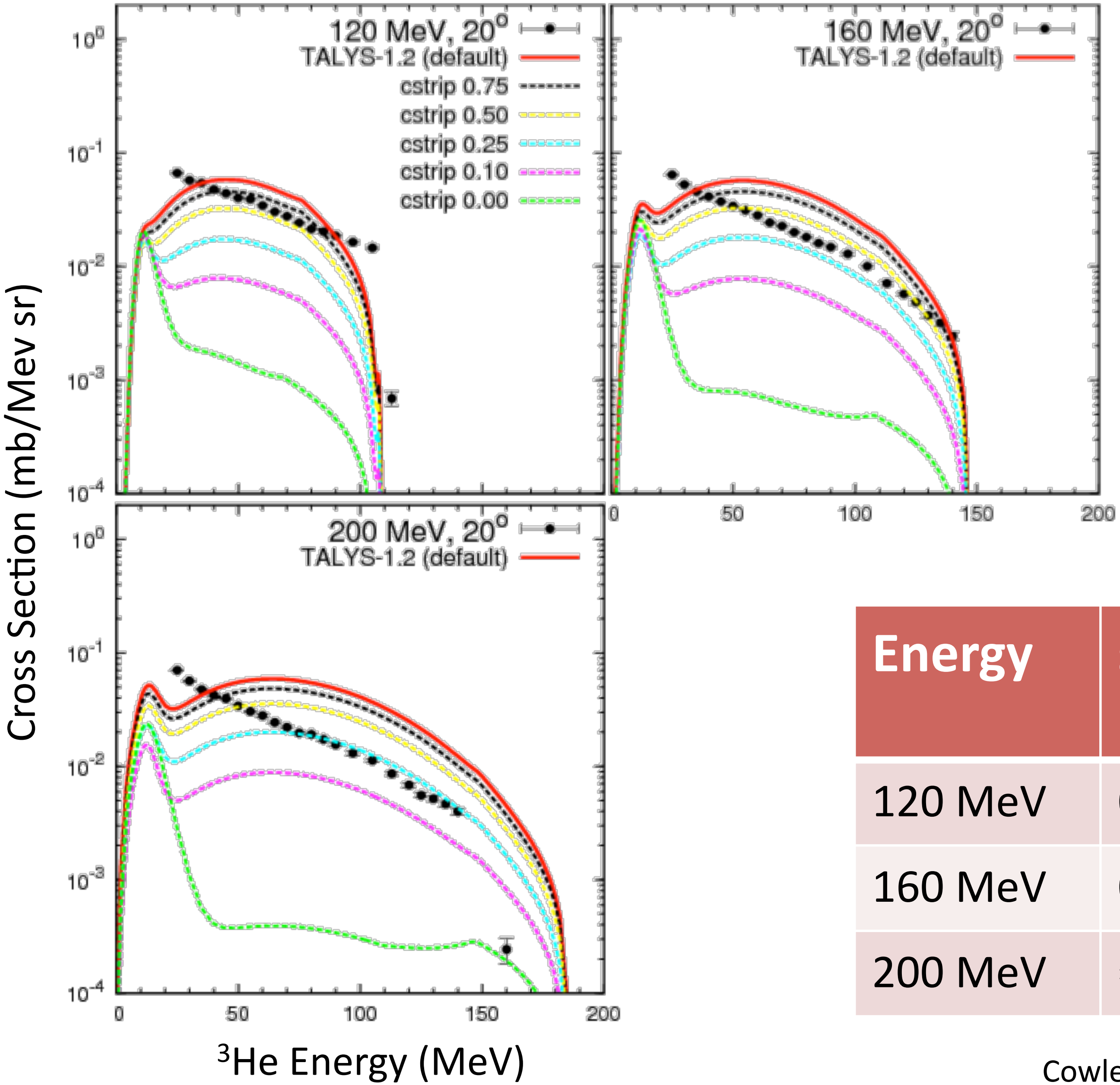
Data: Budzanovski *et al.* Phys. Rev. C 80, 054604 (2009) – Calculations: TALYS-1.2

Proton induced light-ion production from Ni at 175 MeV



Cstrip: scaling factor for the Nucleon Transfer contribution (Kalbach)

Data: Budzanovski *et al.* Phys. Rev. C 80, 054604 (2009) – Calculations: TALYS-1.2



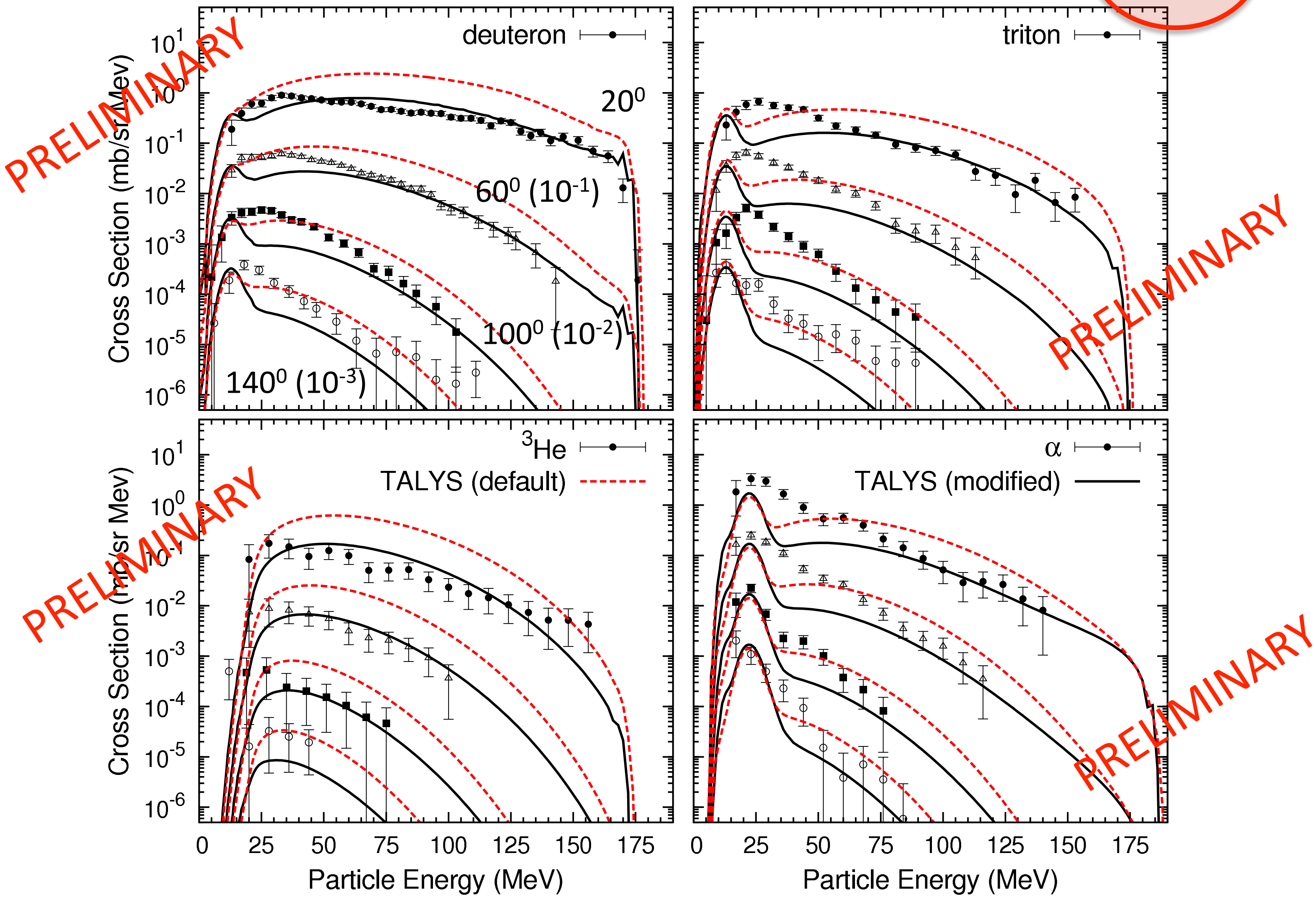
$^{59}Co(p,^{3}He\ x)$
at 120, 160, 200 MeV

Energy	scaling factor Nucleon Transfer
120 MeV	0.75 ≤ cstrip ≤ 0.5
160 MeV	0.5 ≤ cstrip ≤ 0.25
200 MeV	≈ 0.25

Cowley *et al.* Phys. Rev. C 54, 778–783 (1996)

Modified Kalbach model

Neutron induced complex particles production from Bi at 175 MeV QMN



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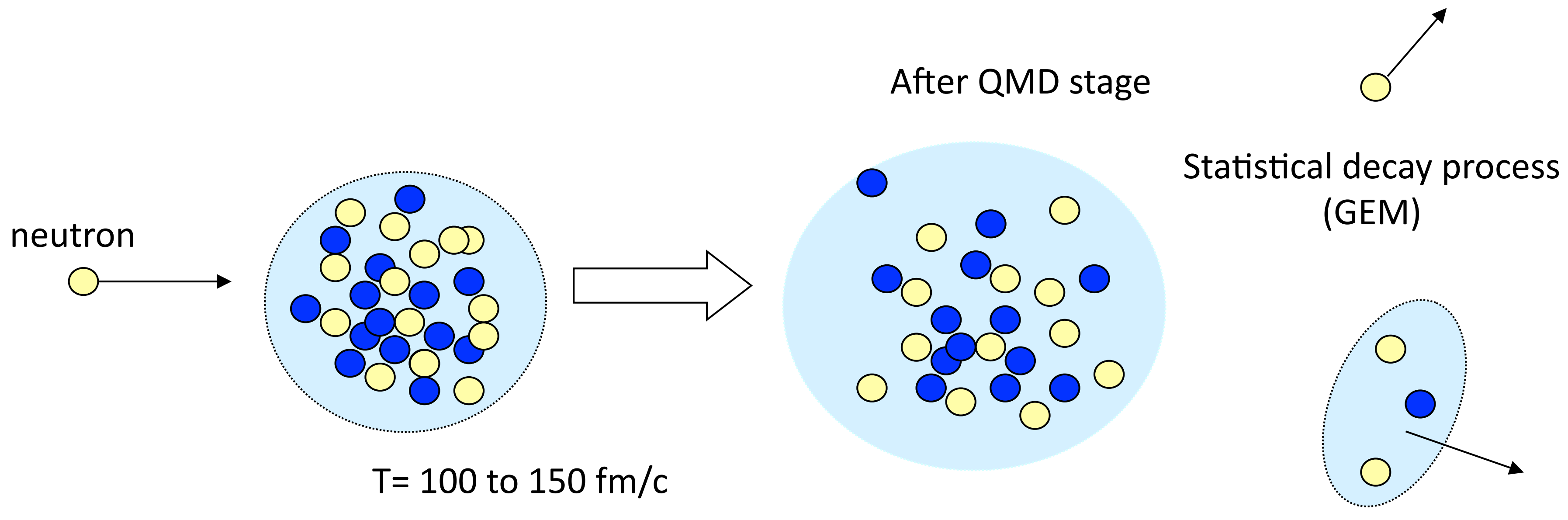
Quantum Molecular Dynamics (QMD)

- QMD: semiclassical simulation method
  time evolution of nucleon many-body system in a microscopic way



- Nucleon propagates in nuclear mean field formed by all other nucleons.
- Stochastic two-body collision.
- At the end of the simulation (T=100-150 fm/c): if two nucleons are within a certain distance, they are considered to be bound in a cluster.

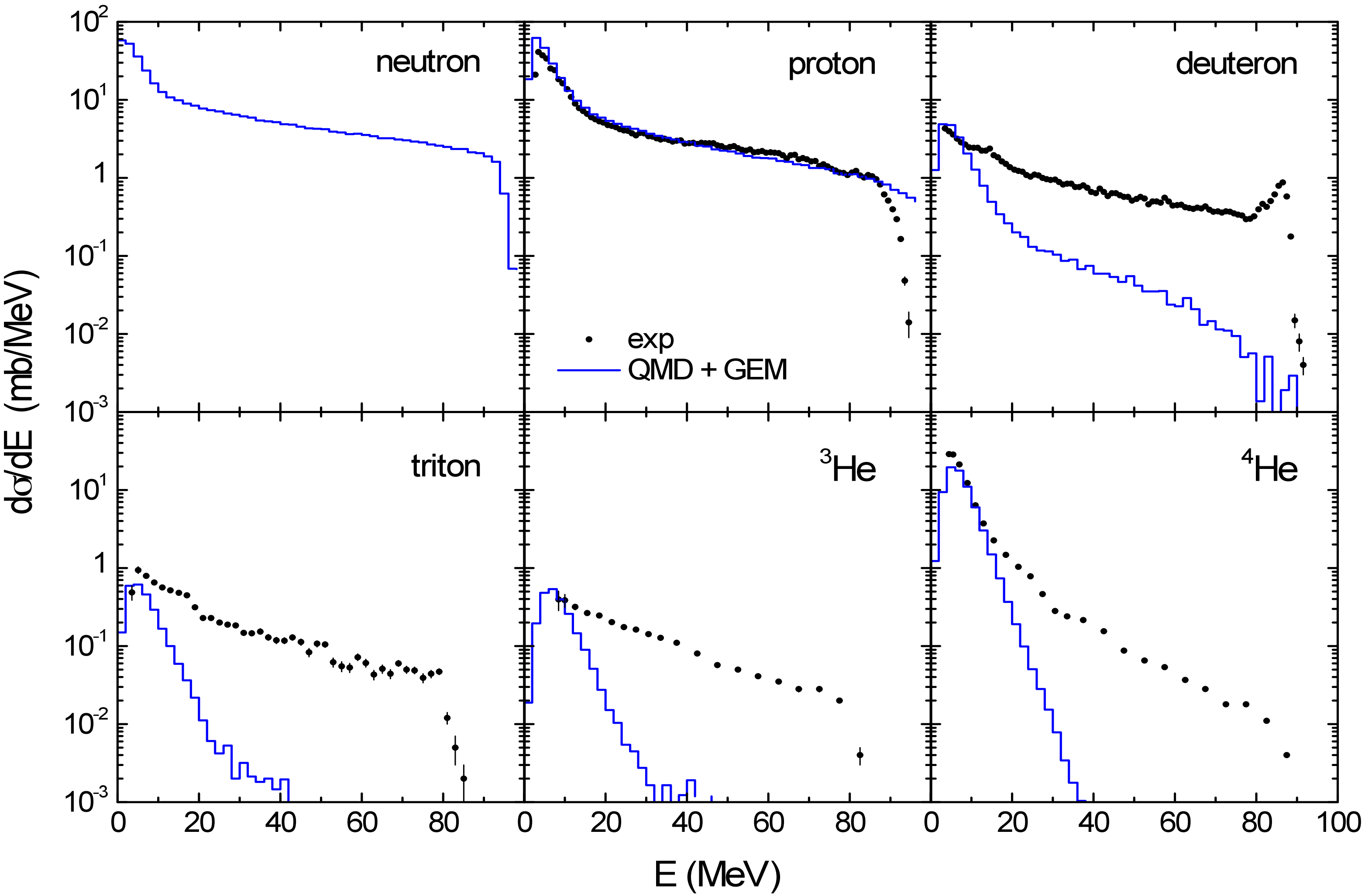
- Equilibrium: Generalized Evaporation Model (GEM)

QMD calculations for LCPs from Si at 96 MeV

Angle integrated neutron induced light-ion differential cross sections from Si at 96 MeV

Medley Setup at TSL (Tippawan et al. Phys. Rev. C 69, 064609 (2004))

JQMD calculations by Y.Watanabe (JQMD code: Niita *et al.* Phys. Rev. C 52, 2620 (1995))

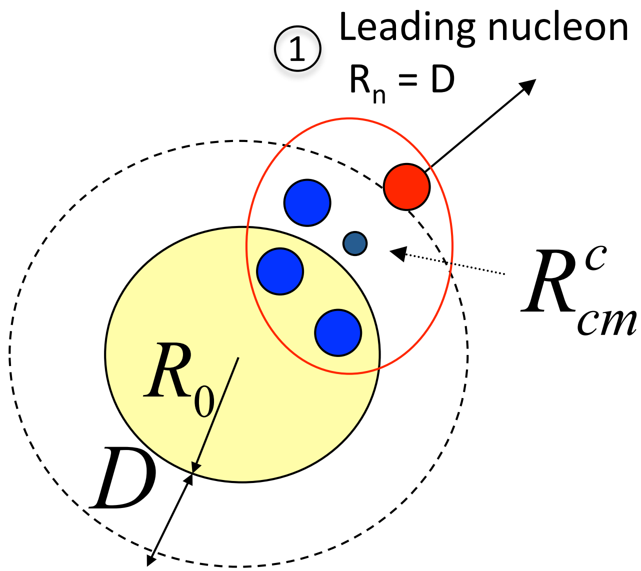


Courtesy of Prof. Y. Watanabe

Surface coalescence model (SCM)

Following: Letourneau *et al.* (2002), Boudard *et al.* (2004), Iwamoto *et al.* (1983), Bisplinghoff(1994)

- A leading nucleon in the surface region of the composite system can form a complex particle by coalescence



- Phase space conditions:

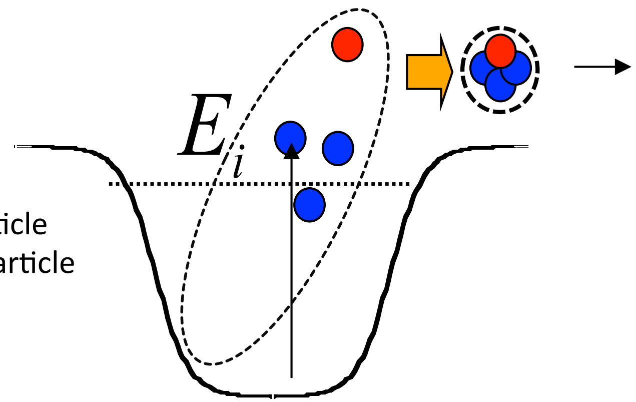
② $$R_{im} \times P_{im} \leq h_0$$

③ $$R^c_{cm} > R_0$$

h_0 = 260 MeV fm/c
D = 2.3 fm
R_o = 3.5 fm

R_{im} (P_{im}) relative spatial (momentum) coordinate
R^c_{cm} position of center of mass of the tentavive cluster

- If kinetic energy ε_c and Columb barrier tunneling allow it, the cluster is emitted



④ $$\varepsilon_c = \sum_i E_i + \sum_i V_i + B_c > 0$$

E_i >0 kinetic energy of the i-th particle
V_i<0 potential energy of the i-th particle
B_c<0 binding energy of the cluster

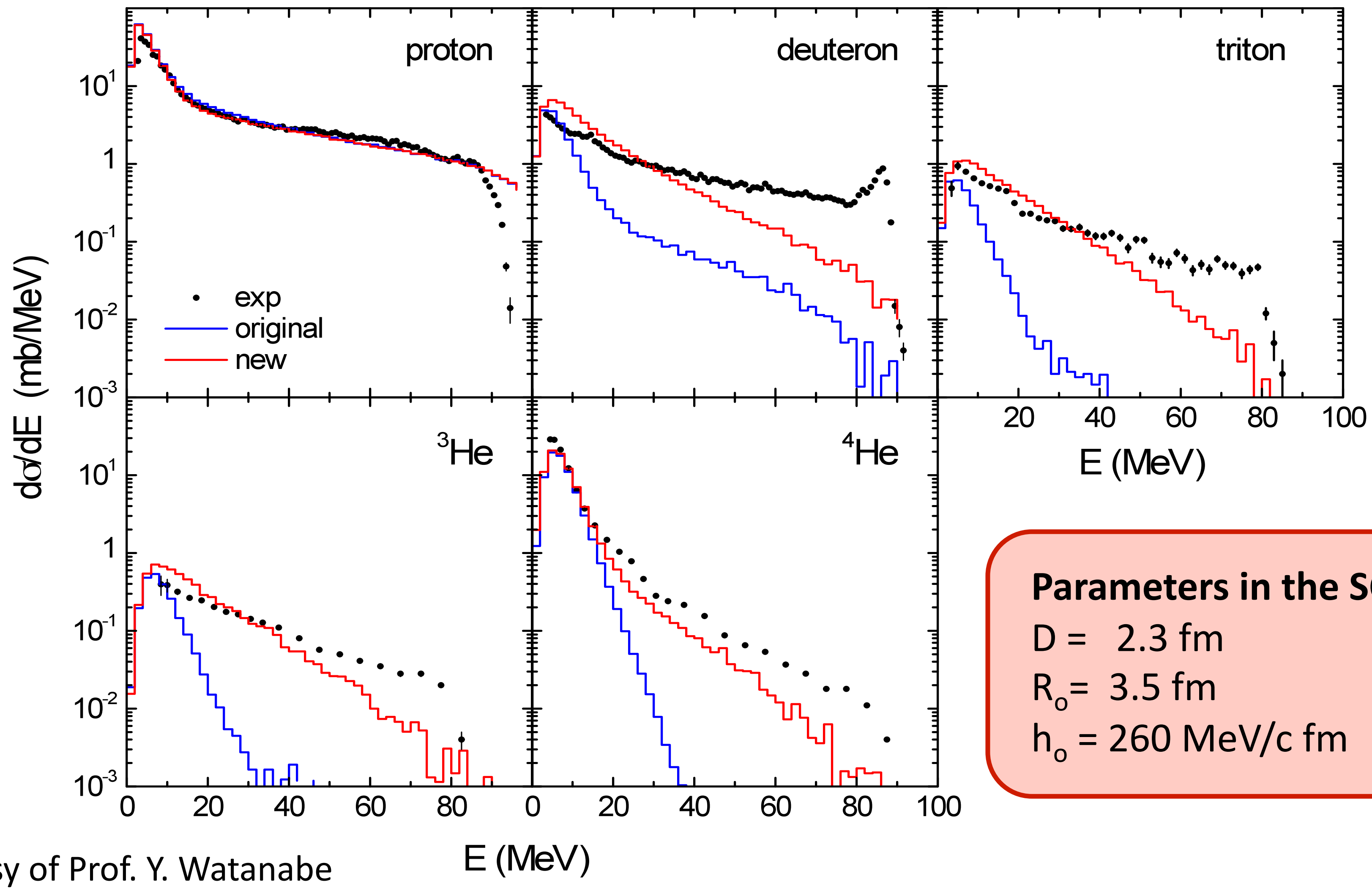
Ref: Y.Watanabe and D.N.Kadrev, *Extension of quantum molecular dynamics for production of light complex particles in nucleon-induced reactions*, Proceedings ND2007 (DOI: 10.1051/ndata:07196)

Si at 96 MeV - QMD with SCM

Angle integrated neutron induced light-ion differential cross sections from Si at 96 MeV

Medley Setup at TSL, Tippawan et al. (2004)

JQMD (original) and QMD calculations with SCM by Y.Watanabe (presented at ND2007)



Parameters in the SCM:

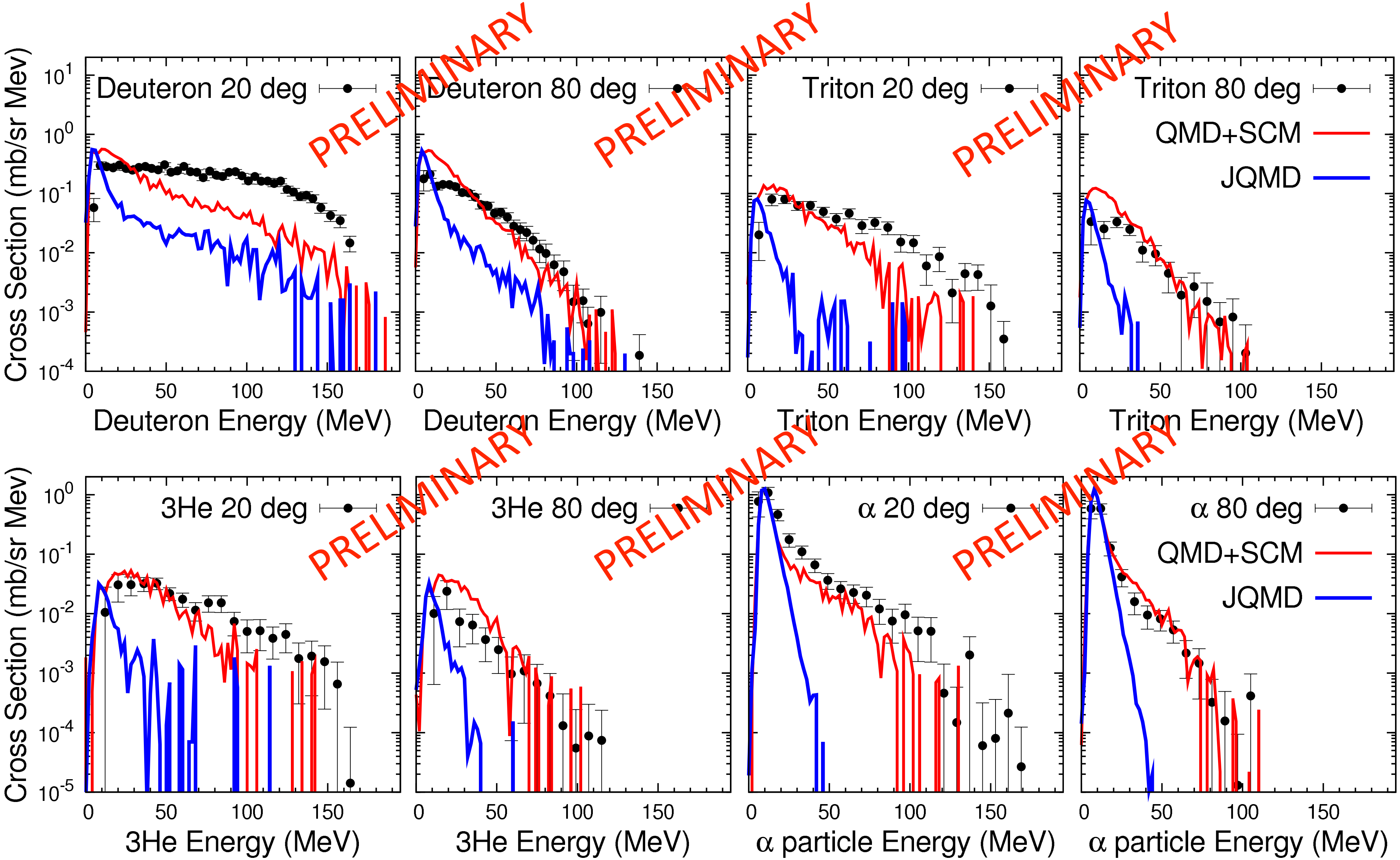
D = 2.3 fm

R_o = 3.5 fm

h_o = 260 MeV/c fm

Courtesy of Prof. Y. Watanabe

LCPs from Fe at 175 MeV QMN - QMD with SCM



Data: present experiment (2009) – Calculations by Prof. Y. Watanabe

Summary and Conclusions

We have measured light-ion production from Fe and Bi (and other targets) at 175 MeV QMN

Focus: pre-equilibrium emission of complex particles

- Exciton Model: single particle emission
  Kalbach systematics: direct like mechanisms to describe cluster emission

  Energy dependence of Kalbach systematics: should be reviewed for E > 90 MeV

- Quantum Molecular Dynamics: single particle emission
  Surface Coalescence Method: clusters formation during dynamical process

  SCM improved agreement with experimental data
  underestimation of high energy end: missing direct-like mechanisms

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Thank you for your attention!

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SKB

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THE ROYAL SWEDISH ACADEMY OF SCIENCES

JASSO

VATTENFALL

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