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Experimental data on evaporation and pre-equilibium emission in GeV p-induced spallation reactions

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Experimental data on evaporation and pre-equilibrium emission in GeV p-induced spallation reactions

frank goldenbaum for the nessi/pisa collaboration

NESSI@COSY & PISA@COSY experiment (data up to 2.5 GeV)

- very brief sketch of exp. facilities
- few words on neutron measurements (multipli. NESSI)
- LCP, IMFs: H, He, Li, and Be…
  - o DDXS $\frac{d\sigma}{dEd\Omega}$ production cross sections /multiplicities
  - o angular and energy distributions of charged particles

    p,d,t,^{3}He, ^{4}He, Li, Be, … IMFs (<Z=16)

    - pre-equilibrium and evaporation contributions
    - (excitation energy distributions)
    - comparison experimental data – simulation (inc-evap.-coal. models)

- ~~fission in GeV p+Bi,Au,U~~
  - o ~~identification of FF, fission cross section, probability~~
  - o ~~post scission LCP(α)-emission~~
- conclusion

Not in yesterdays list

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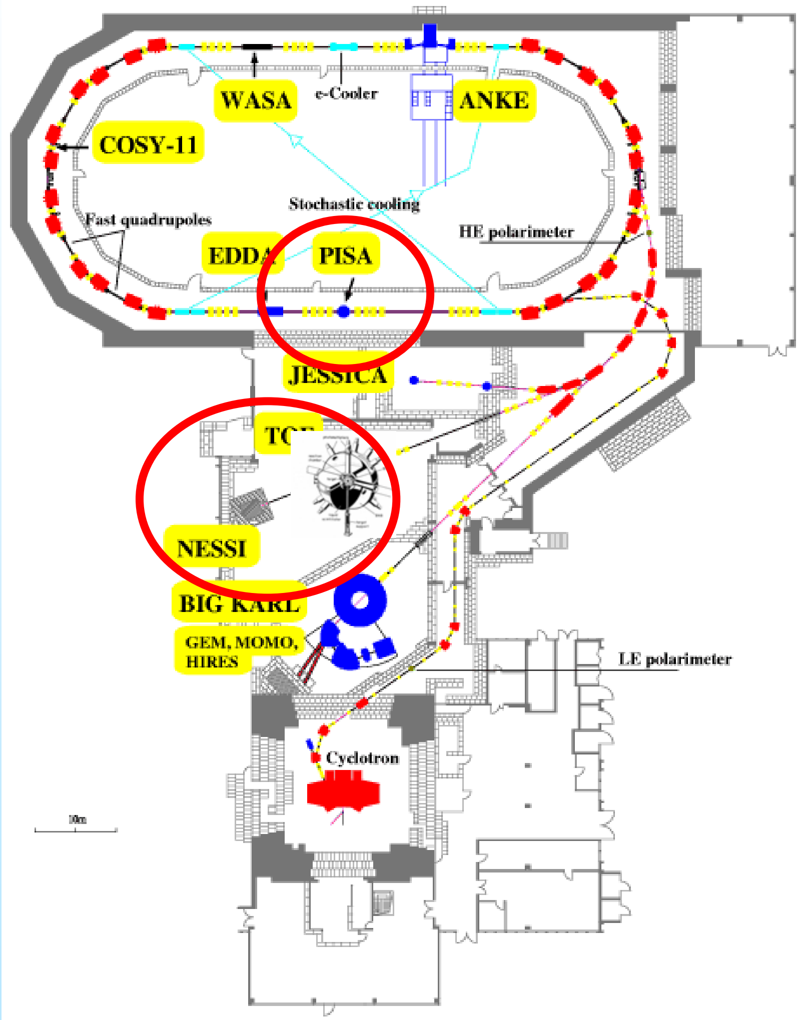
Motivation

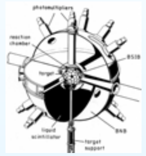
- nuclear data required for ADS facilities planned: shielding layout, irradiation damage in target and structural materials, dpa, embrittlement, gas production, radioactive inventory, activation
- decay modes of highly excited hot nuclear matter
- systematics on production cross sections for H,He,Li,Be isotopes (complex particles) in GeV pN reactions
- understanding of reaction mechanism and cluster formation (coalescence, exciton model, successive elementary reactions,...)
- decomposition of evaporative and pre-equilibrium components
- systematic comprehensive data set on angular-, energy distributions (over wide range of target nuclei) provide test grounds for model development and improvements and sensitive benchmarking

Schematic layout of the COSY (FZJ, Germany) (COoler SYnchrotron) facility (p,d<2.5GeV)



NESSI (external experiment)

NEutron
Scintillator and
SIlicium detector



PISA (internal experiment)

Proton
Induced
SpAllation

- Energy range: 150 MeV – 2.5GeV
- Luminosity: 6.6*10^{34} cm^{-2}s^{-1}
- Low absorption, small energy loss of ejectiles due to target thicknesses (down to 50 µg/cm^2)

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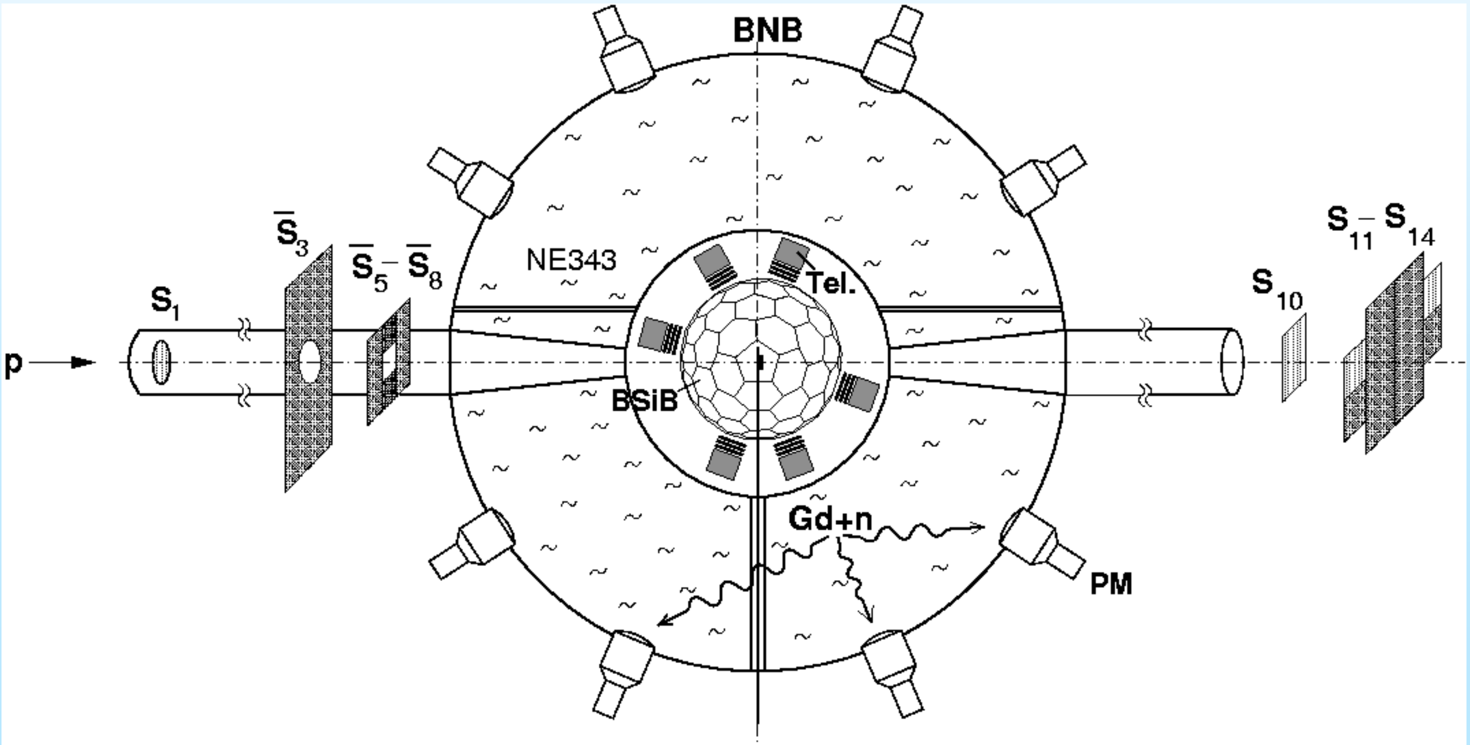
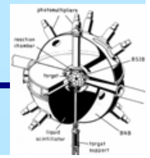
Experimental set up: Neutron-, Si-ball, telescopes…

BSiB: 20cm, 151, 500µm Si, 67msr

Telescope: 30, 2x75, 2x105, 150°
4-element Si/CsI
26, 85, 1000µm (Si) and 7cm (CsI)

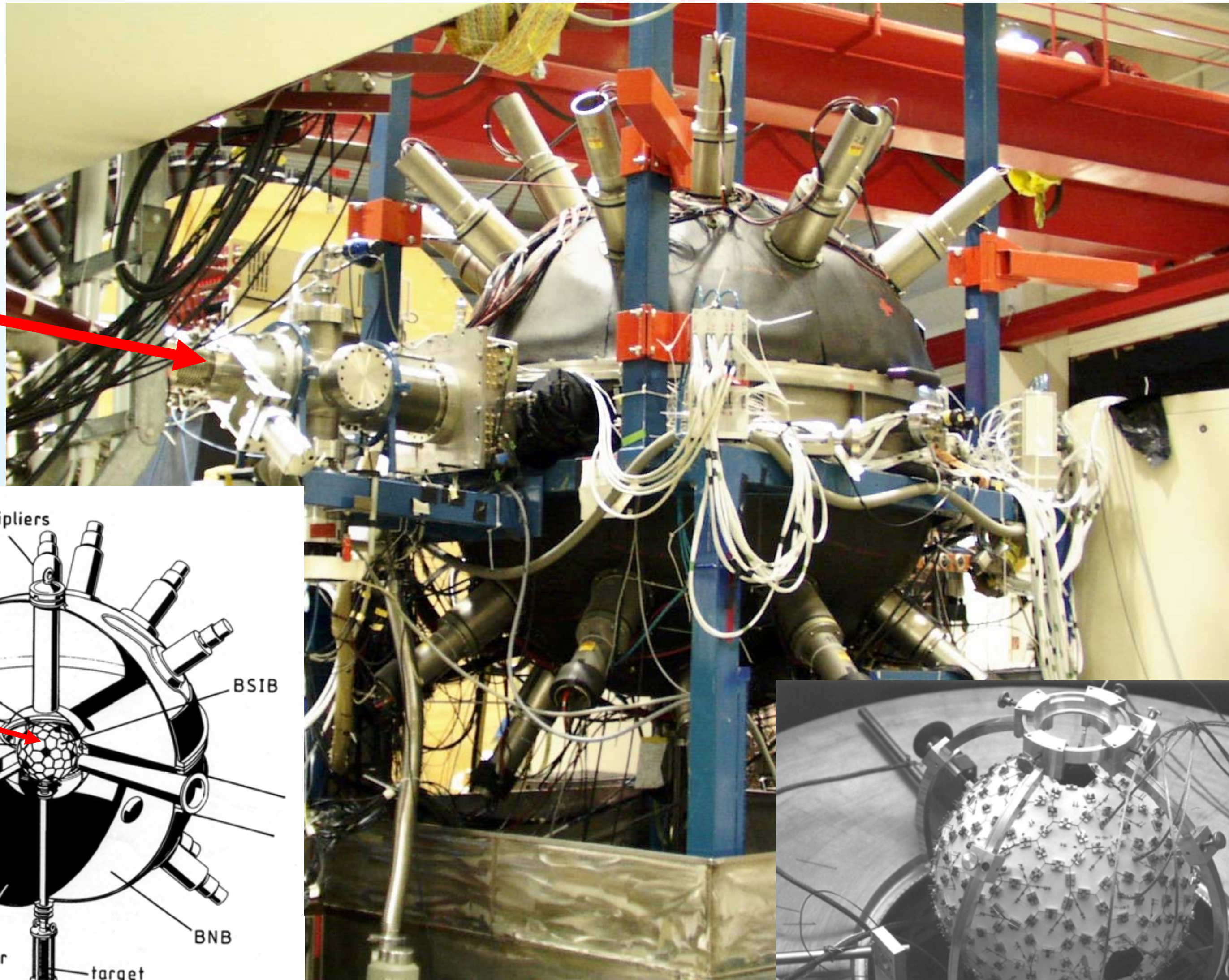
Targets: 0.5-10mg/cm²

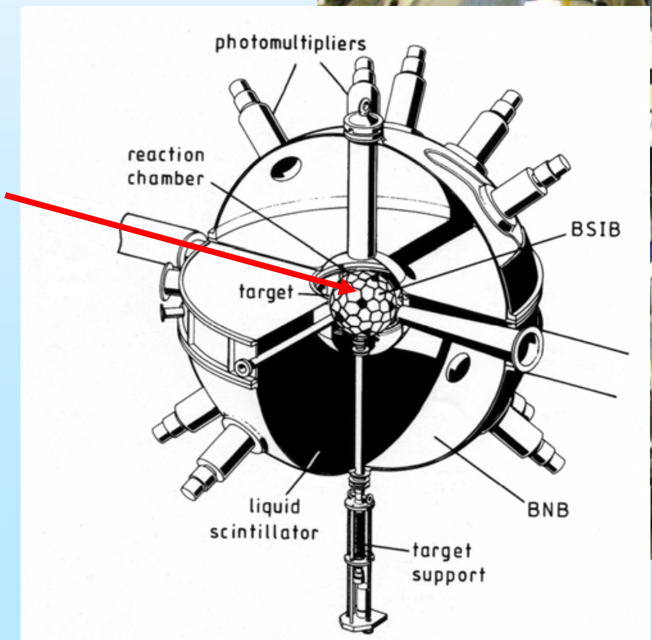


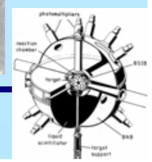


NESSI @ COSY

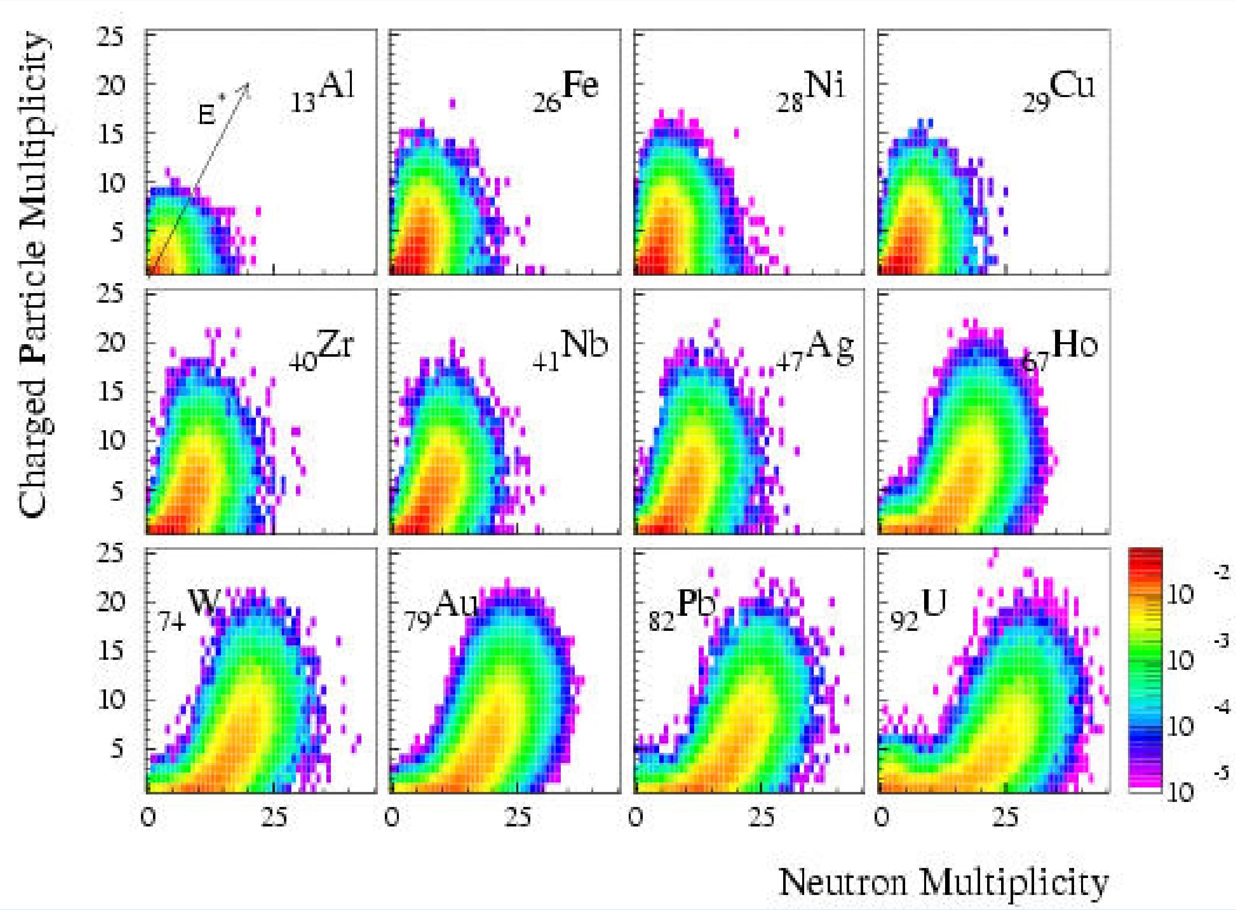
GeV p







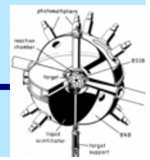
Light particle production in spallation reactions induced by protons of 0.8 to 2.5 GeV incident kinetic energy



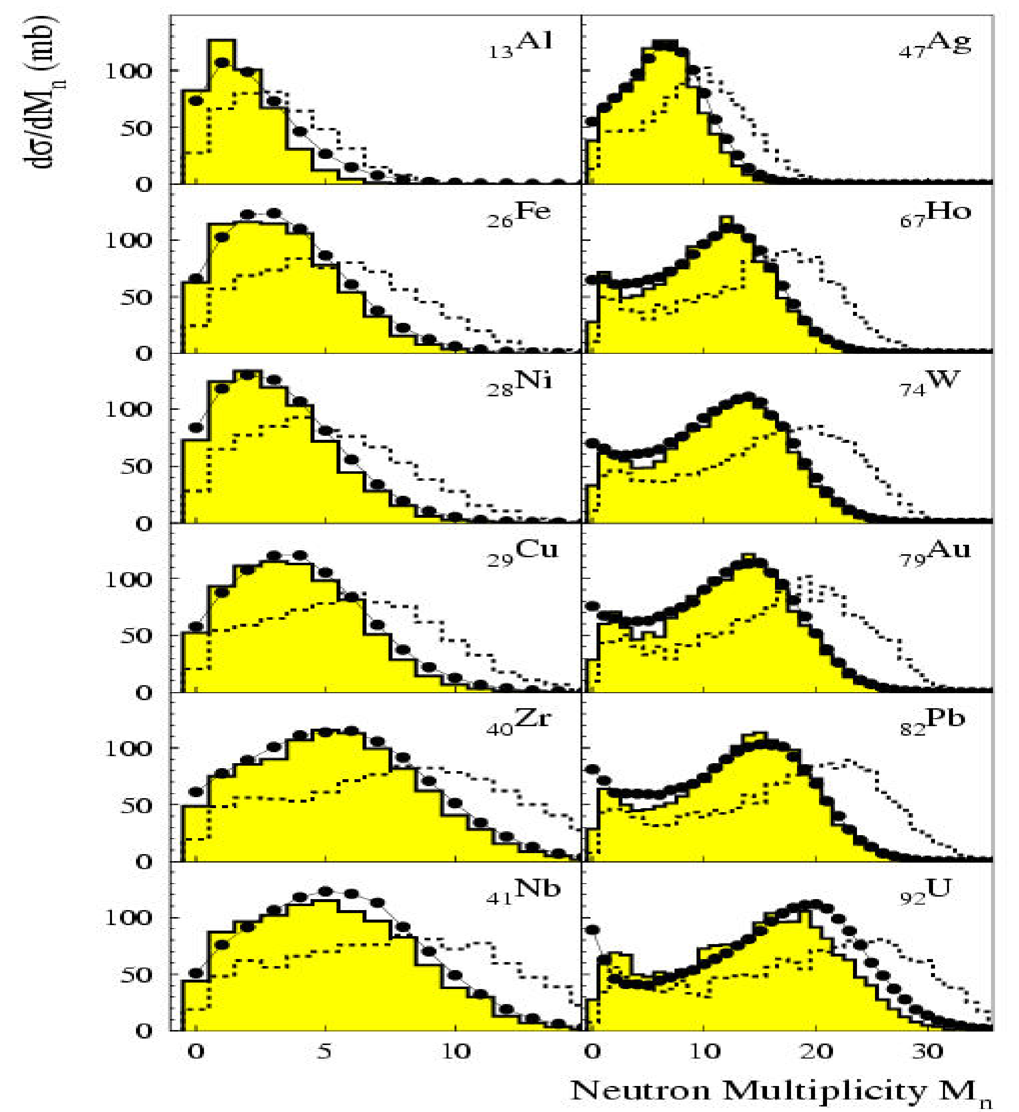
correlation of measured LCP-vs. n-multiplicity for 2.5 GeV proton-induced spallation reactions

the color scale gives the relative yield for each target per multiplicity bin

thermal excitation is following indicated arrow



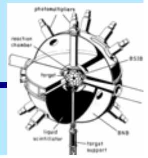
Neutron multiplicity distributions for 1.2 GeV p+Al,...,U.



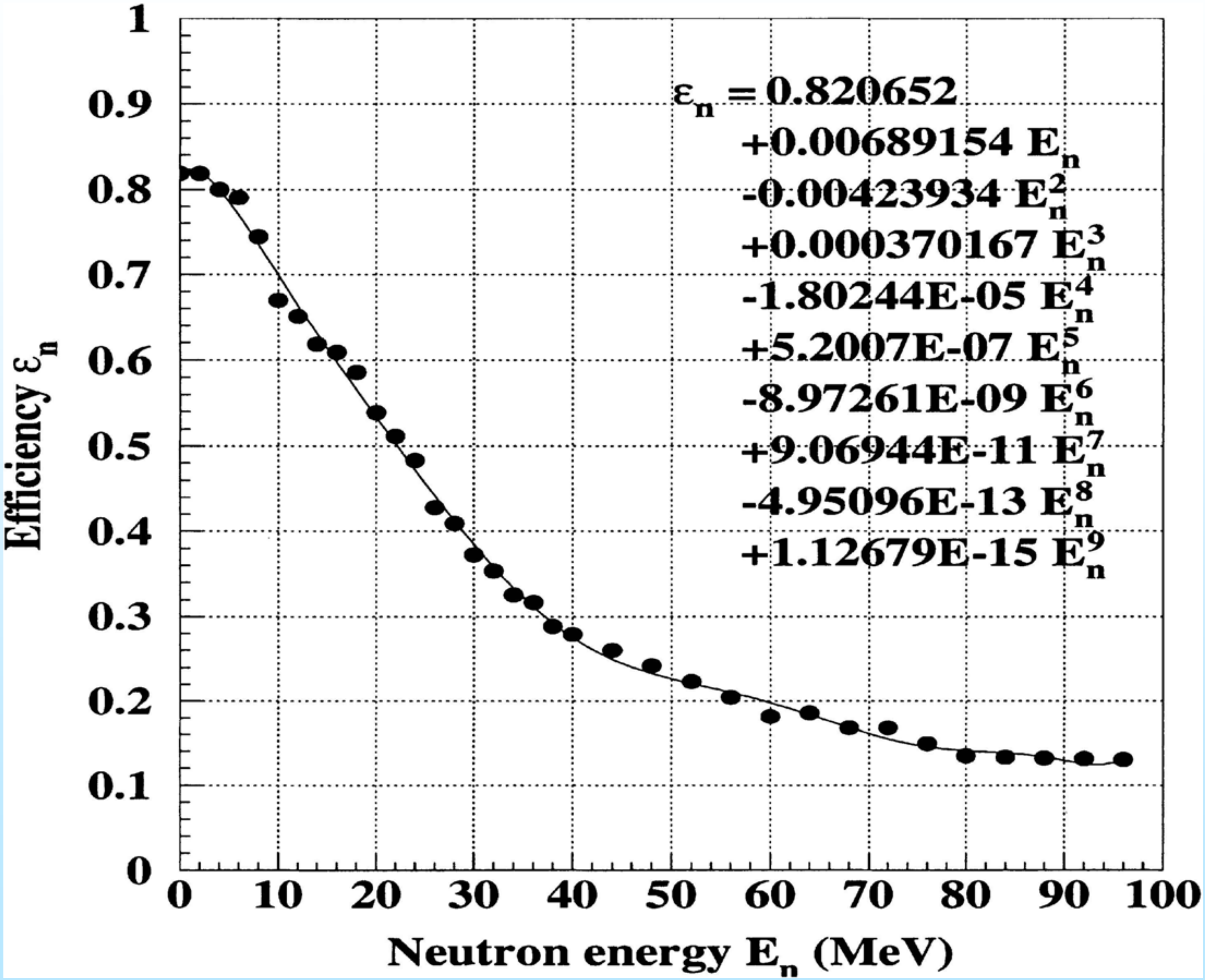
measured (symbols) and calculated (histograms) neutron multiplicity distributions.

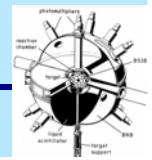
calculated (INCL2.0+GEMINI) distributions are shown before (dashed histogram) and after (shaded histogram) folding with the neutron energy dependent detector efficiency.

note different M_n scales for the left and the right panels.

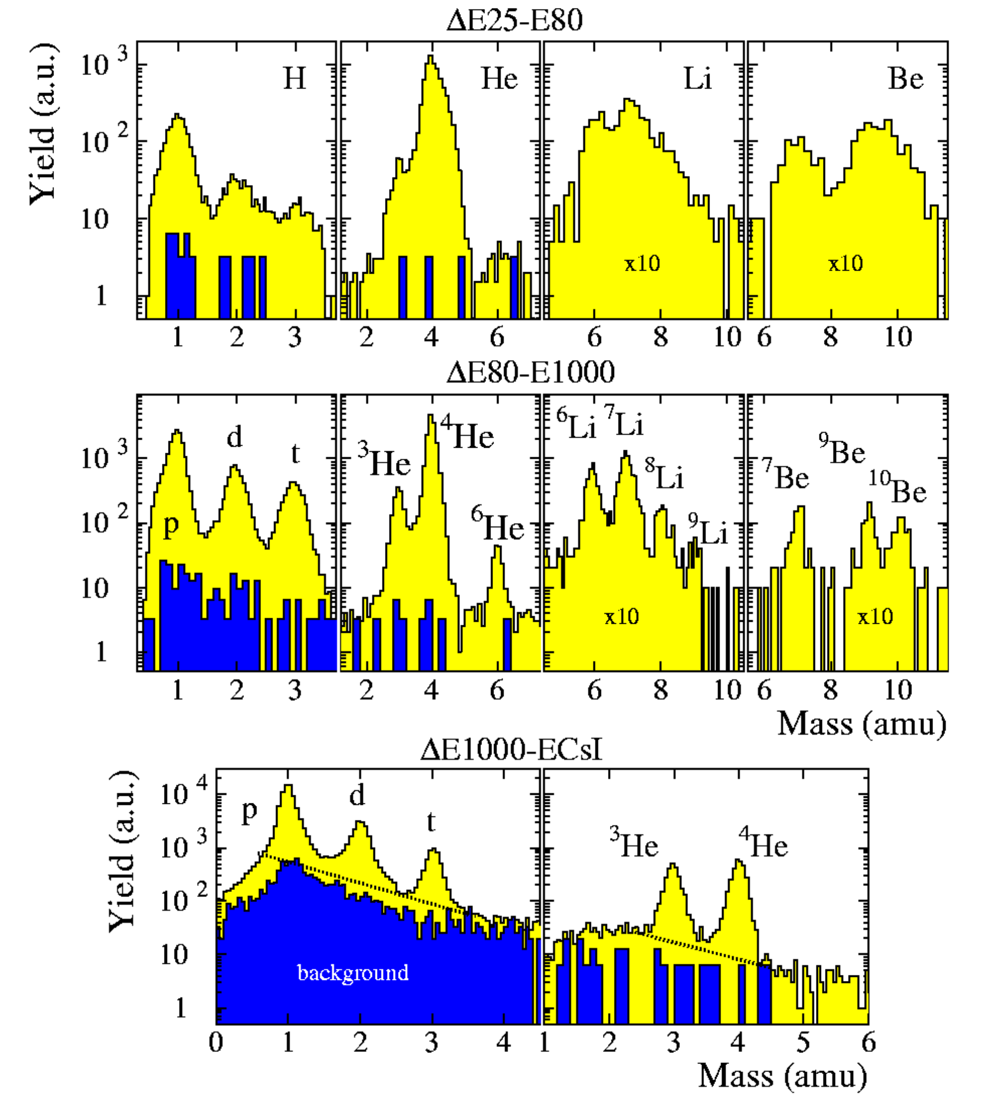


Neutron detection efficiency





Mass spectra of H, He, Li and Be

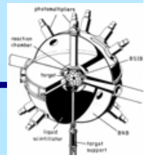


measured with different combinations of ΔE-E telesc.

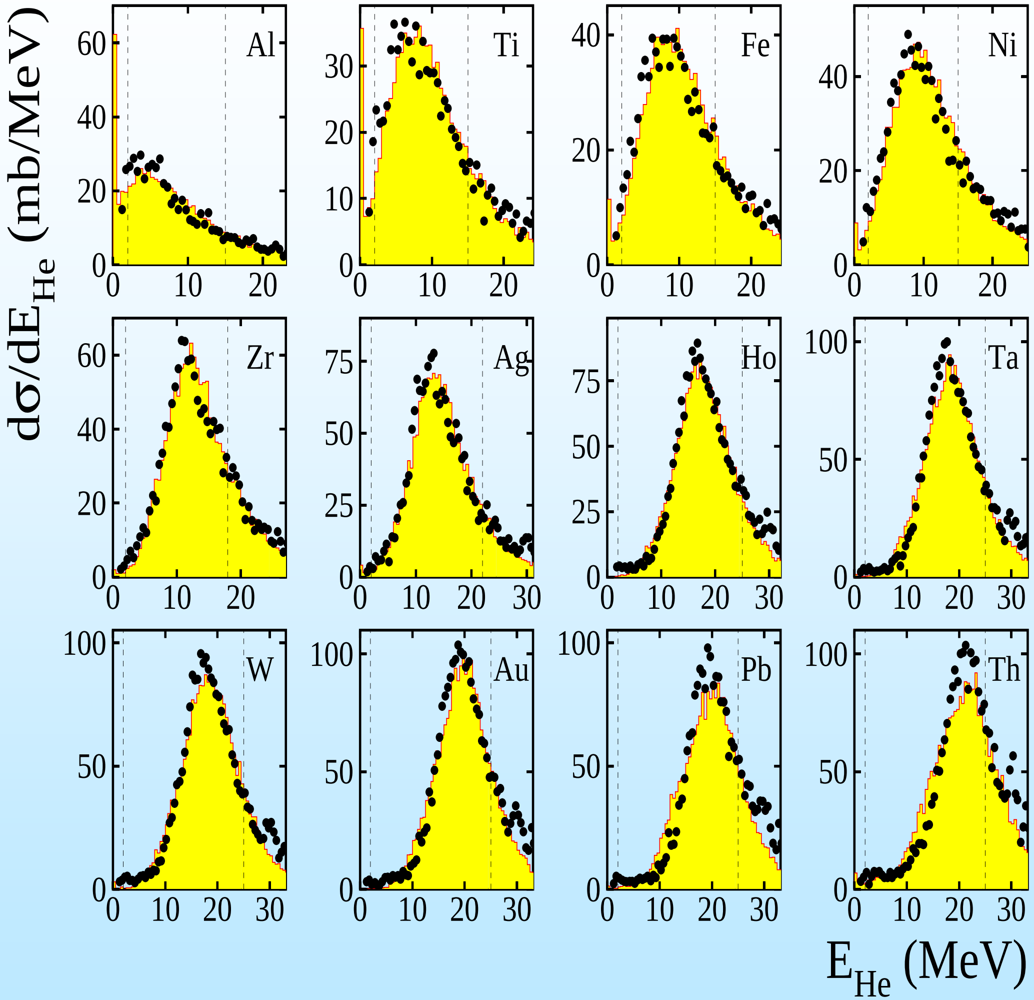
blue: background empty target frame

For CsI high background due to sensitivity and high light output for neutrons and gammy rays

Energy calibration of CsI for individual particles by reference to the energy loss in the 1000µm Si detector in front; for high energy H ions CsI punch-through energies were used for calibration (160, 210, 250MeV for p,d,t)



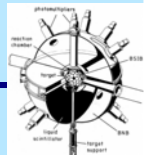
He-spectra (1.2GeV p+X)



He-spectra measured with BSiB (dots) and calculated with INCL2.0 & GEMINI (shaded histos)

Dashed lines indicate energy ranges for „normalization"

Threshold: 2MeV
17%, 3% correction for Al, Fe targets most obvious for Al due to low Coulomb barrier!



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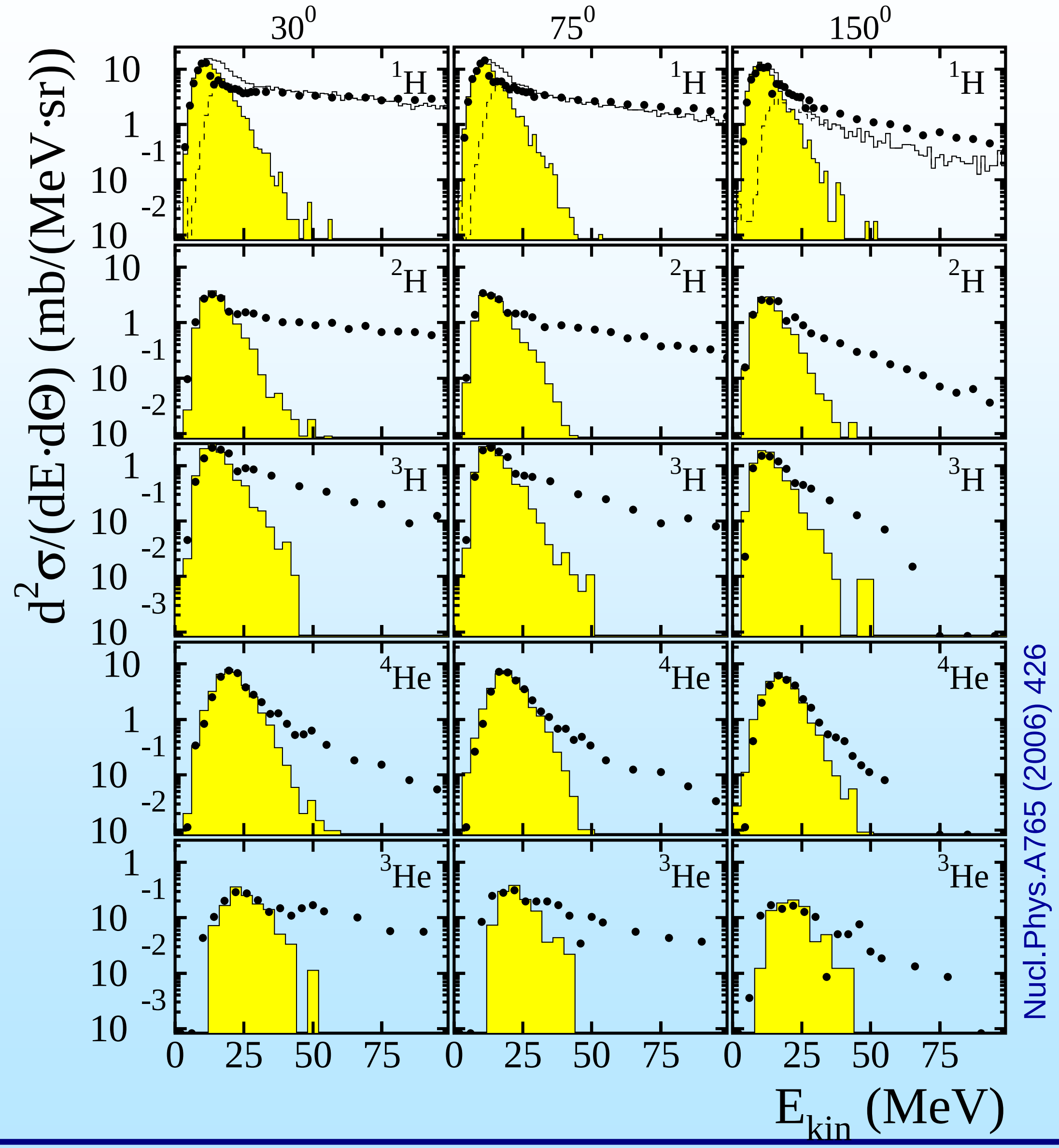
Energy spectra of $^{1,2,3}H$ and $^{3,4}He$



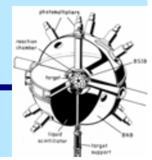
@30, 75 and 150⁰ for the reaction 1.2 GeV p +Ta

dots: experimental data
→ clearly feature two components!

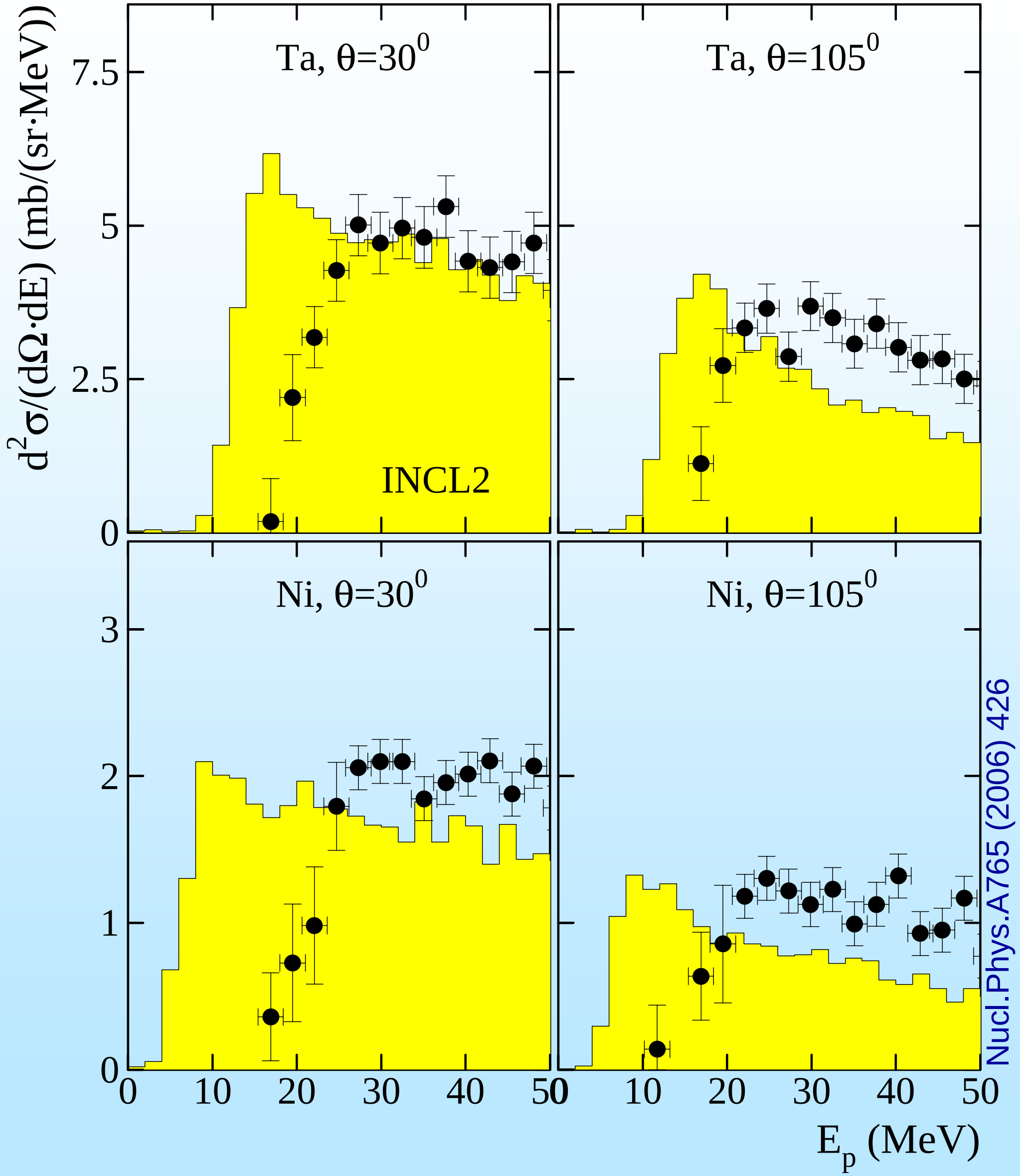
shaded histos: calculated evaporation spectra INCL2.0 & GEMINI

dashed histo: INC-protons by INCL2.0

1.2 GeV p+Ta



Energy spectra of INC protons



shaded histo: calculated INC proton spectrum

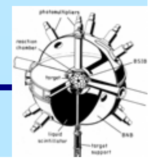
dots: experimental difference spectrum

$$\frac{d^2\sigma_{exp}}{d\Omega dE} - \frac{d^2\sigma_{EV}}{d\Omega dE}$$

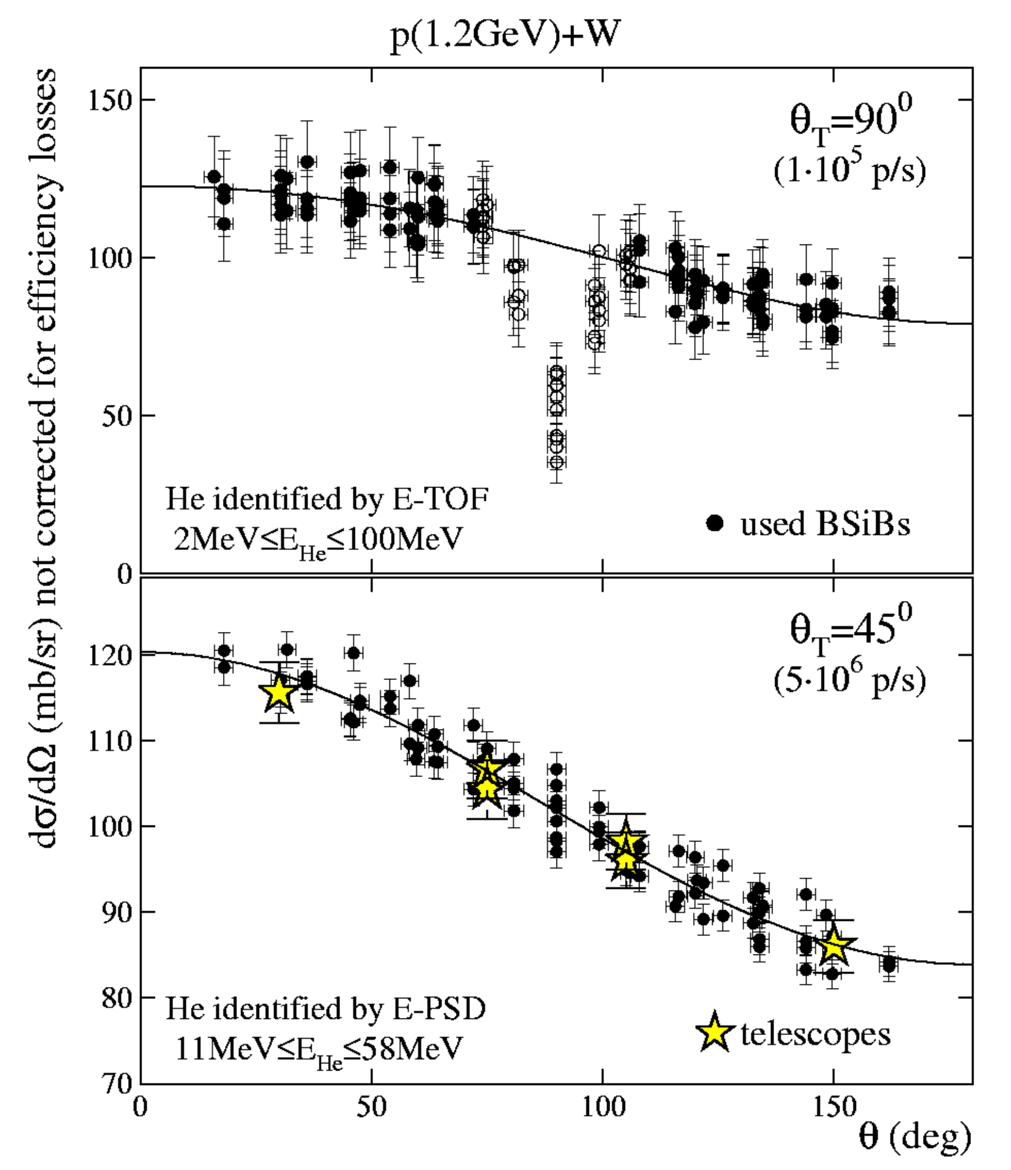
at E<20 MeV large discrepancy!

→ Cut off time INC to Evap should be shorter?! Which is however in contradiction to the asumptions in the new version of INCL4.2, 4.3….

1.2 GeV p+Ta



Angular distribution of He ions for 1.2 GeV p+W



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measured with BSiB

upper panel: 90° in respect to beam

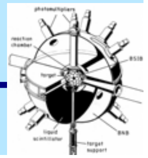
lower panel 45°

Lines are fits to the eqn.:

$$Y(\theta) = P_0 \cdot (1 + P_1 \cdot \cos(\theta) + P_2 \cdot \cos^2(\theta))$$

Integrated over 4π sr :

$$Y_{4\pi} = 4\pi\, P_0 \cdot (1 + P_2 / 3)$$



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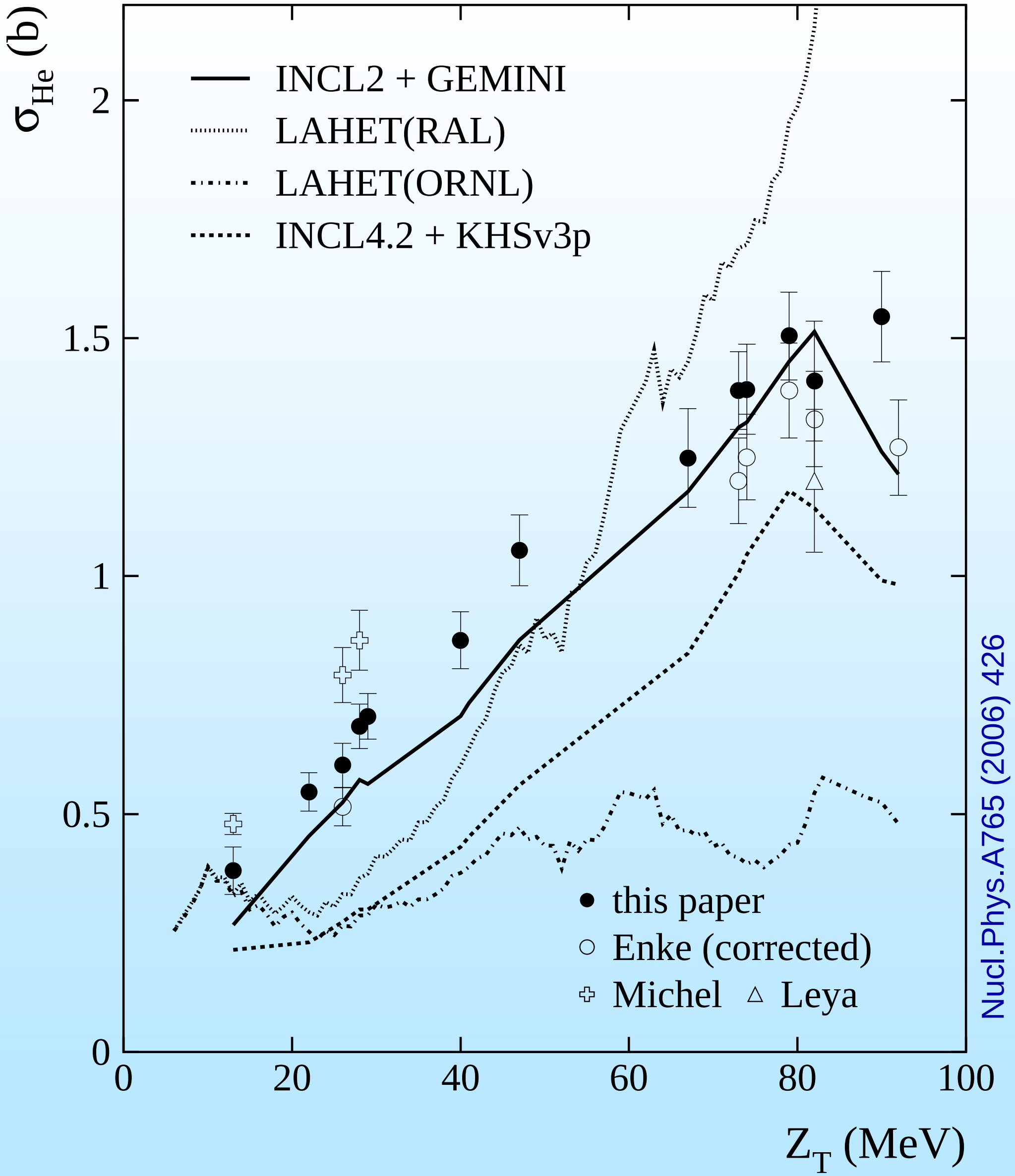
Total He (He^3+He^4) production cross sections



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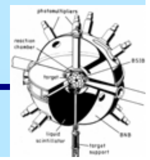
Generally underestimation of the measured data, because of 5-20% pre-equilibrium emission (not taken into account in INCL+GEMINI)

1.2GeV p+X (NESSI)

- Solve discrepancies between different sets of data
- Solve deficiencies of models



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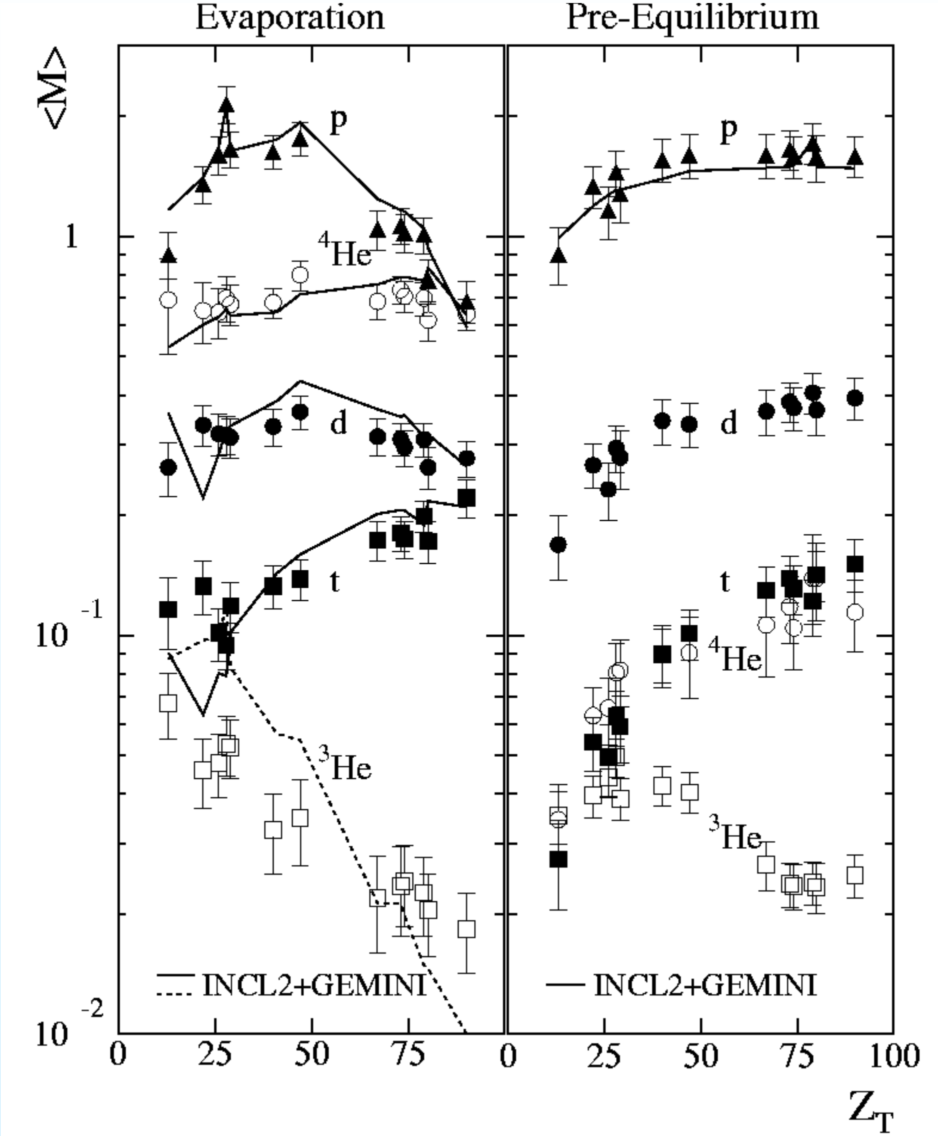
Average particle multiplicities 1.2 GeV p+X



$$\sigma_{pe} = \sigma_{tot} - \sigma_{ev}$$

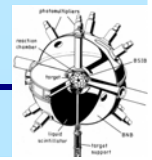
$$M_{ev} = \sigma_{ev} / \sigma_{inel}$$

$$M_{pe} = \sigma_{pe} / \sigma_{inel}$$

Evaporation well described

Pre-equilibrium for E_{ejc}<100MeV

d,t,^{3}He similar to evap. component, but note ^{4}He !!! (difficult to understand within framework of the coalescence)



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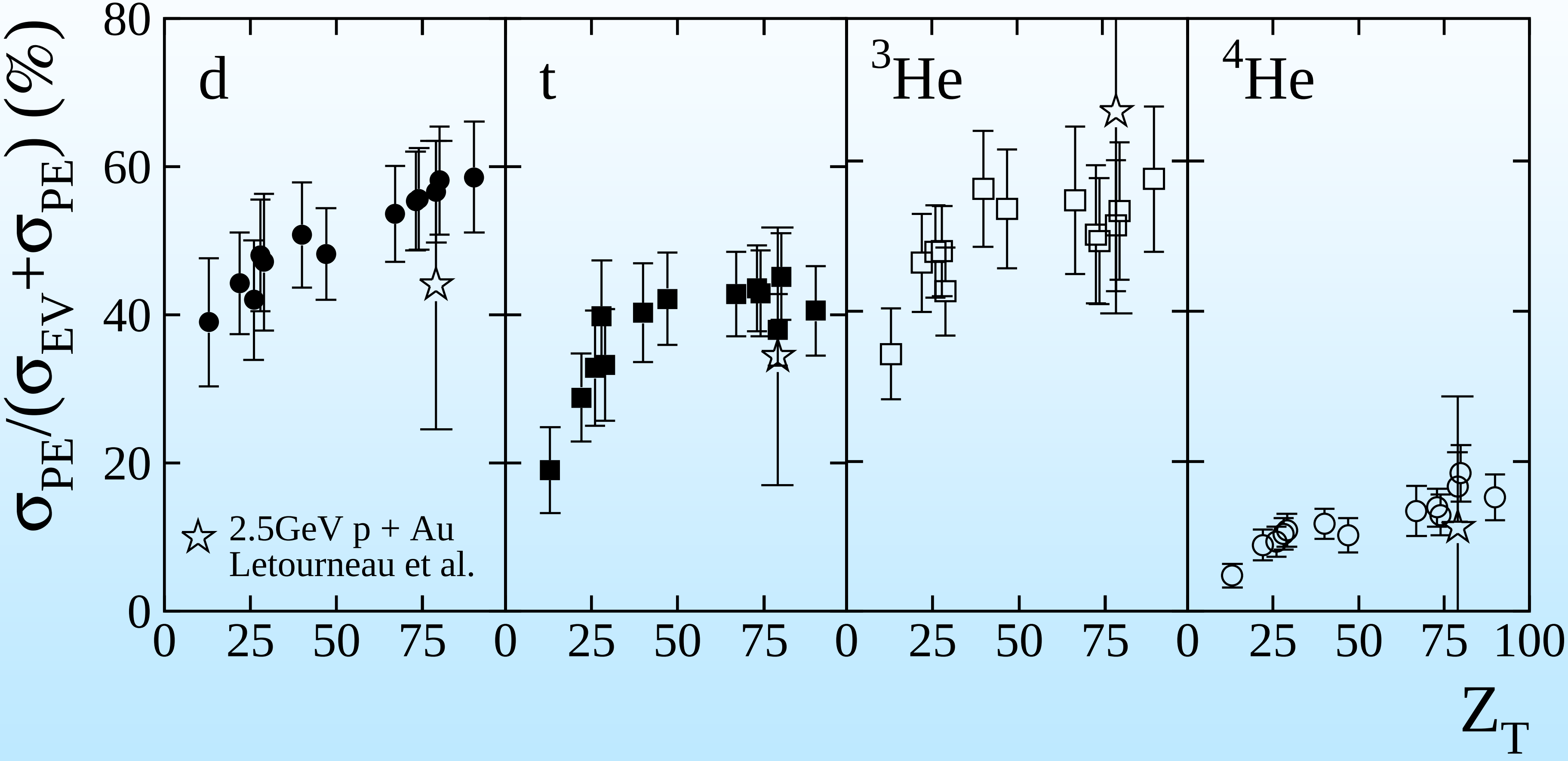
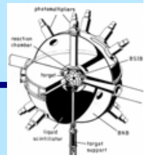
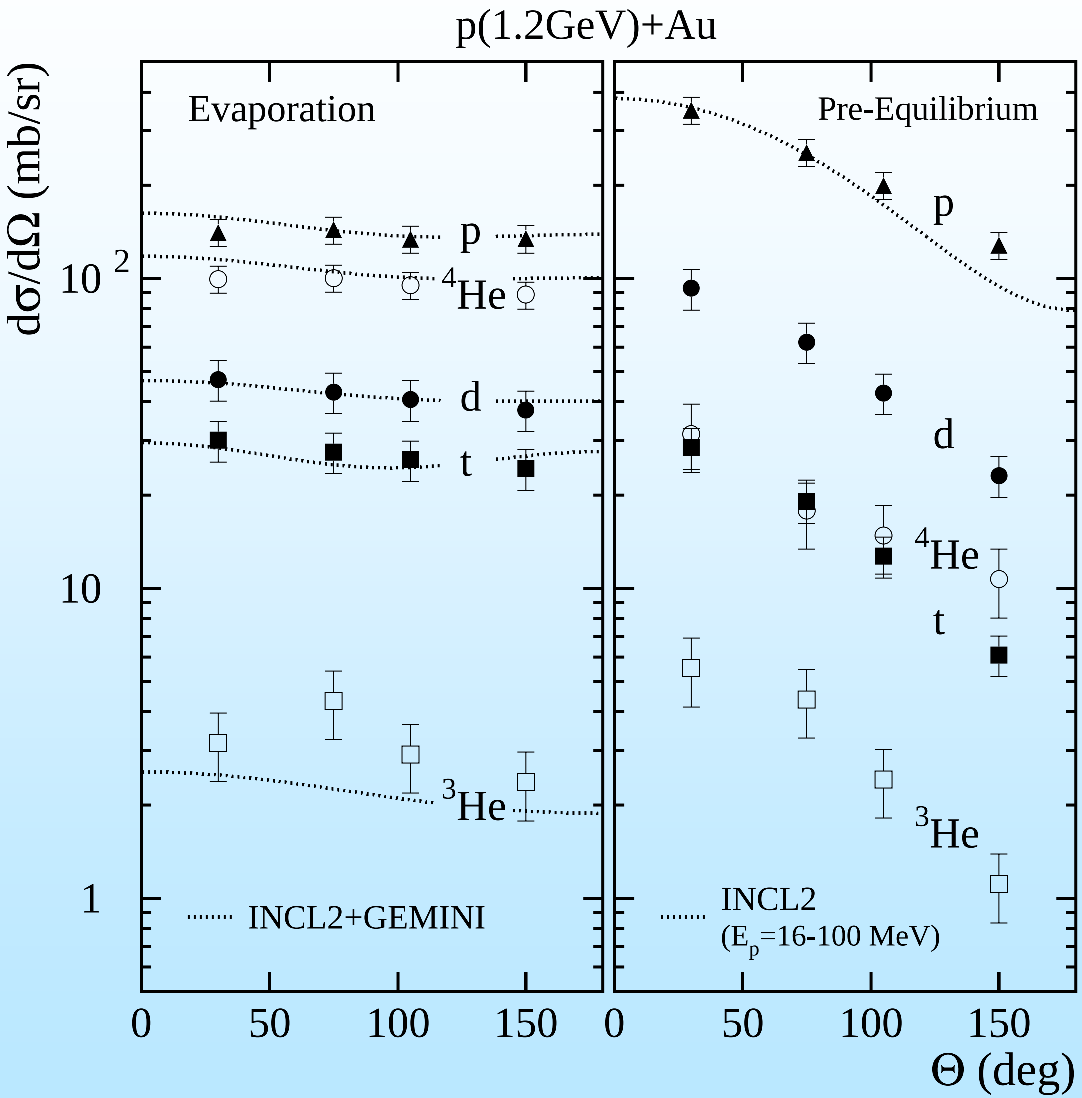
Pre-equilibrium emission relative to total yield of light composite particles for 1.2(2.5) GeV p+X



Pre-equilibrium not legledible, however frequently not considered in models!



Angular distributions of LCPs in the 1.2 GeV p+Au



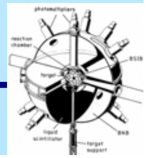
Symbols exp.

Lines: INCL2.0+GEMINI

Left panel isotropic evap

Right panel: more directly emitted particles exhibit larger forward/backward asymetry;

Protons are well described also in pre-equilibrium process…



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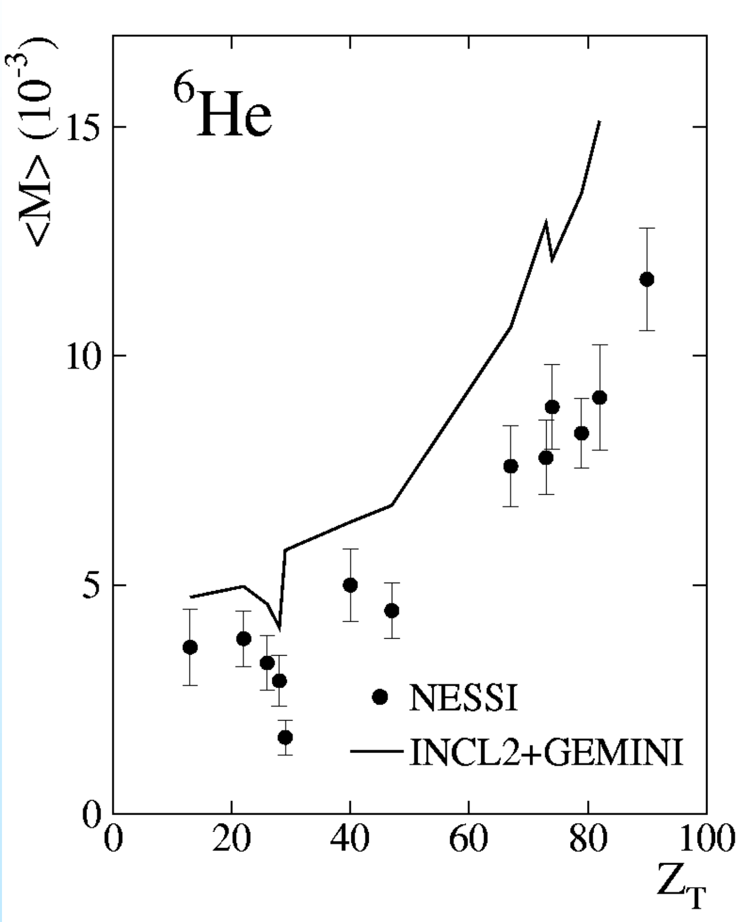
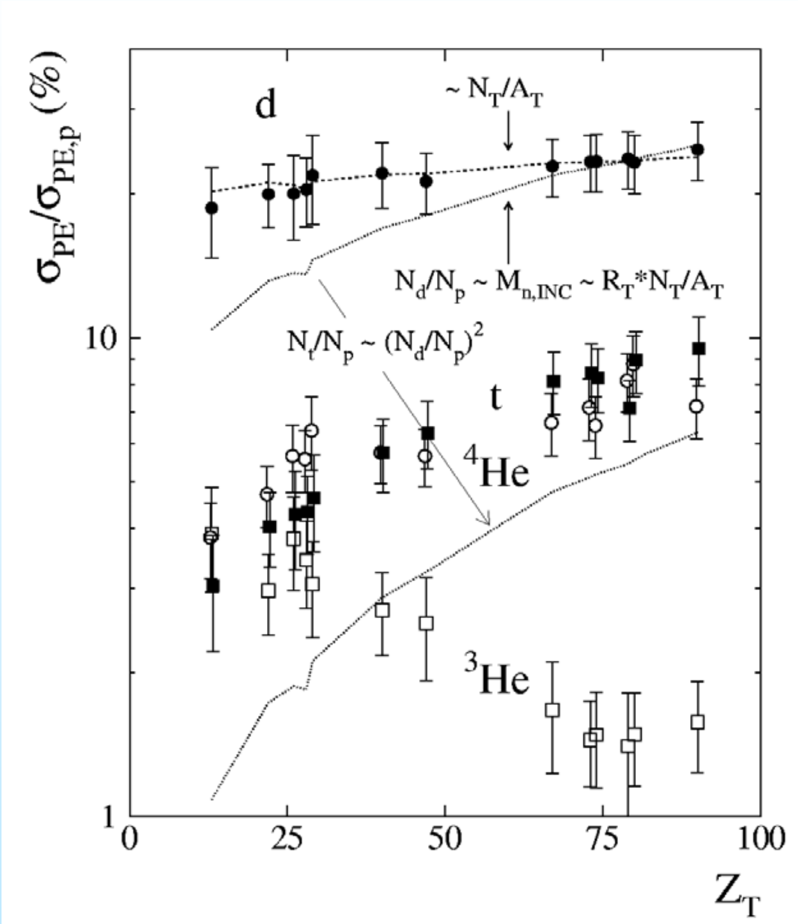
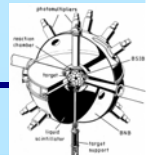
He6 Multiplicity





Multiplicity of this neutron rich He isotope strongly increases with Z_T–similar to the neutron rich triton! Due to larger neutron excess (N-Z)/A of heavier targets??



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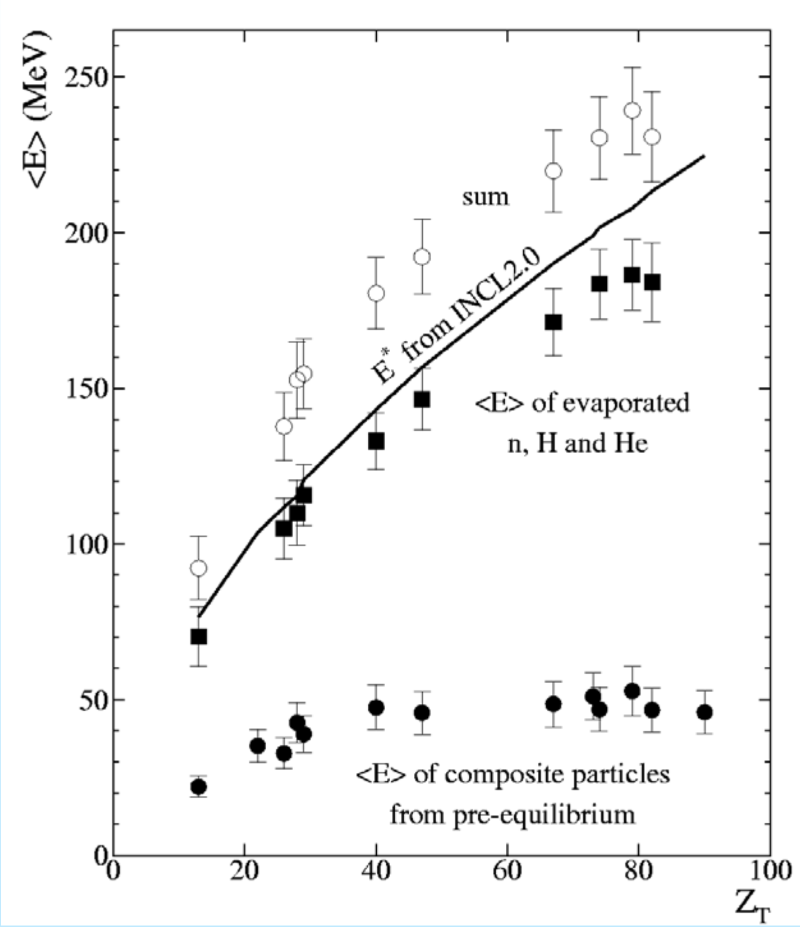
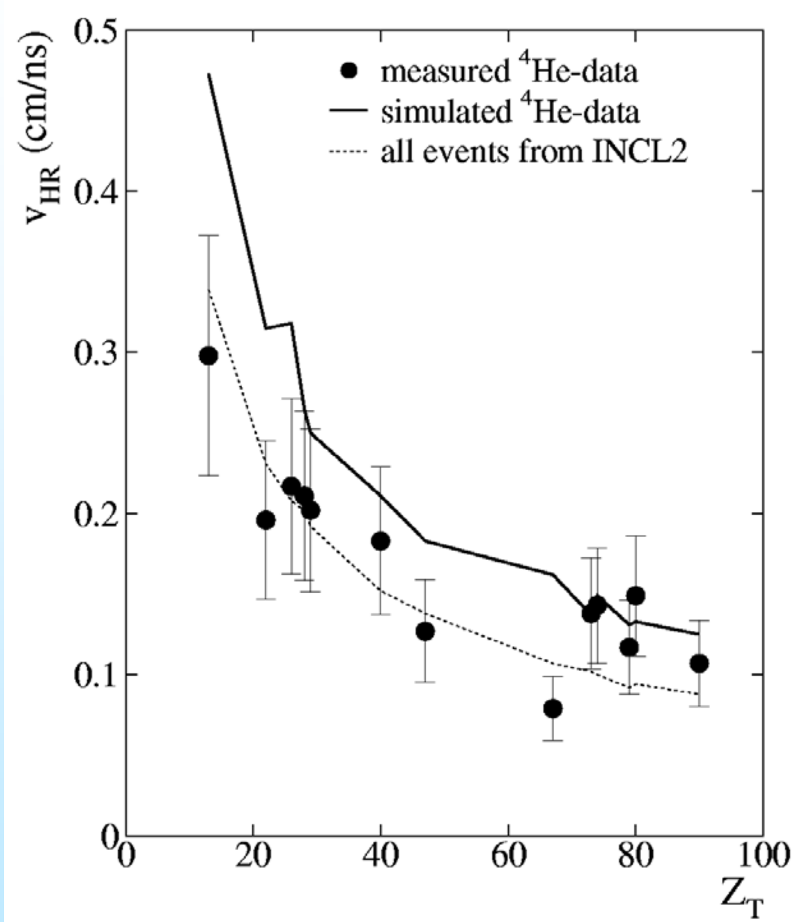
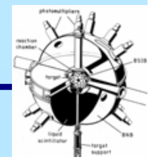
Average dissipated thermal E* and LMT





Note that here protons do not contribute to the pre equilibrium component; conversion 6-16% of E_{inc}

v_{HR} as extracted from the forward backward emission asymmetry of He (cf. previous eq.)



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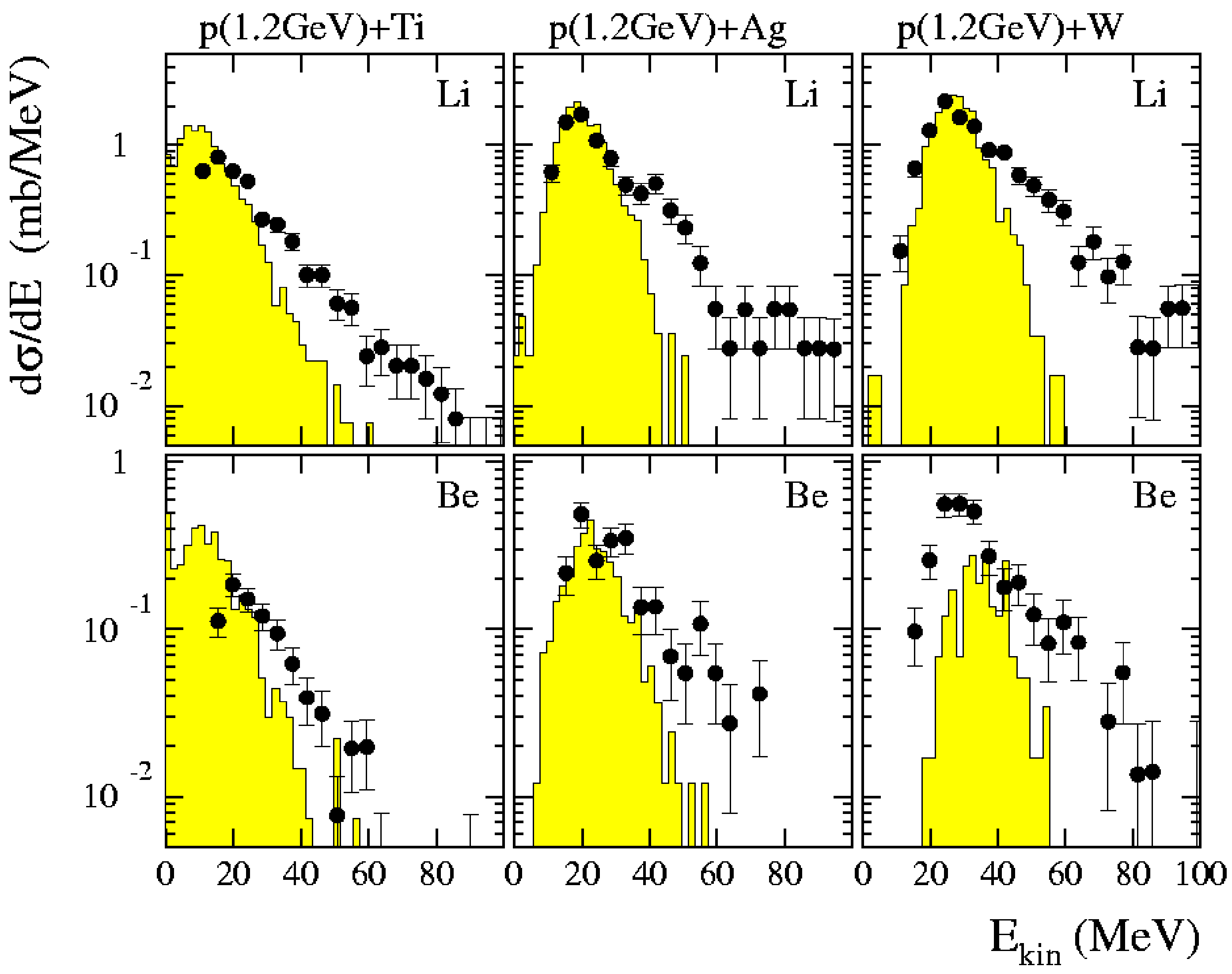
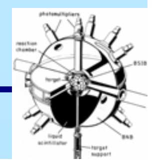
Energy spectra of Li and Be





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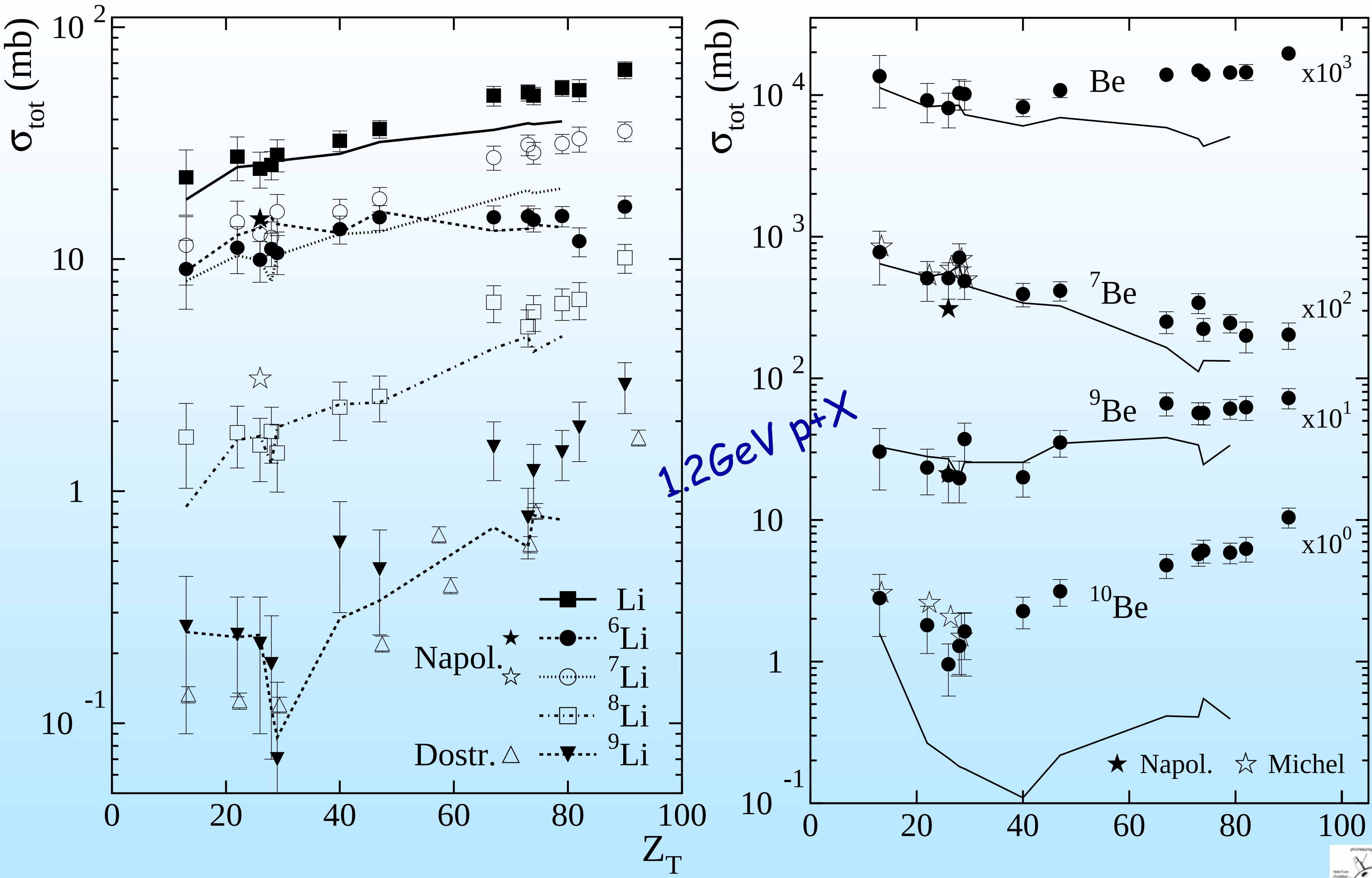
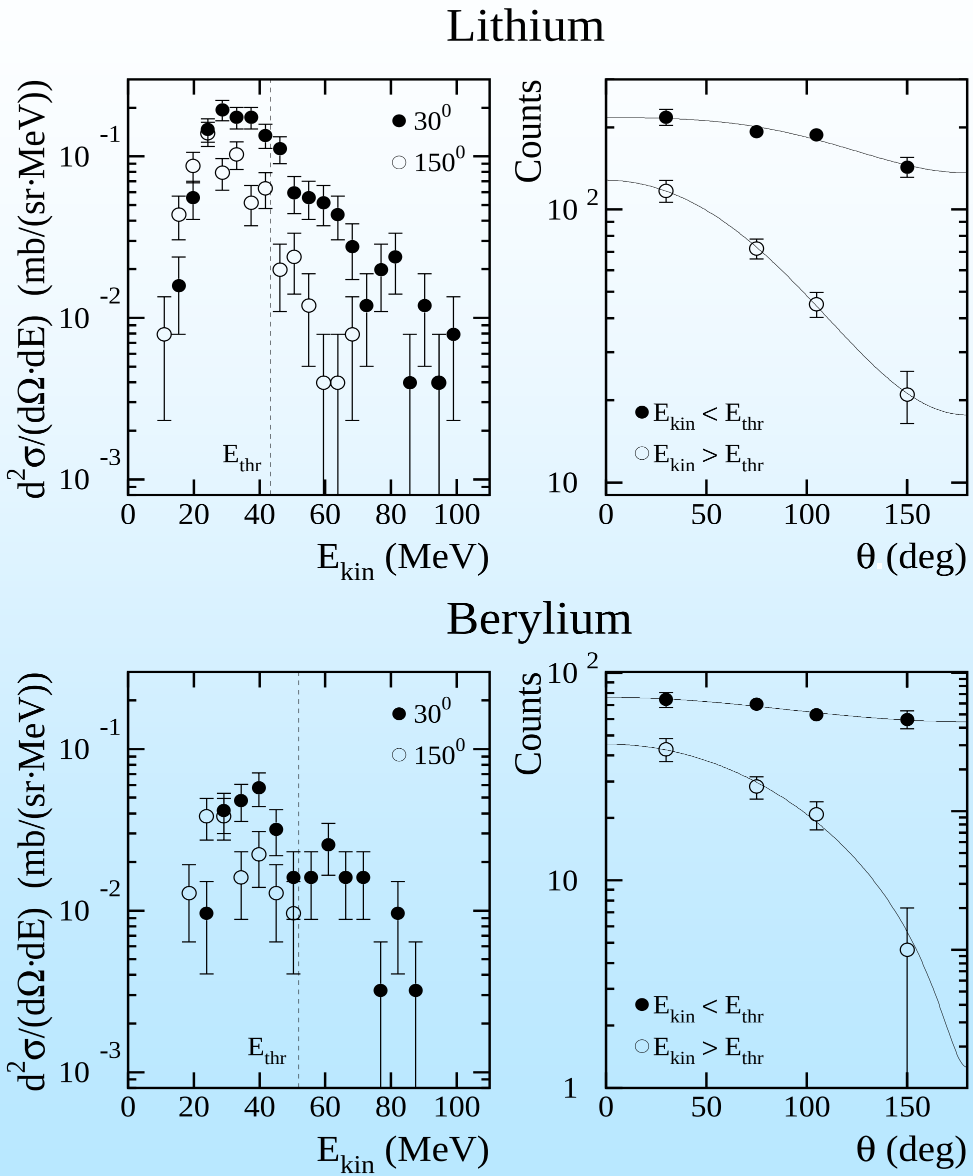
Production cross sections for ^{6,7,8,9}Li and ^{7,9,10}Be



Dostrovsky et al. Phys.Rev.139, B1513(1965)

Michel et al. Nucl.Inst&Meth B103,183 (1995)

Cross sections for Li and Be in 1.2 GeV p+Au



15-25% of pre-equilibrium emission for Li and Be

right panels: angular distributions of Li and Be with energies larger and smaller than the energy defined by the dashed vertical line in the left panels at 42 MeV for Li and 52 MeV for Be

Unisotropy indicates IMFs originating from a PE process similar to that leading to the emission of energetic LCP

->initiative with model devel.

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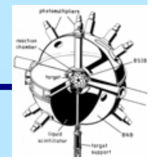
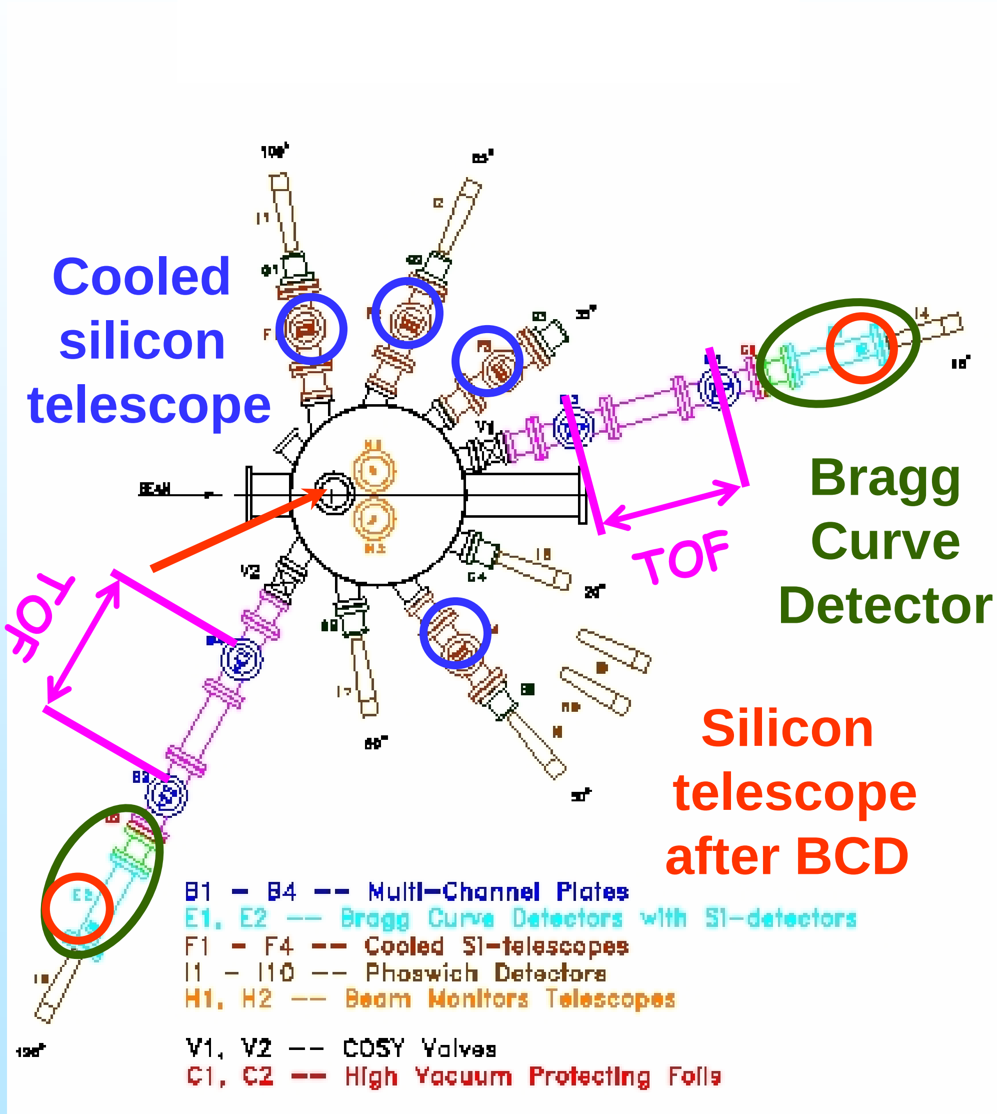
A.Boudard, S.Leray(CEA)
J.Cugnon (Liege)
S.Mashnik (LosAlamos)
Y.Yariv (Israel)



PISA (previous) experimental setup



- 2 det. arms (15° & 120°) consisted of
  - TOF telescope (2 MCPs)
  - Bragg Curve Detector
  - silicon detector telescope
  - phoswich detector
- Cooled silicon detector telescopes (35°, 50°, 65° & 100°)
- Phoswich detectors in 7 arms

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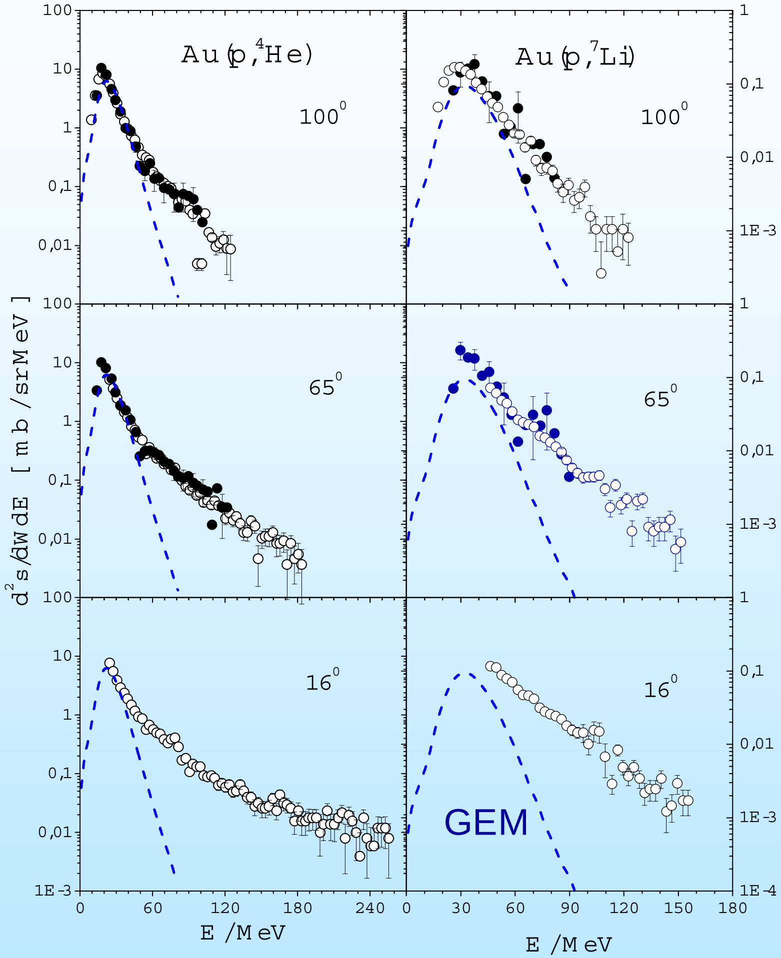
PISA measurement

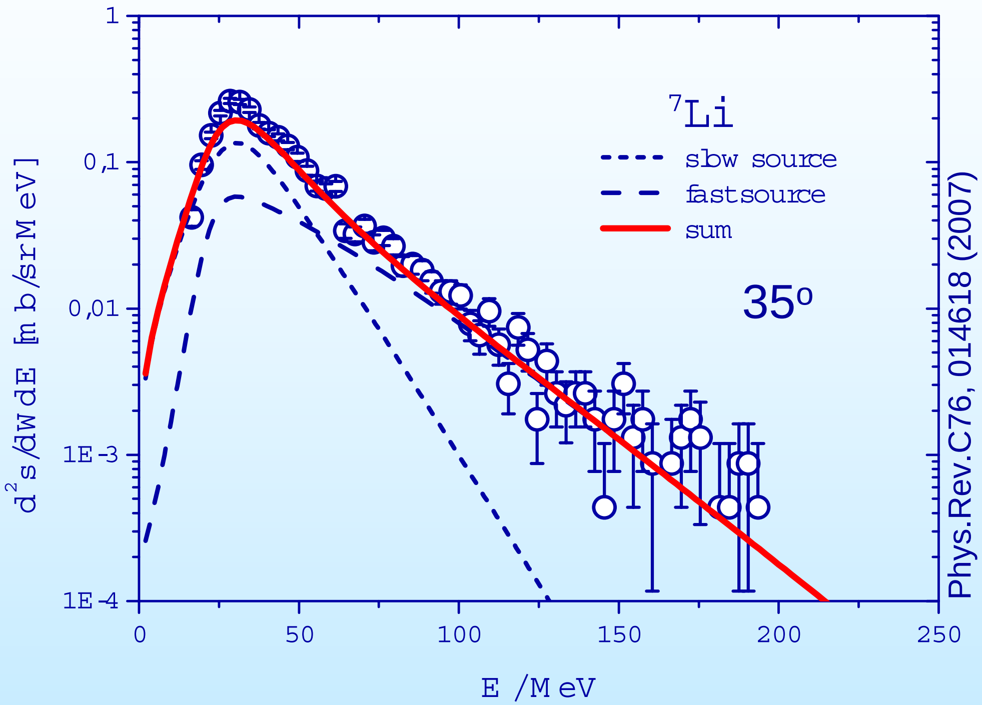
- Measurement of double differential cross-section $\frac{d\sigma}{dEd\Omega}$ for 9 angles :12, 15, 20, 35, 50, 65, 80, 100, 120 degree
- Mass identification from H up to C,
- Charge identification up to Mg (Si)
- Very low energetic threshold, wide energy range
- Measured target: Au, Ag, Ni, Nb, Al
- Proton beam energy: 1.2, 1.9, 2.5 GeV in supercycle mode
- For Ni target additional low beam energy: 175 MeV
- including CsI detectors!

Particle	p	d	t	^{3}He	^{4}He	^{6}Li	^{7}Be	^{10}B	^{11}C	^{14}N	^{16}O
E_{min} [MeV]	2.0	2.6	3.0	2.0	2.5	4.0	4.5	9.0	11	14	16
E_{max}[MeV]*	160	215	250	580	650						

*punch through

2.5 GeV p+Au PISA@COSY, NESSI@COSY:





full dots: NESSI Nucl.Phys.A765 (2006) 426

open symbols: PISA Phys.Rev.C76, 014618 (2007)

Note change of slope with angle in respect to beam direction

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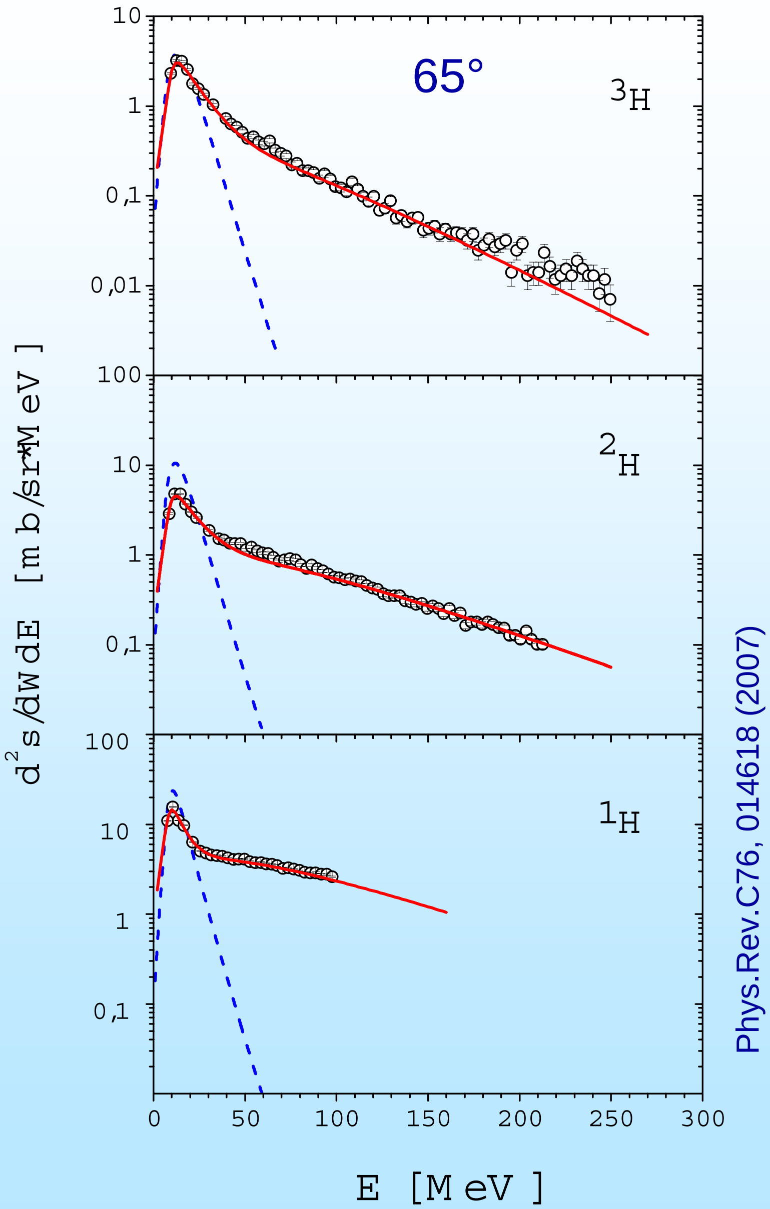
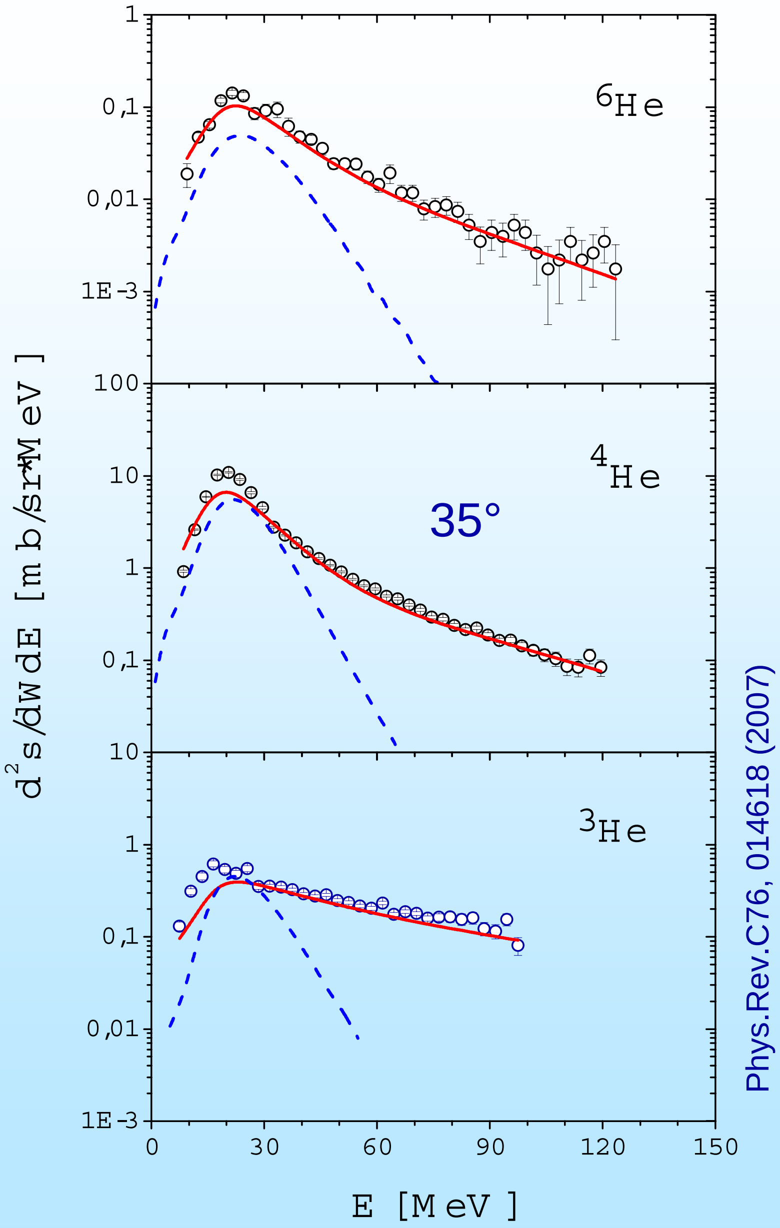
2.5 GeV p+Au

PISA@COSY:





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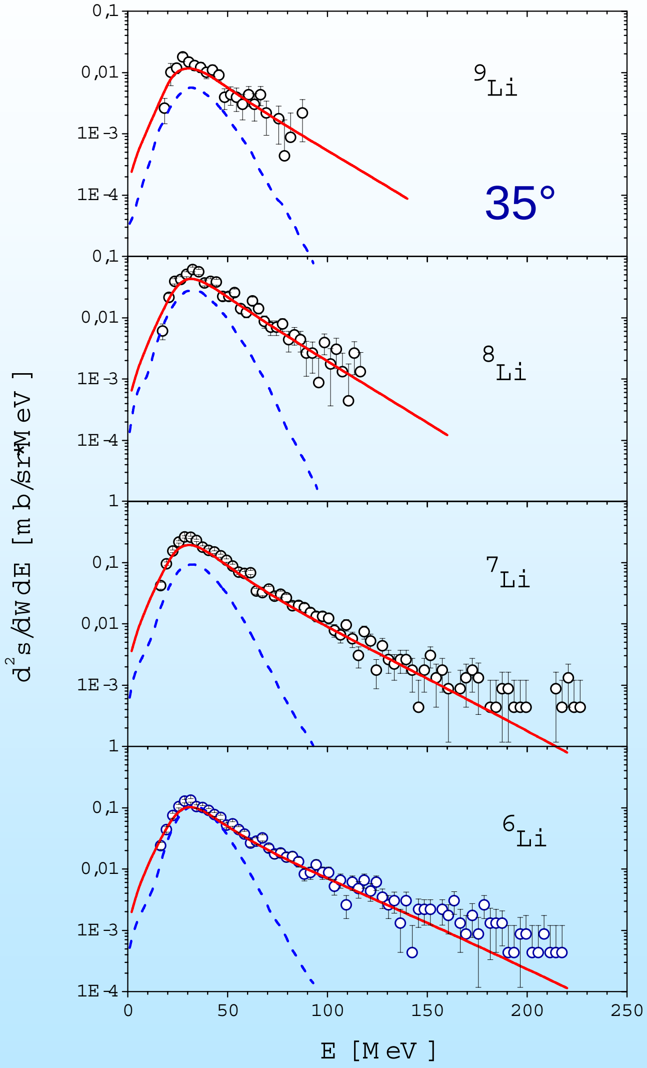
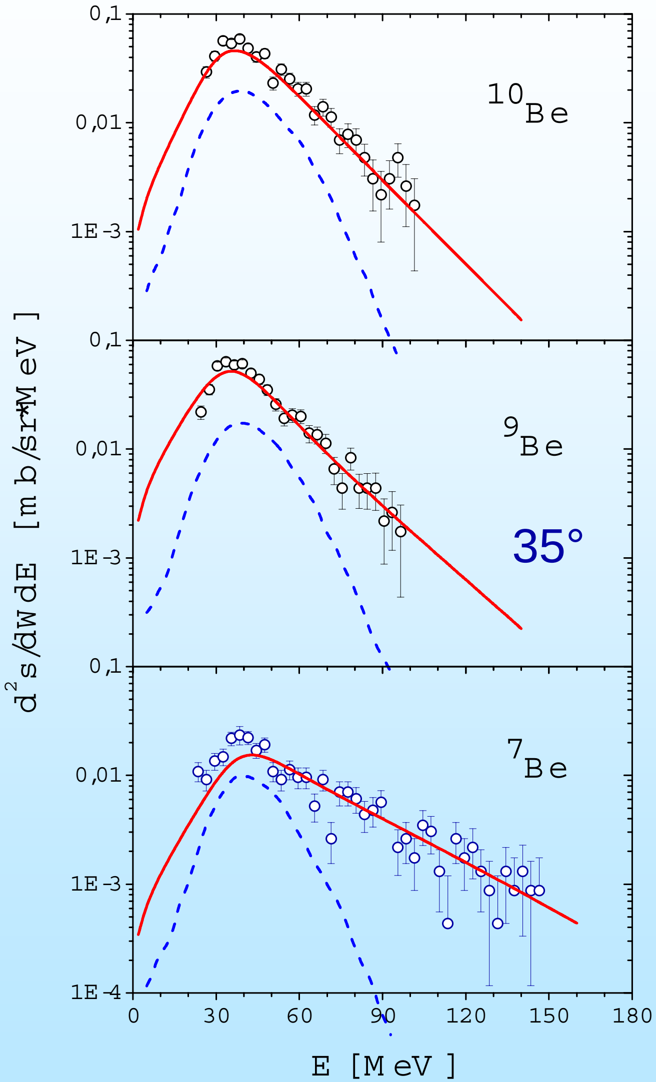
2.5 GeV p+Au

PISA@COSY:



Phys.Rev.C76, 014618 (2007)



Phys.Rev.C76, 014618 (2007)

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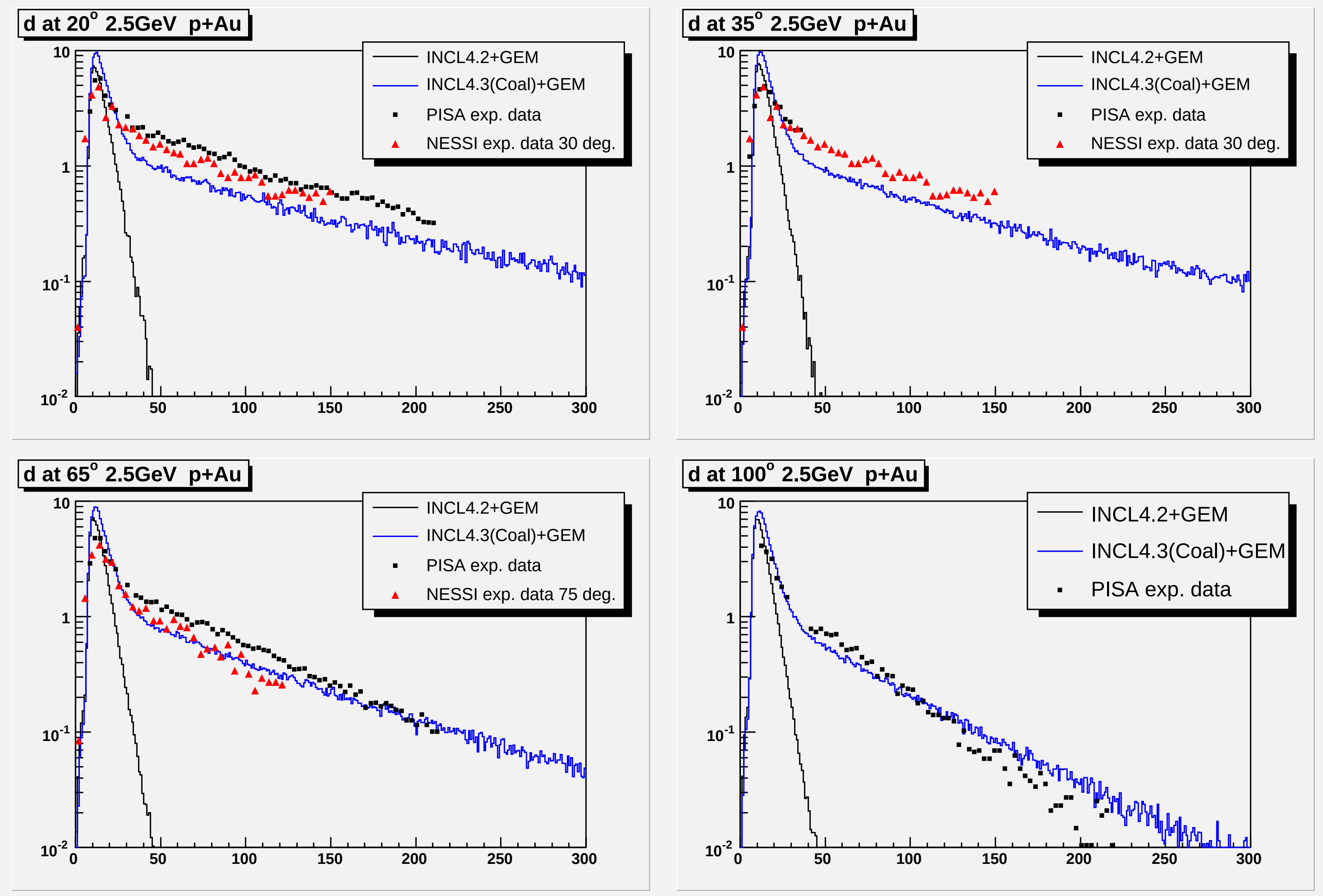
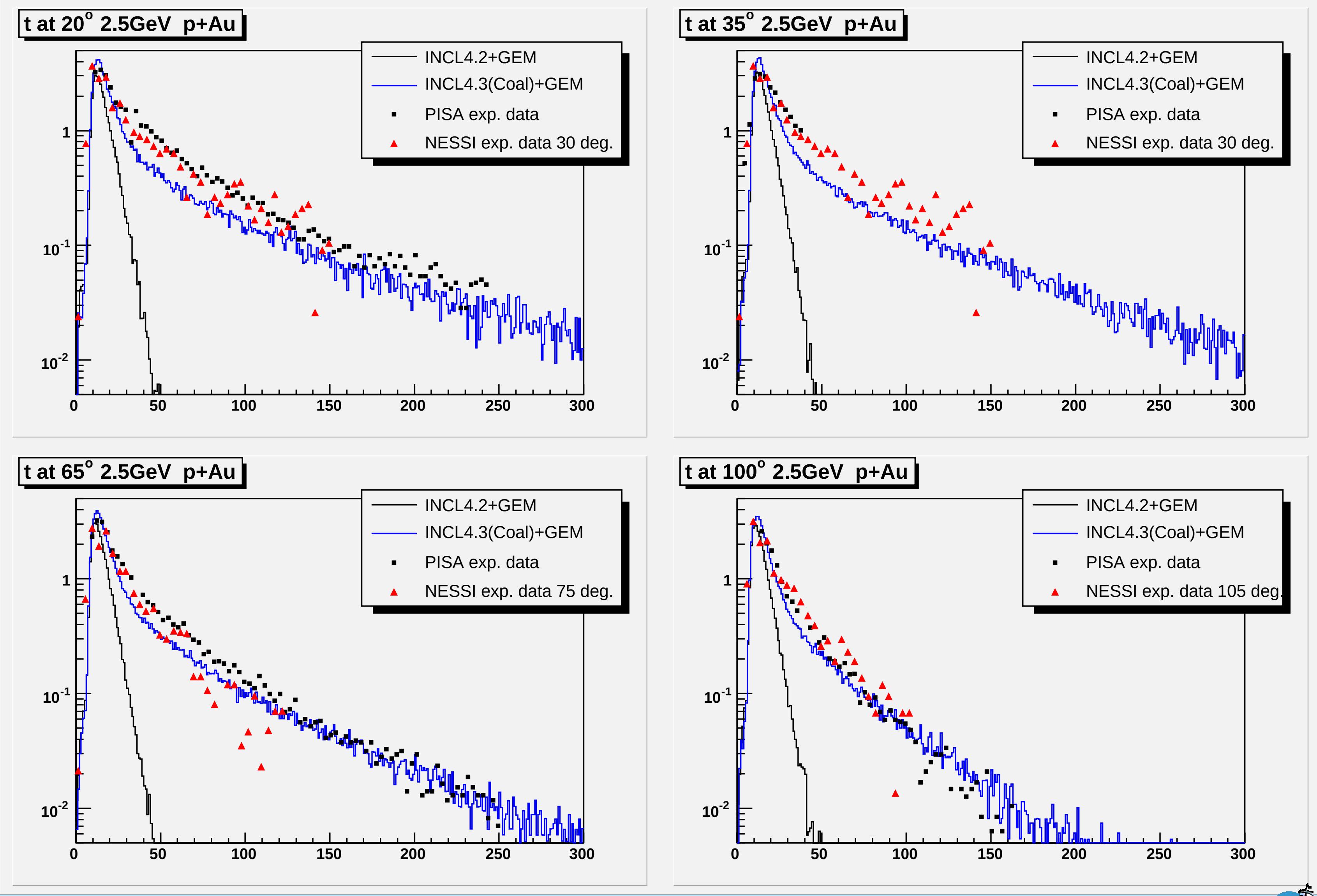
Comp.NESSI/PISA -INCL4.X 2.5 GeV p+Au



Comp.NESSI/PISA -INCL4.X 2.5 GeV p+Au



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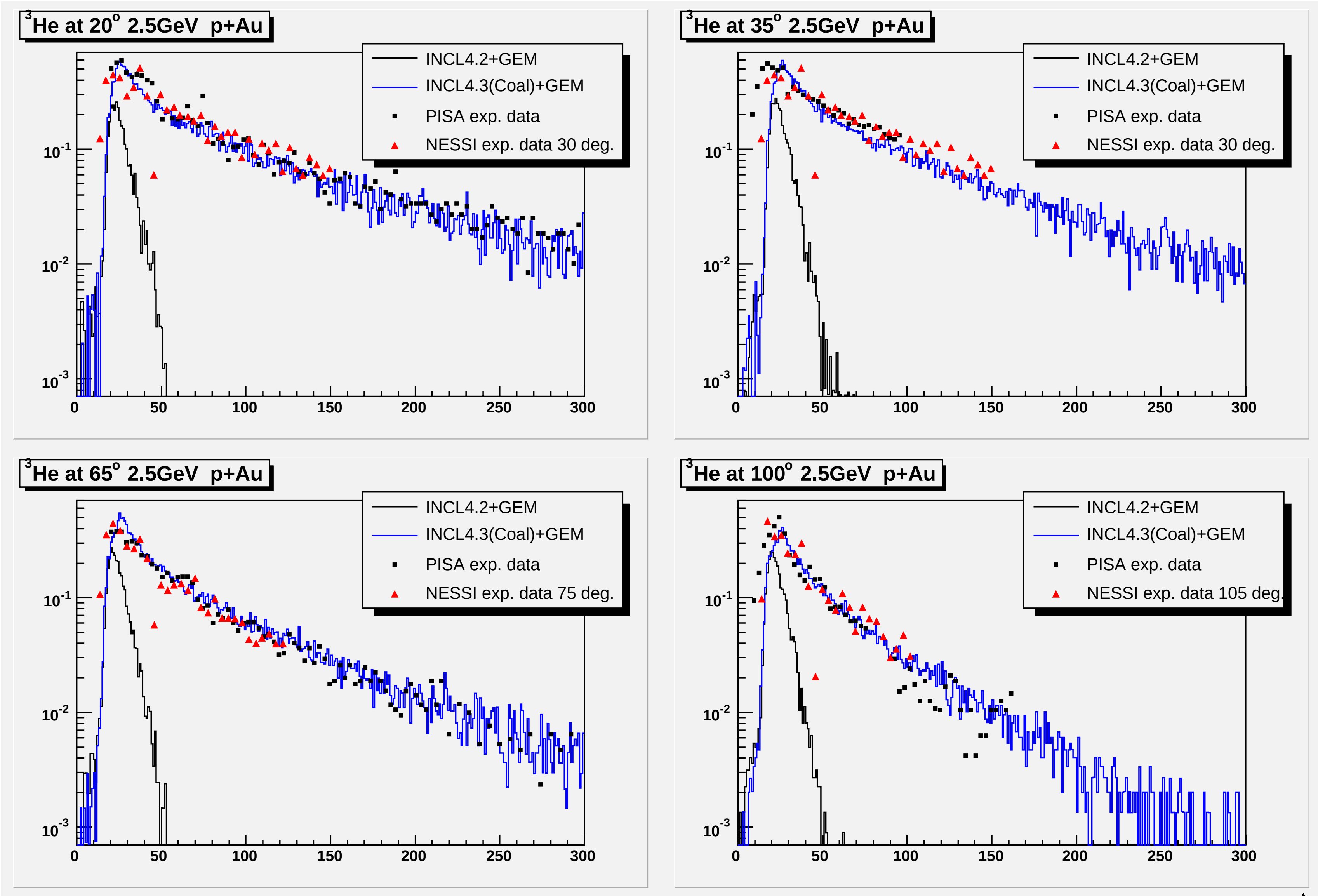
Comp.NESSI/PISA -INCL4.X 2.5 GeV p+Au



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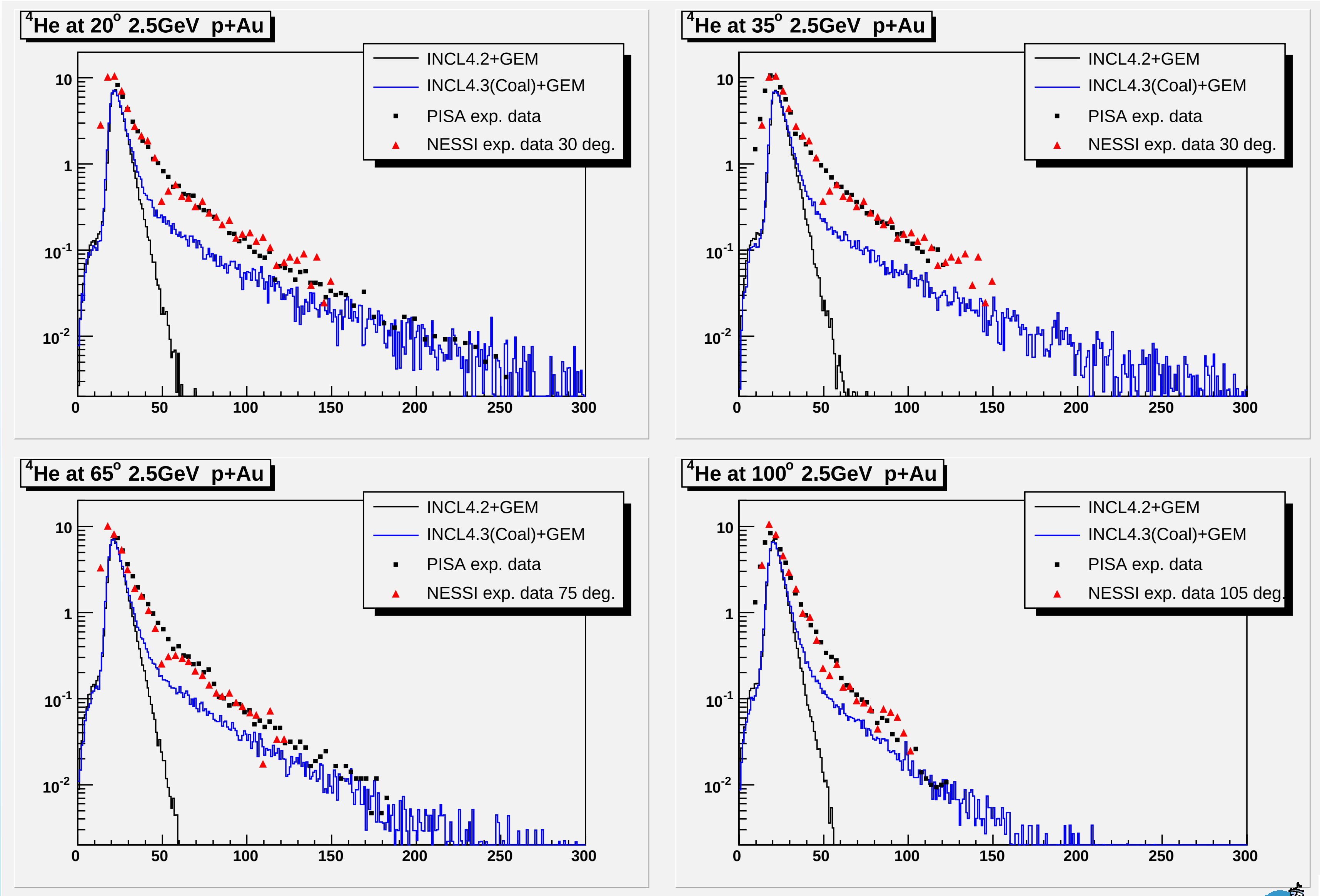
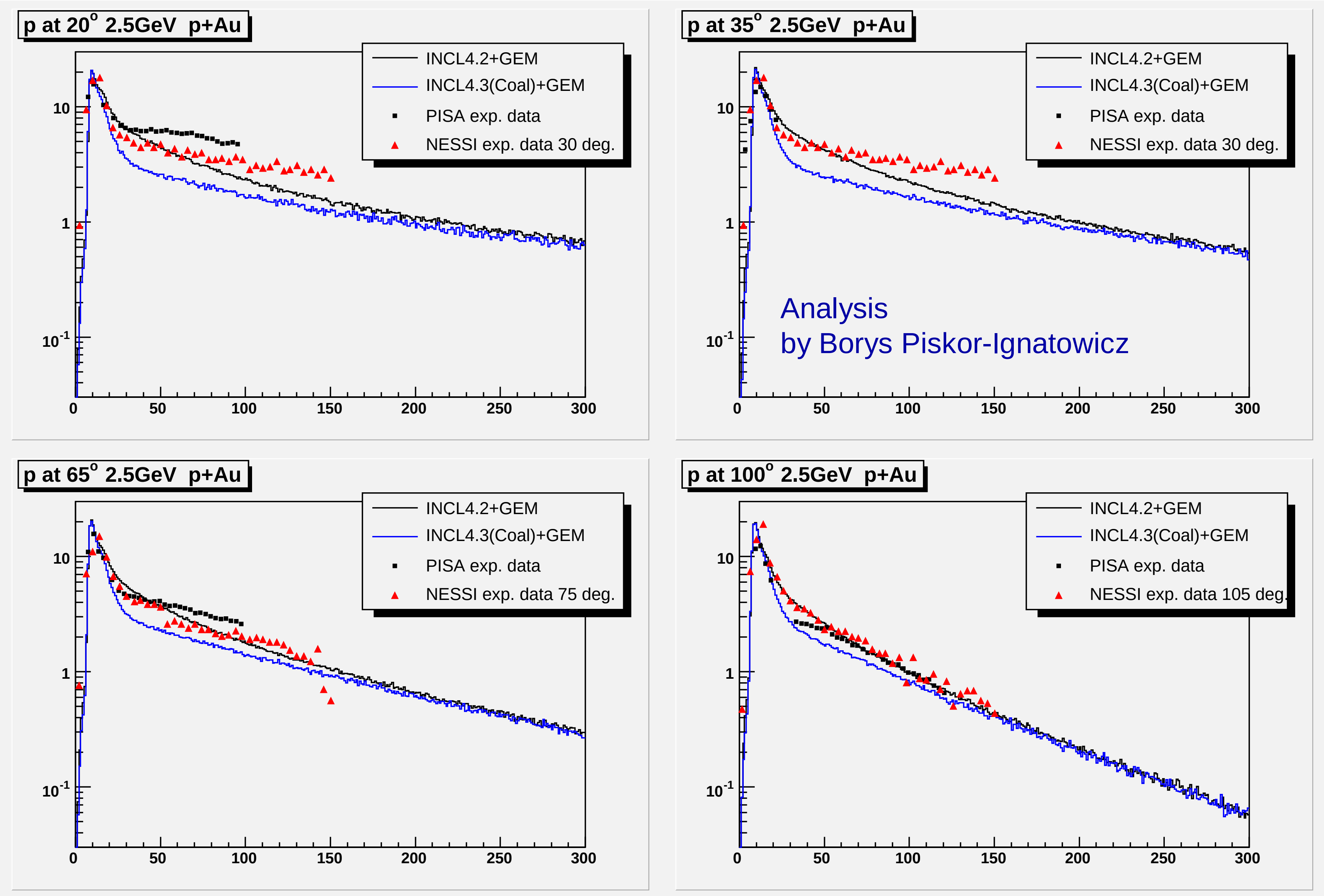
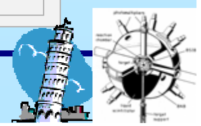
Comp.NESSI/PISA -INCL4.X 2.5 GeV p+Au



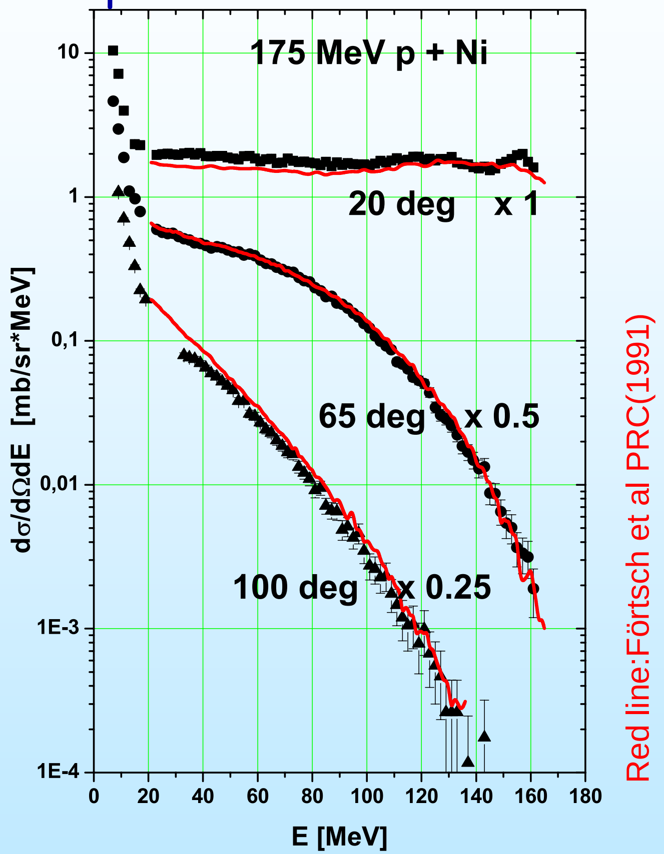
Comp.NESSI/PISA -INCL4.X 2.5 GeV p+Au



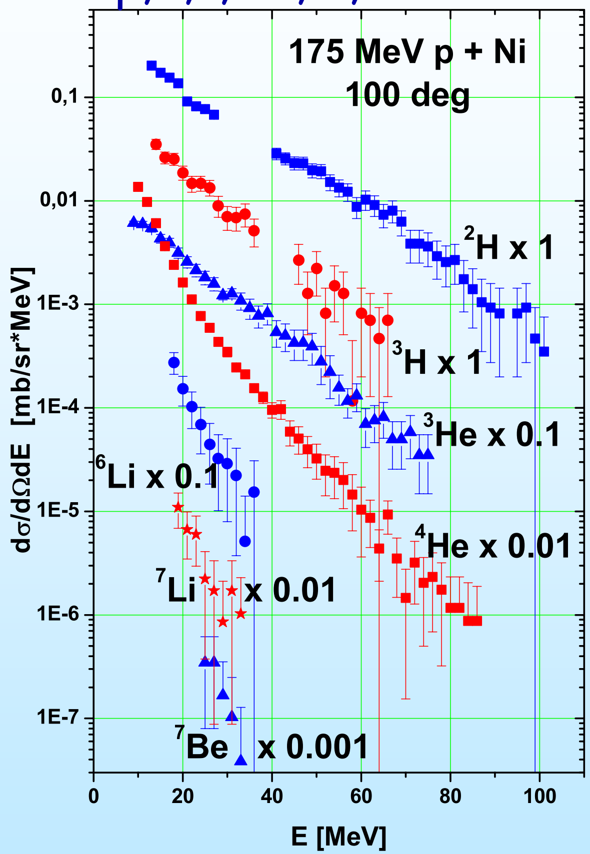


PISA 175 MeV p+Ni

protons



p,d,t,He,Li,Be



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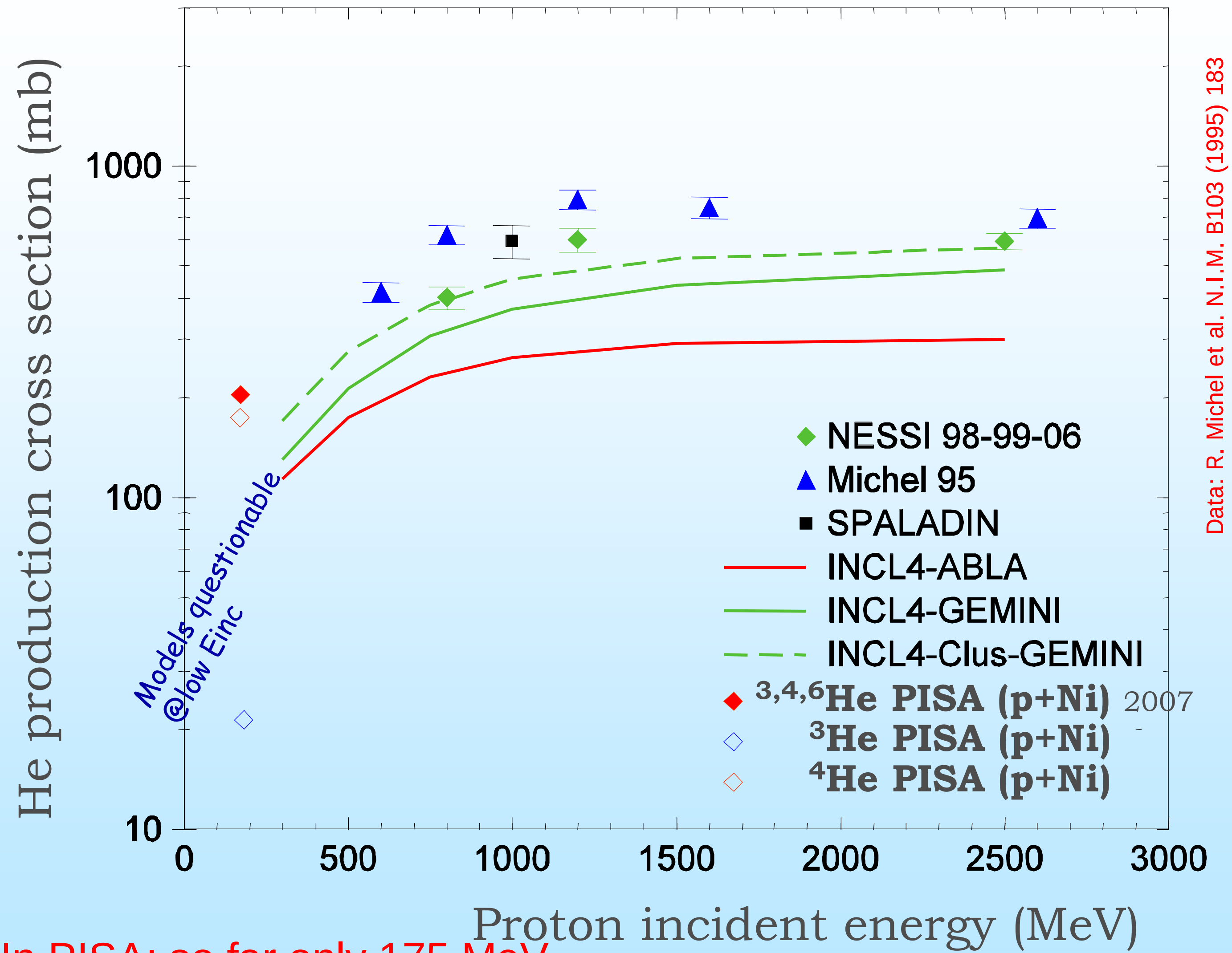
p+Fe (Ni) He-production



Data: R. Michel et al. N.I.M. B103 (1995) 183

SPALADIN: E. LeGentil et al. To be published

NESSI new: C.M. Herbach et al Nucl. Phys. A765 (2006) 426

INCL4.4 + ABLA07
In progress;
resonable!

In PISA: so far only 175 MeV,
1.2, 1.9, 2.5 GeV p+Ni currently analysed

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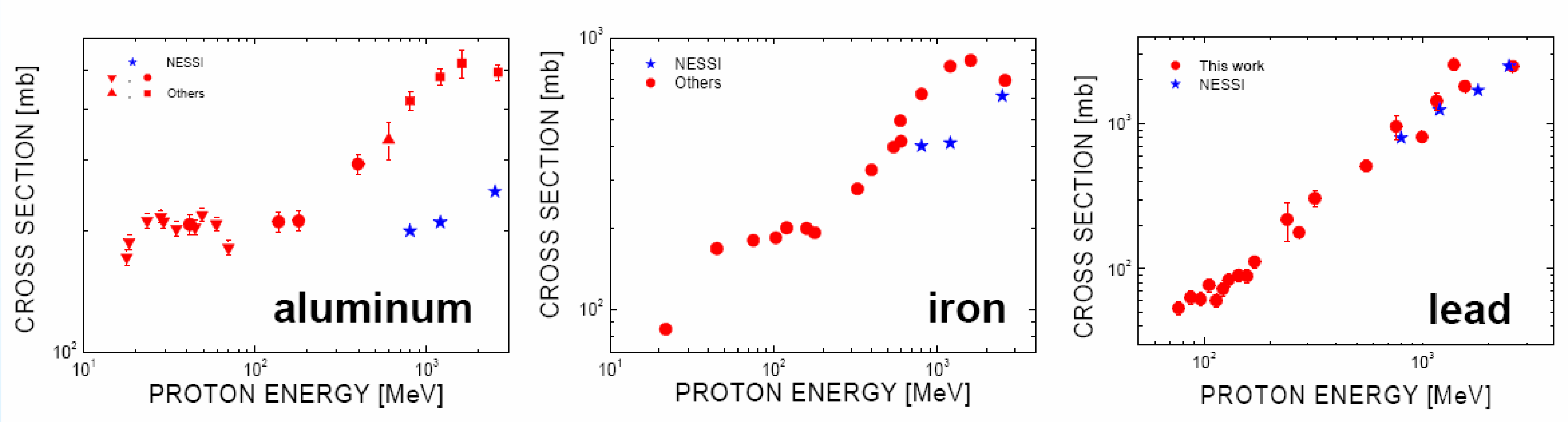
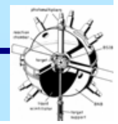
σ_{He} measured by mass spectrometry Hannover Univ.



Production of He (=3He+4He) from natural aluminium, iron and lead by proton-induced reactions; data are from R.Michel, I.Leya (full circles) NIM. Phys. Res. B229 (2005) and NESSI (blue stars). -> I. Leya ND2007

- excitation functions in the whole energy range of interest
- discrepancies between the two experimental methods for light targets is not yet understood
- data valuable for the identification of deficiencies of existing INC/evaporation codes.



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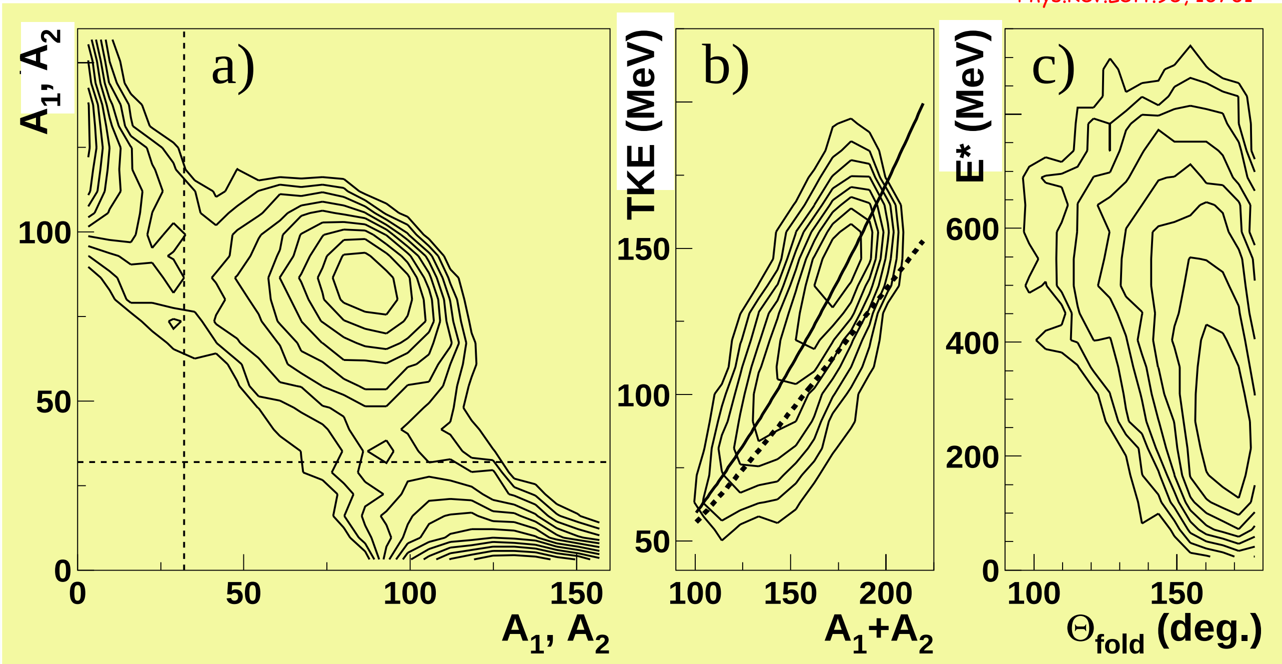
Time scale of fission in GeV proton induced reactions on Au, Bi and U

setup NESSI@COSY(Jülich) as shown before

Phys.Rev.Lett.95, 16701, (Dec2005)

Selection of fission fragments

Phys.Rev.Lett.95, 16701



2.5 GeV p+Bi

a) Correlation between heaviest fragm. A_1,A_2

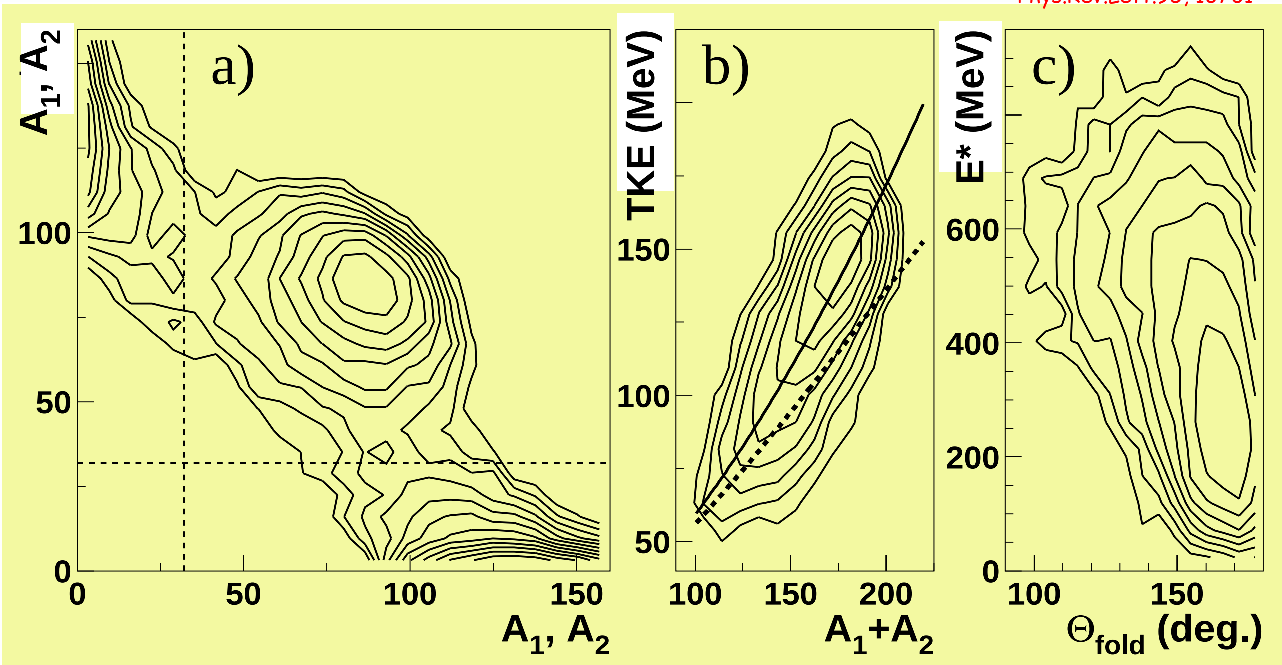
b) Total kinetic energy of the two FF as a function of A_1+A_2

c) Folding angle θ_{fold} between FFs as a function of E*

- Fission events selected fulfill the more conventional conditions on the b) total kinetic energy (TKE) and c) folding angle θ_{fold}
- TKE: events grouped around solid line $\langle TKE \rangle = 0.1189\ Z^2/A^{1/3} + 7.3$ MeV (Viola) with $Z=0.45(A_1+A_2)$
- θ_{fold}: growing broadening and deviation from 180° with increasing E* as result of more numerous emission of LP and increasing momentum transfer -> here we refrained from choosing a limiting folding angle

Selection of fission fragments

Phys.Rev.Lett.95, 16701



2.5 GeV p+Bi

a) Correlation between heaviest fragm. A_1, A_2

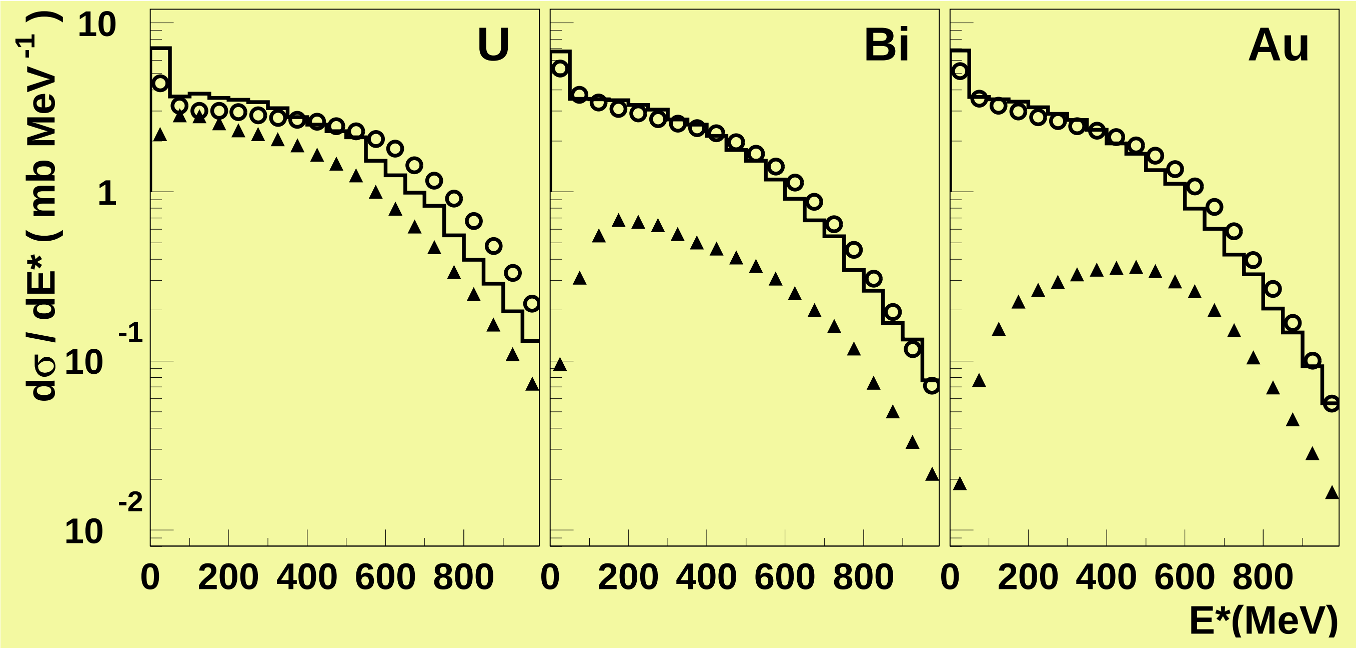
b) Total kinetic energy of the two FF as a function of A_1+A_2

c) Folding angle θ_{fold} between FFs as a function of E*

- FFs centered in the middle $A_1, A_2 \approx 80$
  only one detected FF (+ some lighter masses) suppressed by $A_{tot} > 70\%$ of A_{targ}
- HR (+ some ligher masses) appear close to x-, y axes $A_1, A_2 \approx 150$
- Multifragmentation events would appear with $A_1, A_2 \leq 30$ (there are no!)
- Separation between „two FFs detected“ from „HR“ by: $A_1, A_2 > 32$ (dashed lines)

Inclusive and fission diff. cross sections

Phys.Rev.Lett.95, 16701



dσ/dE*

for 2.5 GeV p+Au,Bi,U

Z^2/A=31.7, 33.0, 35.6 (fissility)

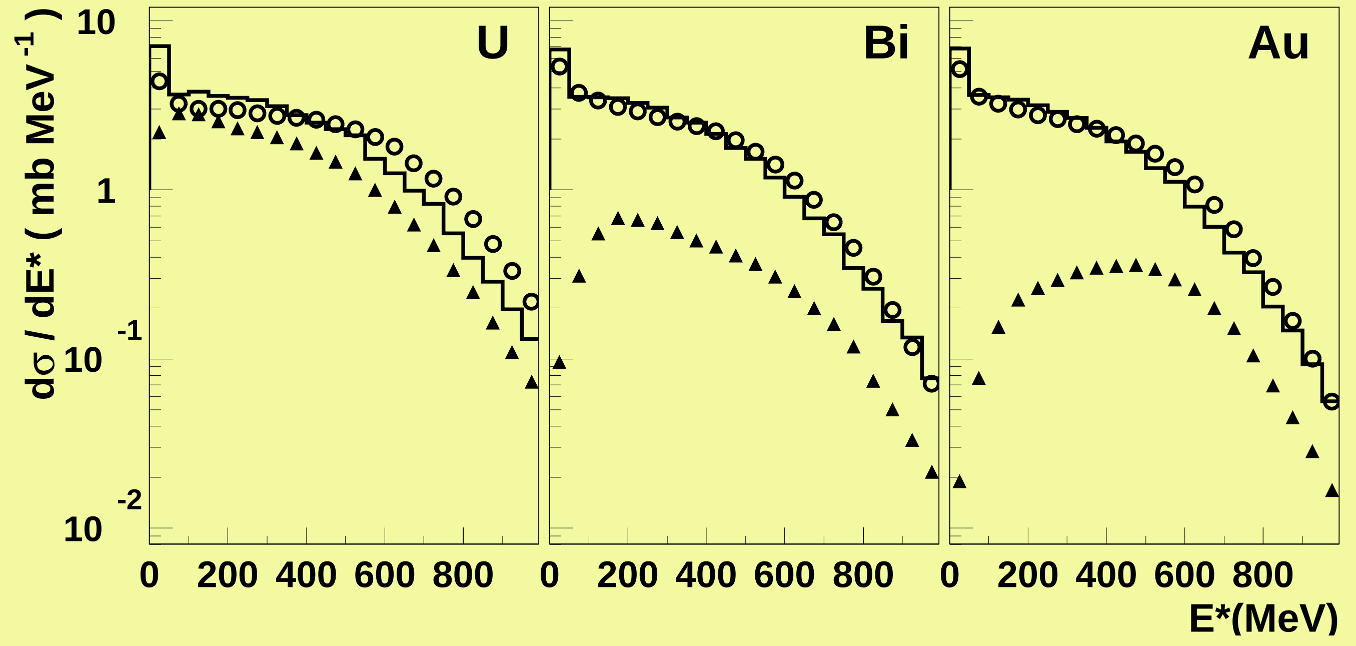
symbols: NESSI

histogram: INCL2.0

- inelastic reaction σ_{inel} and fission σ_f studied as a function of E* and fissility
- fission probability $P_f(E^*) = \sigma_f(E^*)/\sigma_{inel}(E^*)$ provides best possible evidence for presence of dissipative and transient effects (if existing!)
- selected reactions deposit high thermal E* with minimum ballast from collective excitations(angular momentum, shape distortions, compression,…)
- shell effects washed out at high E*

Inclusive and fission diff. cross sections

Phys.Rev.Lett.95, 16701



dσ/dE*

for 2.5 GeV p+Au,Bi,U

Z^2/A=31.7, 33.0, 35.6 (fissility)

symbols: NESSI

histogram: INCL2.0

- E* deduced event by event from number of evaporated light particles (n,H,He)
- Maximum E* 4-5 MeV/N or ~1000 MeV (below onset of multifragmentation) -> essantially fission, evaporation observed
- INCL2.0 in agreement -> A,Z population correctly described by model

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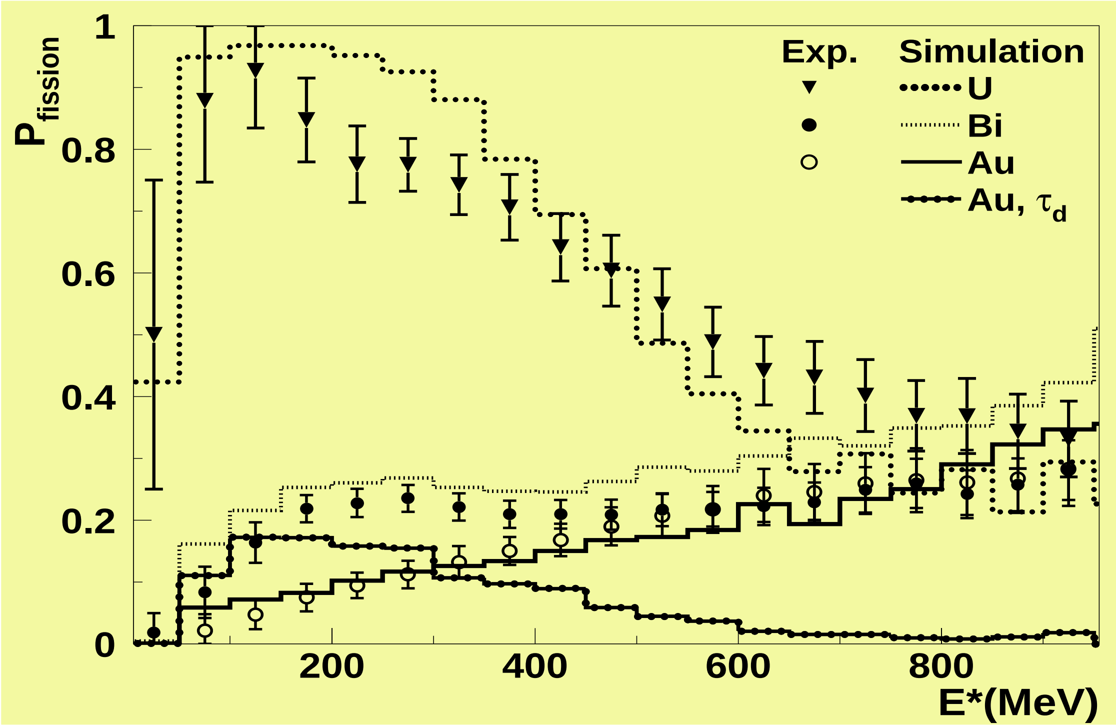
Fission probability



Phys.Rev.Lett.95, 16701

2.5 GeV p+Au,Bi,U

Z^2/A=31.7, 33.0, 35.6 (fissility)

σ_f= 200±60 mb (Au)

320±50 mb (Bi)

1350±120 mb (U)

agree. Vaishnene Z.Phys.A318, 97 (1984)

symbols: NESSI

histo: INCL2.0 + GEMINI

- fission probability $P_f(E^*)= \sigma_f(E^*)/\sigma_{inel}(E^*)$
- At low E*, A and Z similar to target nucleus (only few nucleons removed during INC) and $P_f(E^*)$ dominated by different initial fissility
- At higher E*, ΔA=12, ΔZ=4-5 (1000MeV) according to INC -> fissility lowered -> strong decline of $P_f(E^*)$ for U; for Au and Bi increase of $P_f(E^*)$ with E*
- Despite large differences in fissility and $B_f \approx$ 5,12, and 21 MeV of initial nuclei U, Bi and Au, $P_f(E^*) \approx 30\%$ for ALL three target nuclei at highest E*

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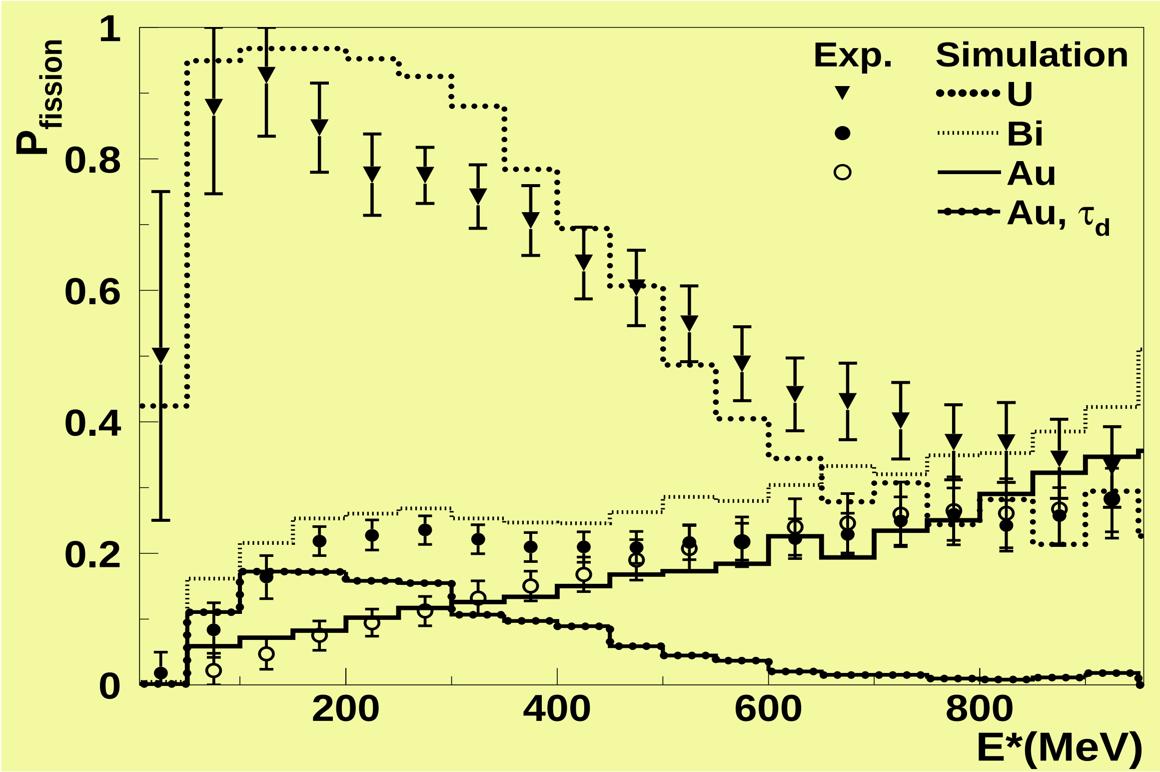
Fission probability



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agree. Vaishnene Z.Phys.A318, 97 (1984)

symbols: NESSI

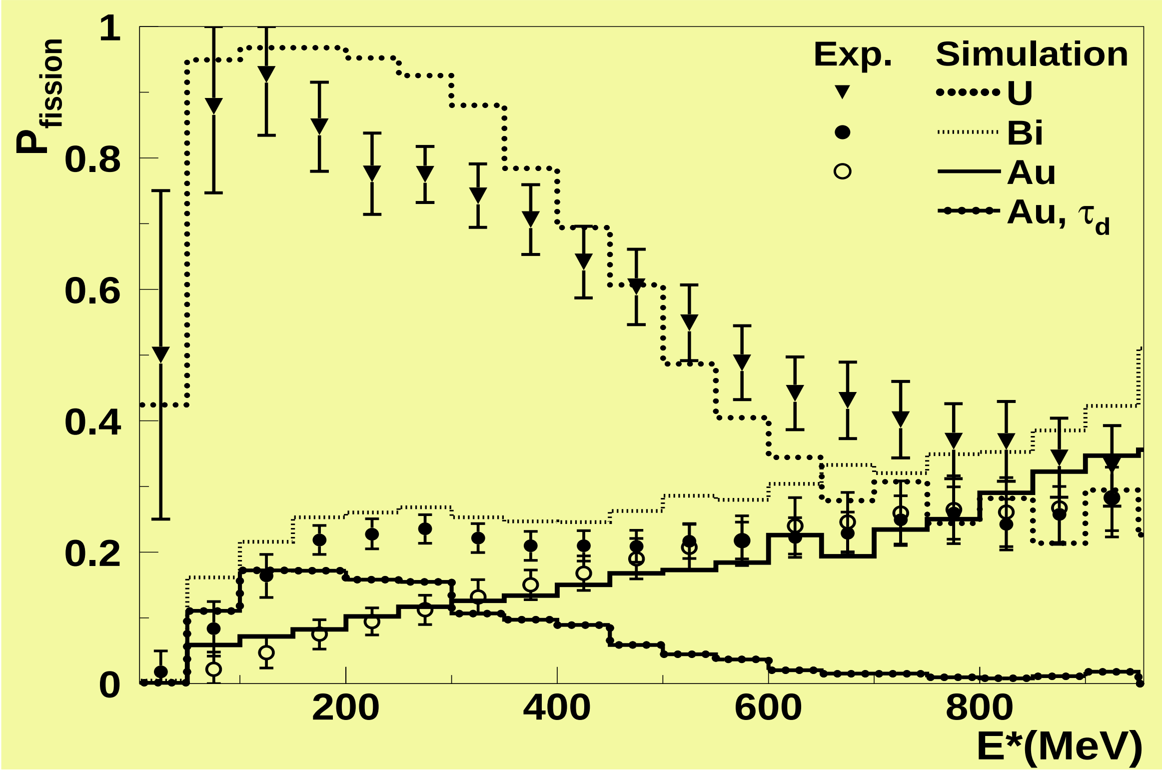
histo: INCL2.0 + GEMINI

Statistical model calculation: INCL2.0 + GEMINI

- angular momentum taken into account (<20ħ)
- level density parameter a_n=A/10 MeV^{-1}, a_f/a_n=1.0, 1.017, 1.022 (U,Bi,Au) [Jah]

-> good description without any aditional transient time!

Fission probability



Phys.Rev.Lett.95, 16701

2.5 GeV p+Au,Bi,U

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320±50 mb (Bi)

1350±120 mb (U)

agree. Vaishnene Z.Phys.A318, 97 (1984)

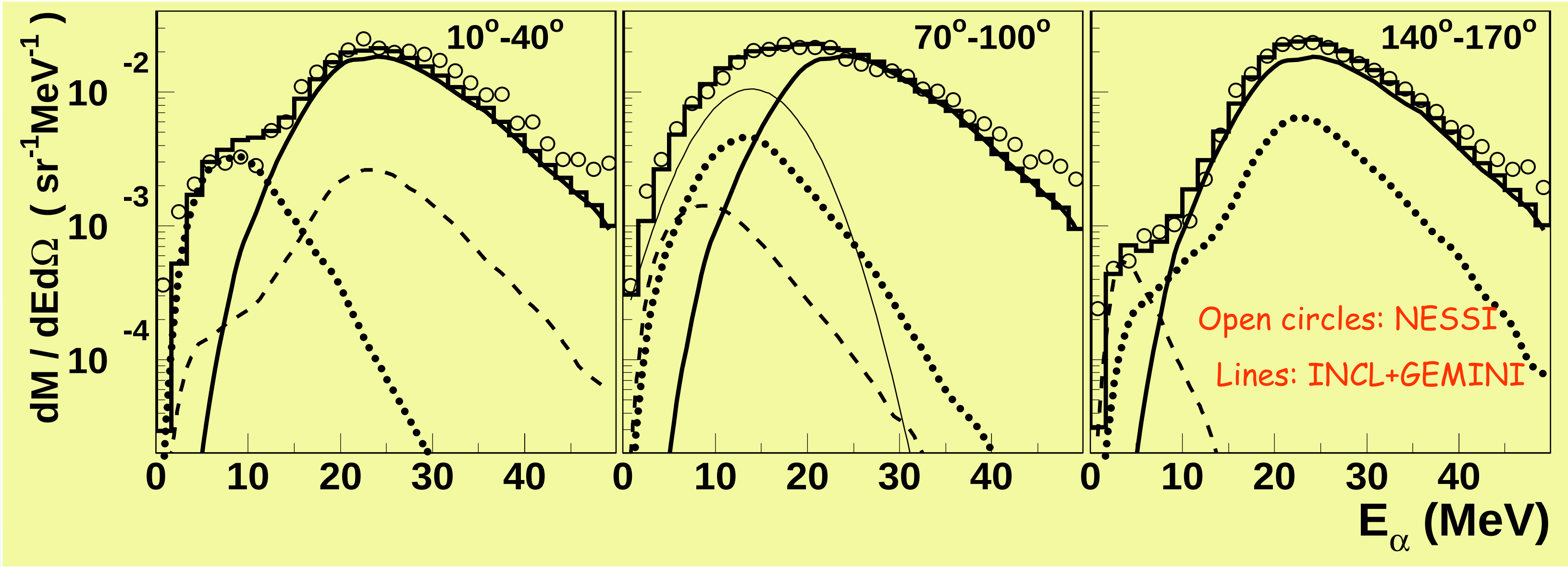
symbols: NESSI

histo: INCL2.0 + GEMINI

- Benlliure et al. [Nucl.Phys.A700,469(2002)] describes his data introducing a dynamical fission hindrance or transient time $\tau_d=2x10^{-21}$s suppressing fission at high E*
- resulting losses in σ_f compensated by large level density at saddle $a_f/a_n=1.05$
- NO agreement with actual Au fission data (dot-dashed line)

-> decisive advantage of differential observation $dP_f(E^*)/dE^*$ over other methods; independent determination of a_n/a_f and τ_d effective at diff. E*s.

Energy spectra of alphas (2.5 GeV p+Au at E*=600-900MeV)



Phys.Rev.Lett.95, 16701

- energy spectra of α-particles (plotted in center-of-mass system of FFs) for $\theta_{\alpha\text{-LF}}$ =10°-40°, 70°-100°, 140°-170° relative to the motion of light FF
  - from compound nucleus prior to scission -- not related to scission axis (cont.line)
  - from light (dashed lines), and heavy (dotted lines) FF
  - at 70°-100° a component for neck emission(5% of total α evap.) added (thin line)
  - Total calculated spectrum shown by histogram – agreement for $E_\alpha \leq$ 35MeV, but deviation at high energy tails originating from pre-equilibrium

-> 80% of total evaporation from compound nucleus prior to scission, 20% from separated FFs

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Summary

- **NESSI:**
  - **4π, neutron multipl. spectra,**
  - **DDXS p,d,t, ^{3,4,6}He, ^{6,7,8,9}Li**
  - **tTargets Al-U,**
  - **incident proton beam energies 0.8, 1.2, 2.5 GeV**
  - NuclPhysA765, 426(2006), PhysRevLett95,162701(2005), NIMA508, 295(2003), NIMA508,315(2003), Nucl.Phys.A712,133(2002),
- **PISA:**
  - **no neutrons, but high statistics, very good Z and A identification of reaction products,**
  - **DDXS p,d,t, ^{3,4,6}He, ^{6,7,8,9}Li, ^{7,9,10}Be, ^{9,10,11,12}B, ^{11,12,13,14}C, N, O,...**
  - ***targets: Al, Ni, Nb, Ag, Au***
  - ***incident proton beam energies: 175MeV (Ni), 1.2, 1.9, 2.5 GeV .***
  - NIMA519,610(2004), Nucl.Phys.A765 (2006) 426 and PISA Phys.Rev.C 76 014618(2007), PhysRevC subm.2008

- →NESSI/PISA in agreement, set of experimental benchmark data for the development and test of models capable of describing (among otherfeatures also) the emission of the high energy component of composite particles

  To do:
  - Solve discrepancies between different sets of data …
  - Solve deficiencies of models…

- FISSION
  - Fission decided upon very fast (no transient delay time for fission dynamics at saddle), but entire fission process slow (major part of all α's emitted prior to scission)! Phys.Rev.Lett.95, 16701, (Dec2005)

Thank you for your attention