INC Model for High-Energy Hadron-Nucleus Reactions

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International Topical Meeting on Nuclear Research, Application and Utilization of Accelerators

IAEA, Vienna, Austria

4-8 May, 2009

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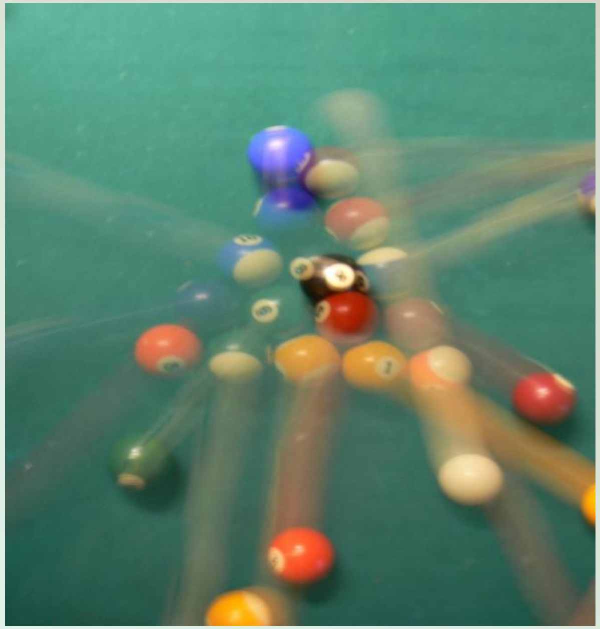
Why INC?

- Transport codes for projectile in energy range up to few GeV important for many applications (e.g. RIB, Spallation Sources)

- Existing cross-section libraries limited to 150MeV or, for some isotopes to 20 MeV (for radioactive “residua” – 20 MeV)

➨ **Need for fast “event generator” code to fill the 20 MeV – 3 GeV gap**

What is INC?



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intranuclear cascade model
(¦in·trə′nü·klē·ər kas′kād ′mäd·əl)

(*nuclear physics*) A model of nuclear collisions that assumes a series of independent nucleon-nucleon collisions between particles that act like billiard balls.

INC Models (seriously)

R.Serber, Phys. Rev. 72, 1114 (1947)

- Particle on Nucleus reaction treated as series of two-body scatterings
- "Realistic" target density and momentum distributions (Fermi sea)
- Approximated Pauli principle
- "Fast Phase" followed by "slow" target de-excitation
- No "fitting parameters"

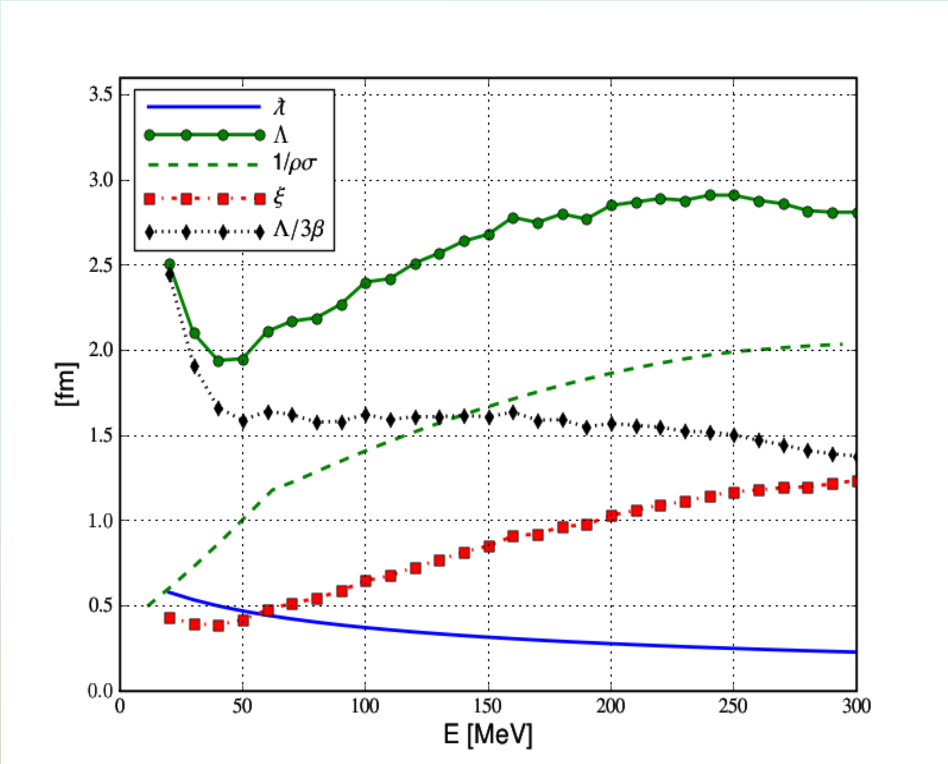
Assumptions ➡ Requirements (1)

- Many-body scattering in terms of on shell single particle cross sections
  - ➨ "Deep Inelastic" collisions, "Energetic" collisions
- Interacting particles followed on classical trajectories
  - ➨ de Broglie wave-length shorter than inter-nucleon distance
    $\lambda\!\!\!^{-} << d$
- Asymptotic value of scattered wave before next collision
  - ➨ de Broglie wave-length shorter than m.f.p.
    $\lambda\!\!\!^{-} < \Lambda$

Assumptions ➡ Requirements (2)

- Interference terms between collisions cancel out
  - ➨ m.f.p. shorter than target radius
    $\Lambda < R$
- Independent scattering from different nucleons in the target
  - ➨ m.f.p. (Λ) larger than inter-nucleon distance (d); Time between interactions ($\Lambda/\beta c$) shorter than interaction time (10^{-23} *sec.*)
    $\Lambda > d$
    $\Lambda/\beta c > \approx 10^{-23}\,sec. \Rightarrow \Lambda/3\beta > \approx 1$

Central collision p+208Pb



$$ƛ << d < \Lambda < R$$

$$\Lambda / 3\beta >\approx 1 fm$$

$$\xi \equiv \Lambda / ƛ / 10$$

$$\xi > 1.0 \Rightarrow E >\approx 200 MeV$$

Expected limitations

- **E_{inc}> ≈ 50 MeV for:**
  - Total nucleon yields
  - Peripheral collisions, e.g. "quasi-elastic",(p,2p)
- **E_{inc} > ≈ 200 MeV for:**
  - "Violent reactions" (high multiplicity, high excitation energy)

Significant discrepancies expected for outgoing particles for E_{inc} lower than few tens MeV

Continuous Target Density Models

- The target nucleus is represented by continuous density distribution in a potential well (e.g. Woods Saxon) and degenerate "local density" Fermi gas momentum distribution
- Probability per unit path length of a particle to interact with the nucleons of the nucleus

$$Q = \frac{1}{v_1}\int \sigma_{12} v_{12} \frac{\partial \rho_2}{\partial \vec{p}_2} d\vec{p}_2 \approx \frac{1}{v_1}\sum \sigma_{12} v_{12} \frac{\partial \rho_2}{\partial \vec{p}_2} \Delta \vec{p}_2$$

- Probability of a particle to interact at a distance between ***a*** and ***a+da*** is:

$$dP_{\text{int}}(a) = e^{-Qa} Q\,da$$

Hadron-Hadron Interactions

On-mass-shell, free cross sections

- **El**astic

$$N + N \Rightarrow N + N$$

- **Inel**astic (1π production & absorption)

$$N + N \Leftrightarrow \Delta_{33} + N$$

$$\Delta_{33} \Leftrightarrow \pi + N$$

Space-Like Basis MC

- The first collision site is determined and the collision partner chosen
- The types and momenta of the particles after the collision are chosen according to isospin and branching ratio considerations. Only “Pauli allowed” interactions are permitted.
- After the collision the particle is followed, and its possible next collision site and partner chosen. The process is repeated until the particle leaves the nucleus or falls below “energy cutoff”
- The interaction partners are treated the same way – one after another

Time-Like Basis MC (1)

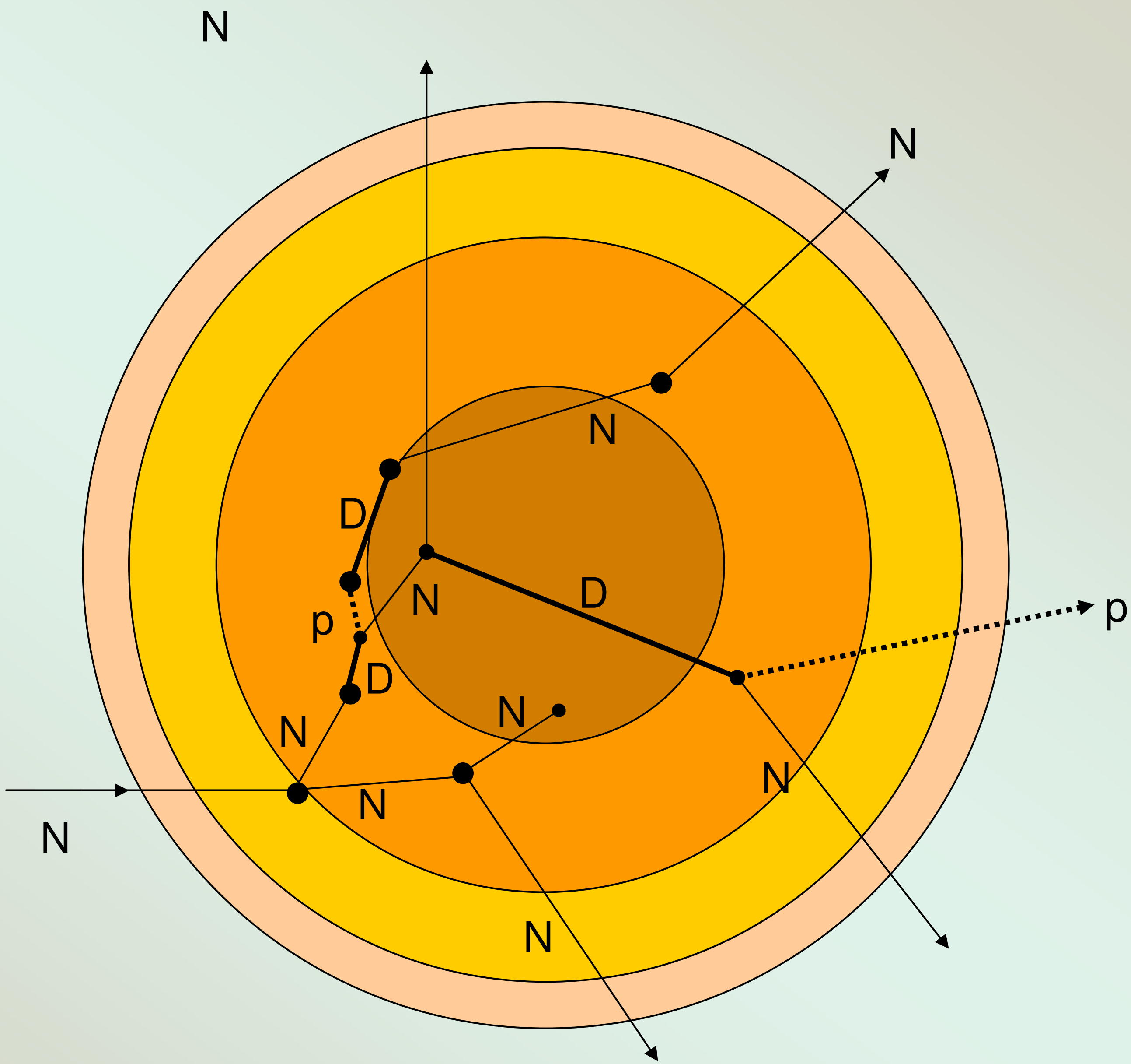
- **Cascade evolution divided into small "time intervals". The probability of interaction of the projectile in a time interval $\delta\tau$ is $P(\delta\tau)\approx\rho\sigma\delta\tau$.**
- **If collision occurs, the types and momenta of the particles after the collision ("participants") are chosen according to isospin and branching ratio considerations. If there is no collision, next time interval is considered**

Time-Like Basis MC (2)

- After each interaction the target Fermi Sea is "depleted"
- In each "time interval" all the "participants" are followed. With each interaction the number of particles to be followed in the next time interval increases
- Event ends when all participants escape or are absorbed

Nucleon Dynamics (INCL)

- The target nucleus is represented by discrete nucleons following nuclear density distributions in a potential well and "local density" degenerate Fermi gas momentum distribution
- The participants are moving on straight trajectories interacting when their "minimal distance of approach" is less than $\sqrt{(\sigma(s)/\pi)}$
- Interactions with Erel<≈100 MeV are not allowed (range restriction of ≈1.3 fm).
- Only "Pauli allowed" interactions are permitted
- Event ends when properties of reaction "stabilize"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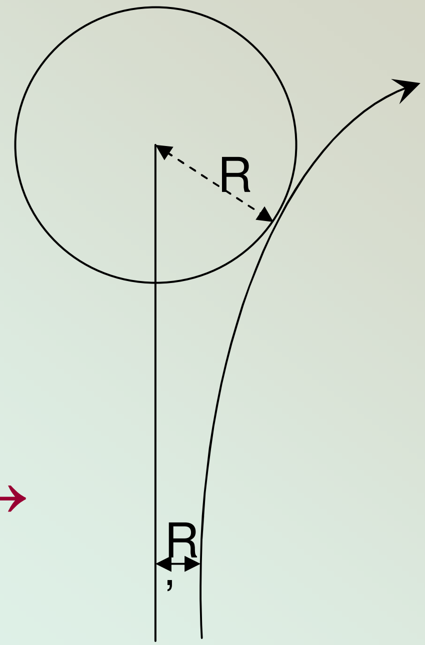
Output

- **Total reaction cross-section**

$$\sigma_R = \pi R^2 * \frac{N_{tot} - N_{Transp.}}{N_{tot}} * \left(1 - \frac{V_{Coul}(R)}{E_K^{Proj.}}\right)$$

- **Outgoing particle statistics → "Fast" particle spectra**

- **Residual target momenta and excitation energy from In-Out balance or Particle-Hole considerations**



איזבל ISABEL

אשד תוך גרעיני
Eshed Toch Gar'ini
→ ETGAR אתגר
Etgar = Challenge

History

- R.Serber, Phys. Rev. 72, 1114 (1947)
- M.L.Goldberger, Phys. Rev. 74, 1269 (1948)
- N.Metropolis et al., Phys. Rev. 110, 185 (1958); Phys. Rev. 110, 204 (1958)
- VEGAS: K.Chen et al., Phys. Rev. 166, 949 (1968)
- ISOBAR: G.D.Harp et al., Phys. Rev. C8, 581 (1973); C10 2387 (1974)
- ISABEL: Y.Yariv and Z.Fraenkel, Phys. Rev. C20, 2227 (1979); Phys. Rev. C24, 488 (1981)
- ETGAR…

Hadron-Hadron Cross Sections (1)

N+N

- σ_{tot}, σ_{inel} , σ_{el}
  G.D.Harp, Phys. Rev. **C10**, 2387 (1974)
  Arndt phase shift analysis
- $d\sigma_{el}/d\omega$
  P.C.Clements, L.Winsberg, UCRL 9043 (1960), unpublished

Hadron-Hadron Cross Sections (2)

◈ N+N → N+Δ

- Type of outgoing N, Δ determined by Isotopic Spin consideration
  Z.Fraenkel, Phys. Rev. **130**, 2407 (1963)
- Mass of Δ is chosen from distribution:

  $$P(m_\Delta, E_{cm}^{N+N}) = const.*\sigma_{tot}^{\pi^+ + p}(E_{cm}^{N+N}) * F(m_\Delta, E_{cm}^{N+N})$$

  $$m_\pi + m_N < m_\Delta < m_\pi + m_N + 500MeV$$

  F = two body phase factor for the produced N+Δ
  S.Lindenbaum and R. Sternheimer, Phys. Rev. **105**, 1874 (1957); **109**, 1723 (1958); **123**, 333 (1961)
- P($\cos_{cm}$)=.25+.75*($\cos_{cm}$)^2

Hadron-Hadron Cross Sections (3)

◈ Δ+N → N+N (π capture)

- Type of outgoing N, Δ determined by Isotopic Spin consideration
- σ, dσ/dω calculated from inverse process (Δ production) using the principle of "detailed balance"
- Δ production calculated using theoretical model (OPE)

Hadron-Hadron Cross Sections (4)

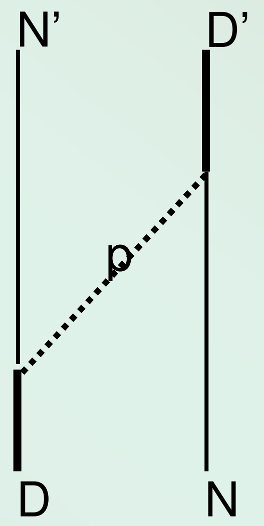
◈ Δ+N → Δ'+N' ("exchange")

- Naively two step process:
  - Decay of initial Isobar, Δ→π+N'
  - Interaction of decay π with another Nucleon, π+N→Δ'

G.D.Harp et al., Phys. Rev. **C6**, 581 (1973),

Z.Fraenkel, Nuovo Cimento **30**, 512 (1963)

Z.Fraenkel, Phys.Rev. **130**, 2407 (1963)



Hadron-Hadron Cross Sections (5)

◈ $\pi+N \rightarrow \Delta \rightarrow \pi'+N'$ (elastic & charge exchange)

- Experimental $d\sigma/d\omega$ + isospin considerations G.Giacomelli et al., CERN/HERA 69-1 (1969)
- For Δ decaying without interaction proper $\pi+N$ differential cross section
- Isotropic Δ decay after scattering or exchange

Hadron-Hadron Cross Sections (6)

$\Delta \rightarrow \pi + N$

- Energy dependant Δ width
  J.N. Ginocchio, Phys. Rev. **C17**, 195 (1978)

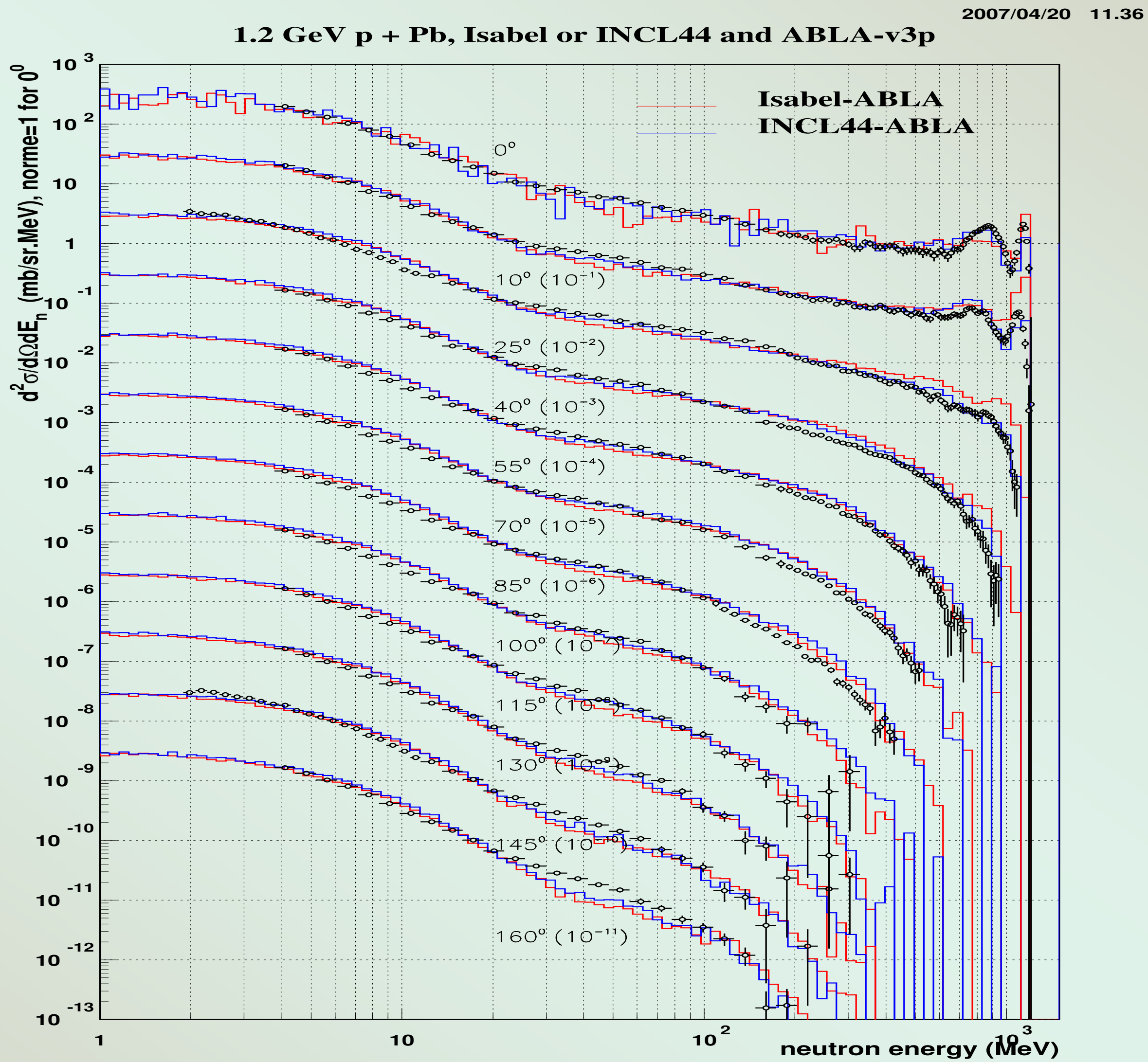
Density depletion

- **After each interaction Fermi sea density, ρ_i, is depleted**
  - **Fast rearrangement**: ρ_i of the "partner type" Fermi sea is uniformly reduced for the whole nucleus
  - **Slow rearangement**: "partner type" hole of radius r is punched in the position of the interaction. No interactions are allowed in the hole with particles of "partner type" .

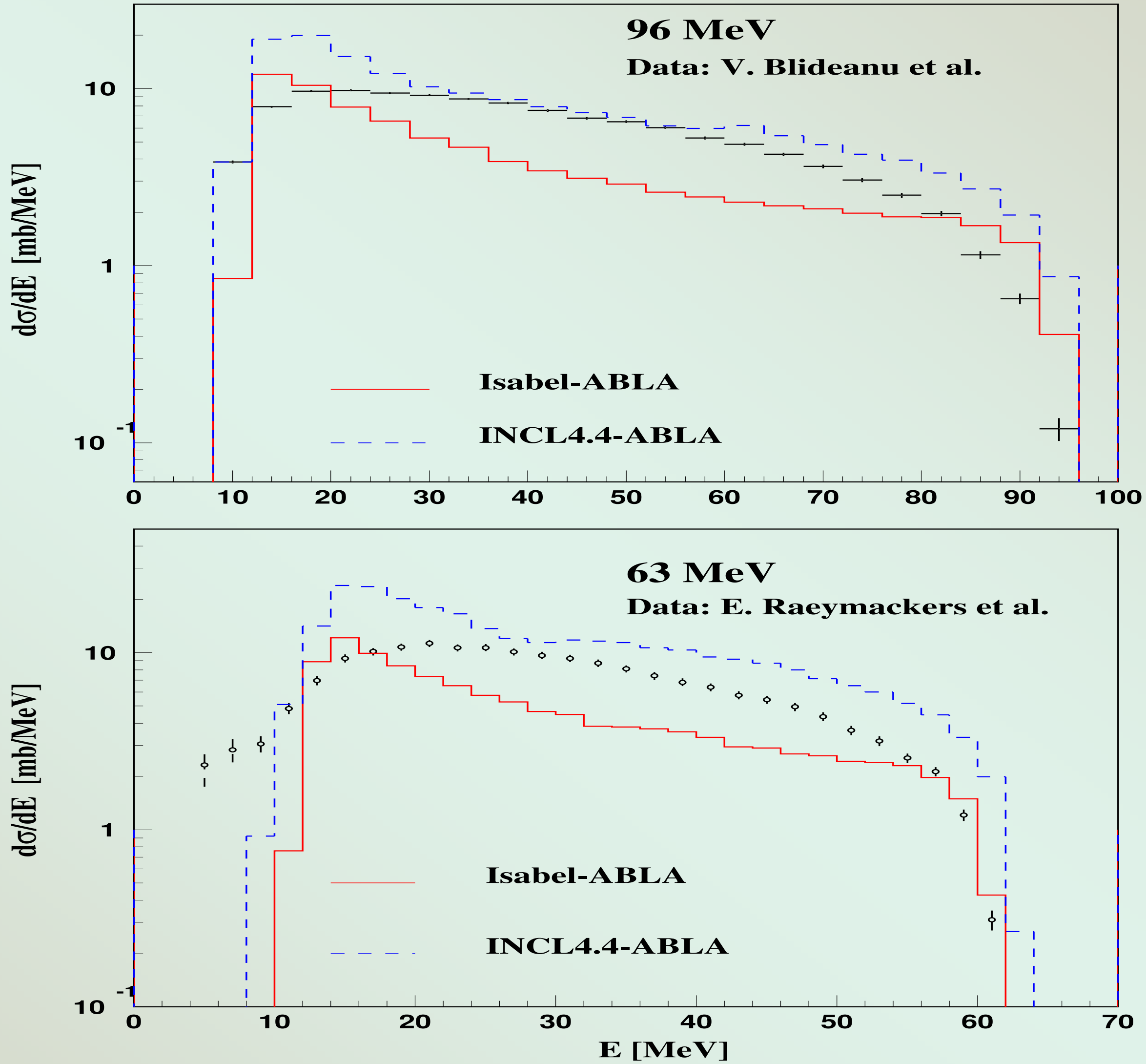
Pauli Blocking

- **Options:**
  - **Full Pauli Blocking**: Interaction resulting in nucleon falling below Fermi sea is forbidden
  - **“Depleted” Pauli Blocking:** Reaction resulting in nucleon falling below Fermi sea is allowed with probability of the relative depletion of the Fermi sea

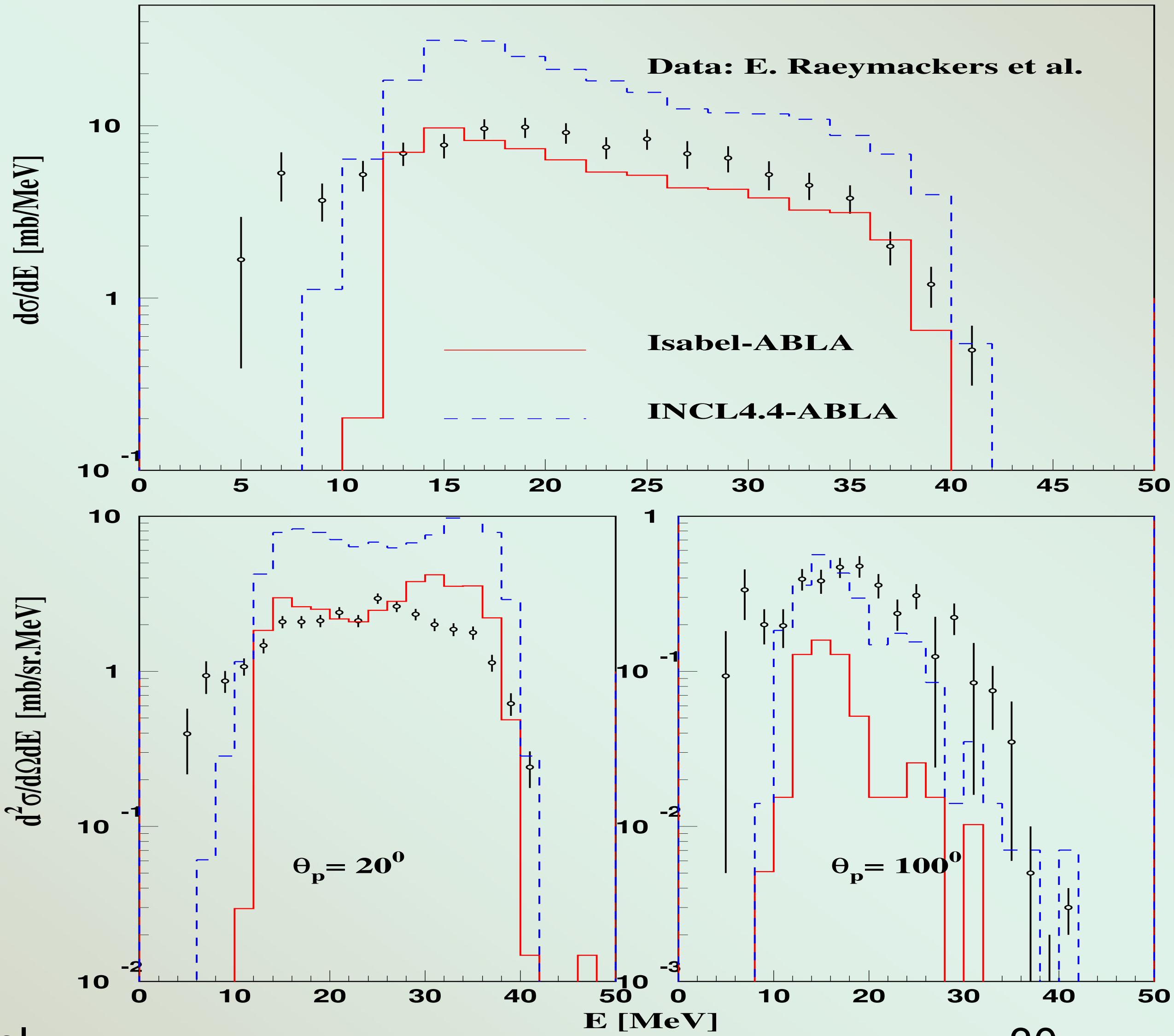
p(^{208}Pb,nX) at 1.2 GeV



n(^{208}Pb,pX) at 96 MeV, n(^{209}Bi,pX) at 63 MeV



n(^{209}Bi,pX) at 41 MeV



Thank You!

Questions, Remarks?