Theory, Astrophysics and Small Accelerators for ENSAR2

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Summary

- Nuclei in external fields:

Time structure vs Energy of Large Scale Facilities.

- Astrophysics and Coulomb break-up:

Collision time vs temperature of neutron stars.

- Solid He Targets for exotic beams:

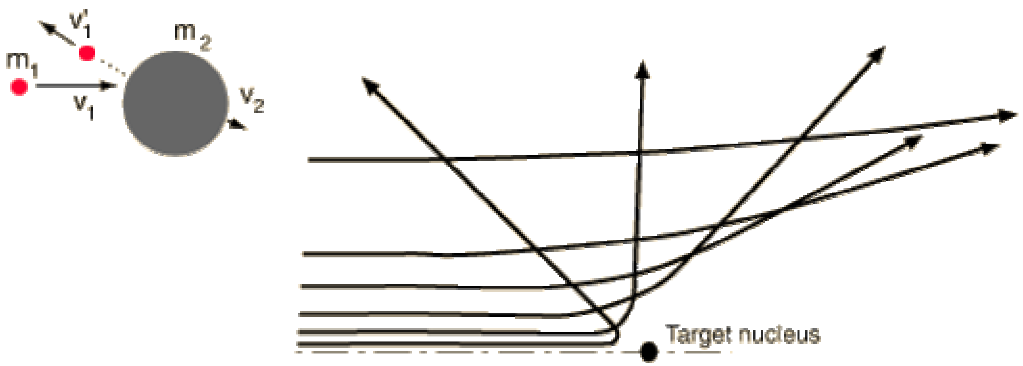
Applications vs basic science in Small Scale facilities.

External fields on nuclei

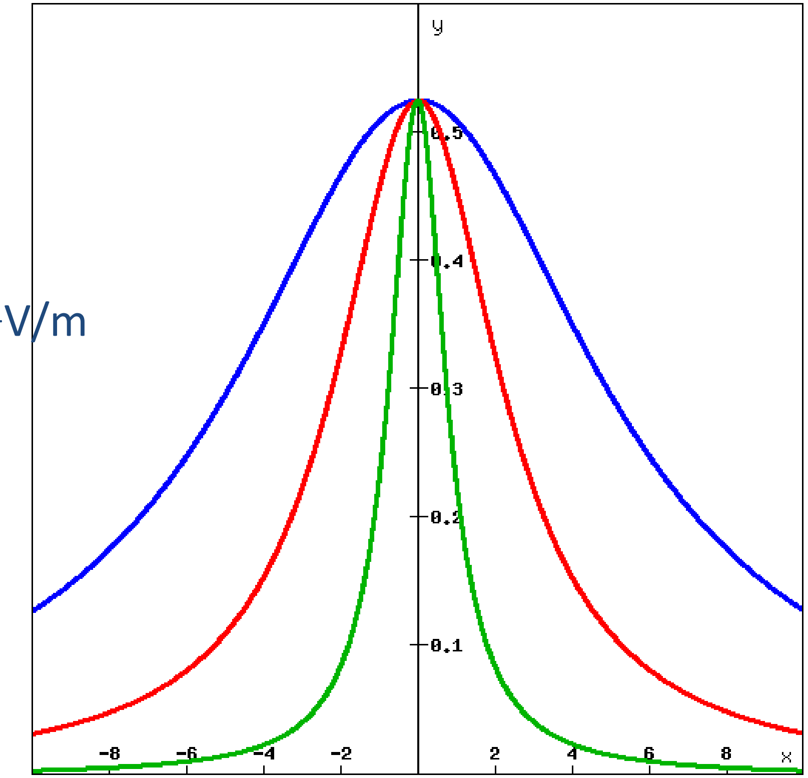
$^{11}Be + ^{208}Pb$

Electric Field: $E(t) = Z e / r^2(t)$;

$r(0)=15$ fm; $E(0)=0.524\ 10^{21}$ V/m



E(t)
10^{21}V/m



t (10^{-22} s)

	Elab (MeV)	v/c	Theta(deg) R(0)=15 fm	T_coll (10^-22 s)	E_x (MeV) P(E_x) = 0.01
ISOLDE	40	0.088	81	13.9	3.6
GANIL	200	0.194	9.8	5.4	7.5
GSI-FAIR	2200	0.568	0.83	1.8	13.7

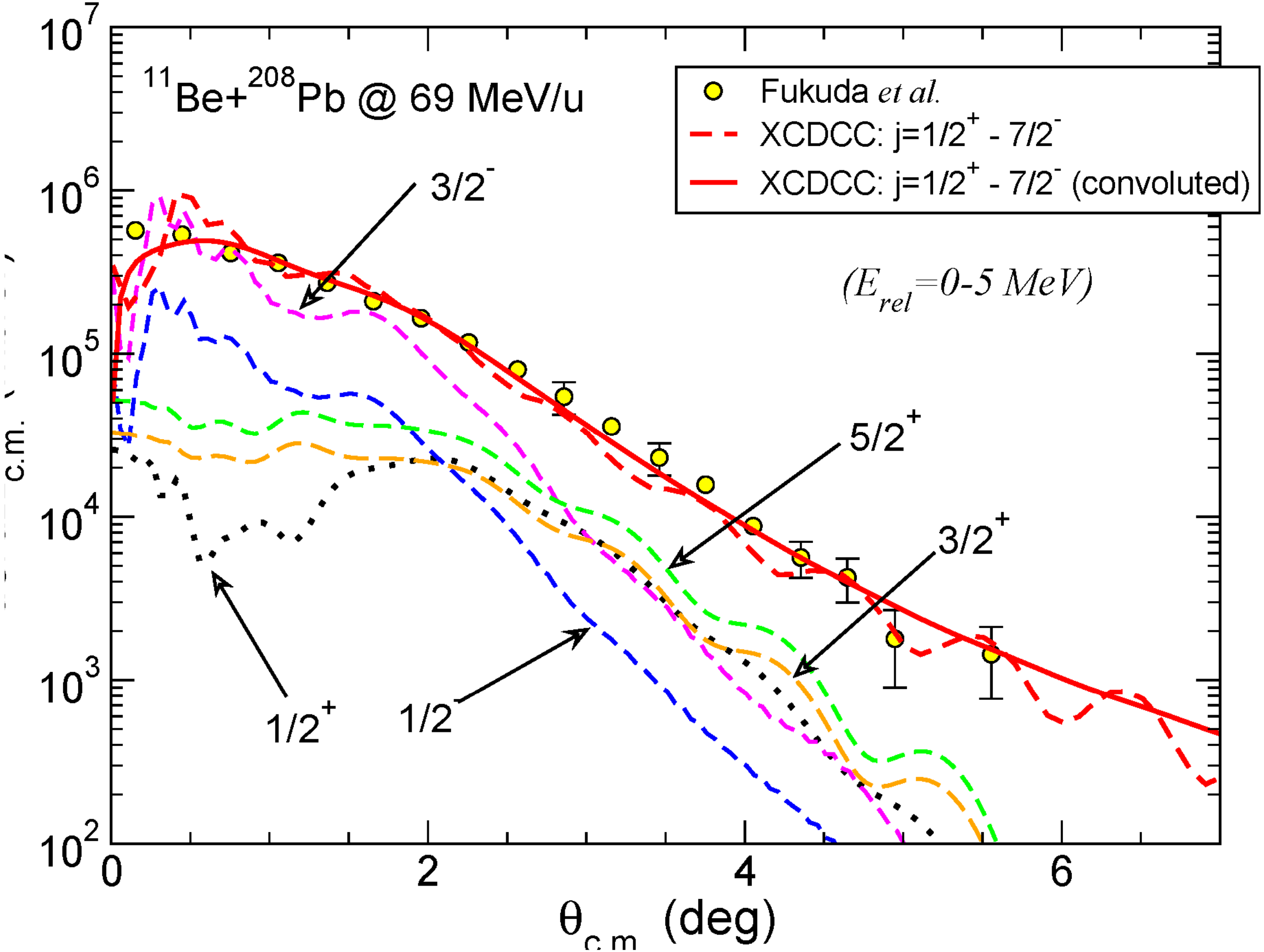
Coulomb break-up as a tool for structure

- B(E,L) values determine the absorption of photons by nuclei.
- For short lived nuclei, “real” photon absorption can be substituted by “virtual” photon absorption in coulomb dominated collisions.
- EPM: Coulomb break-up cross sections are proportional to the B(E,L) distribution.

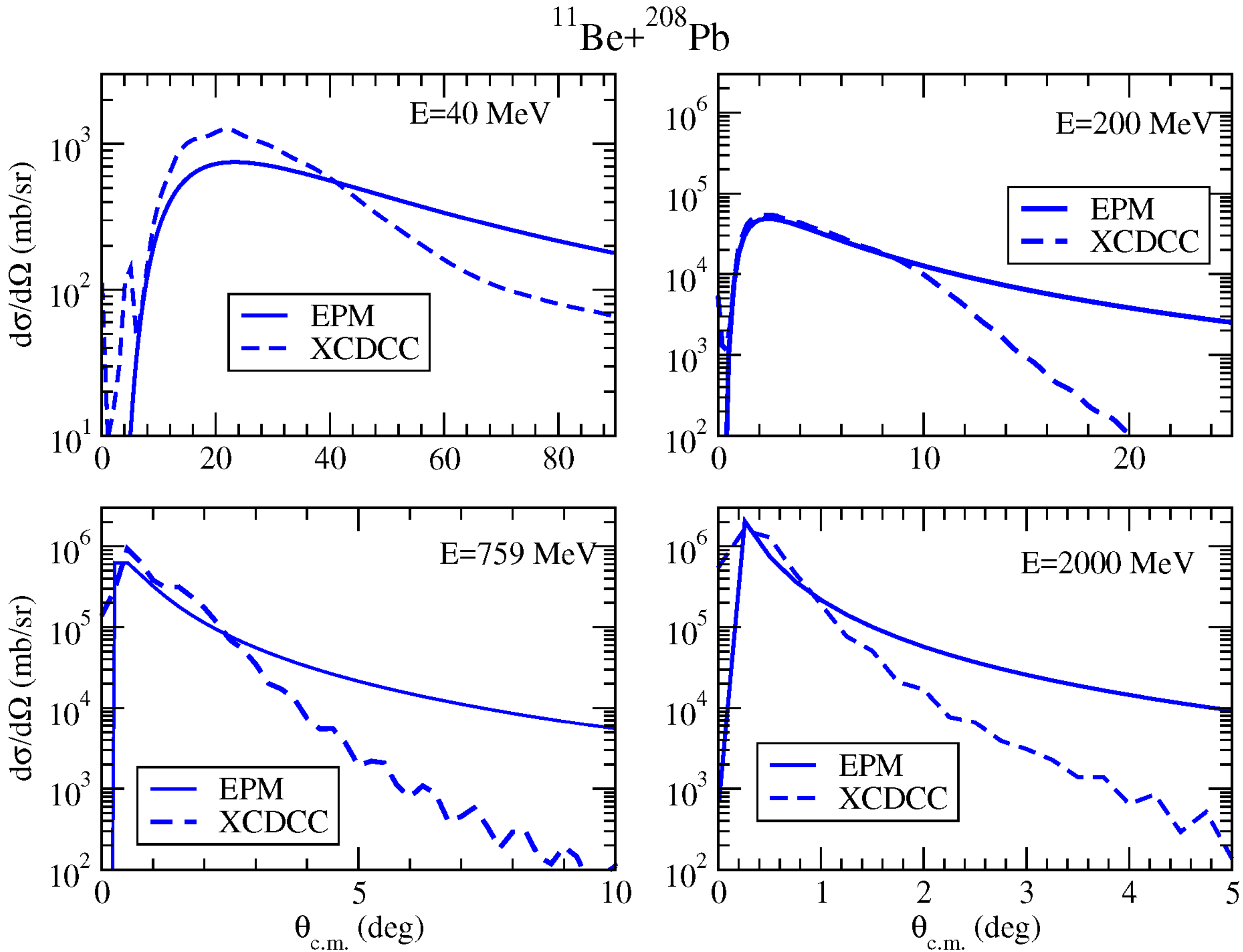
1st order, Semiclassical, Coulomb trajectory (EPM)

All orders, Quantum, Coulomb+nuclear (XCDCC)

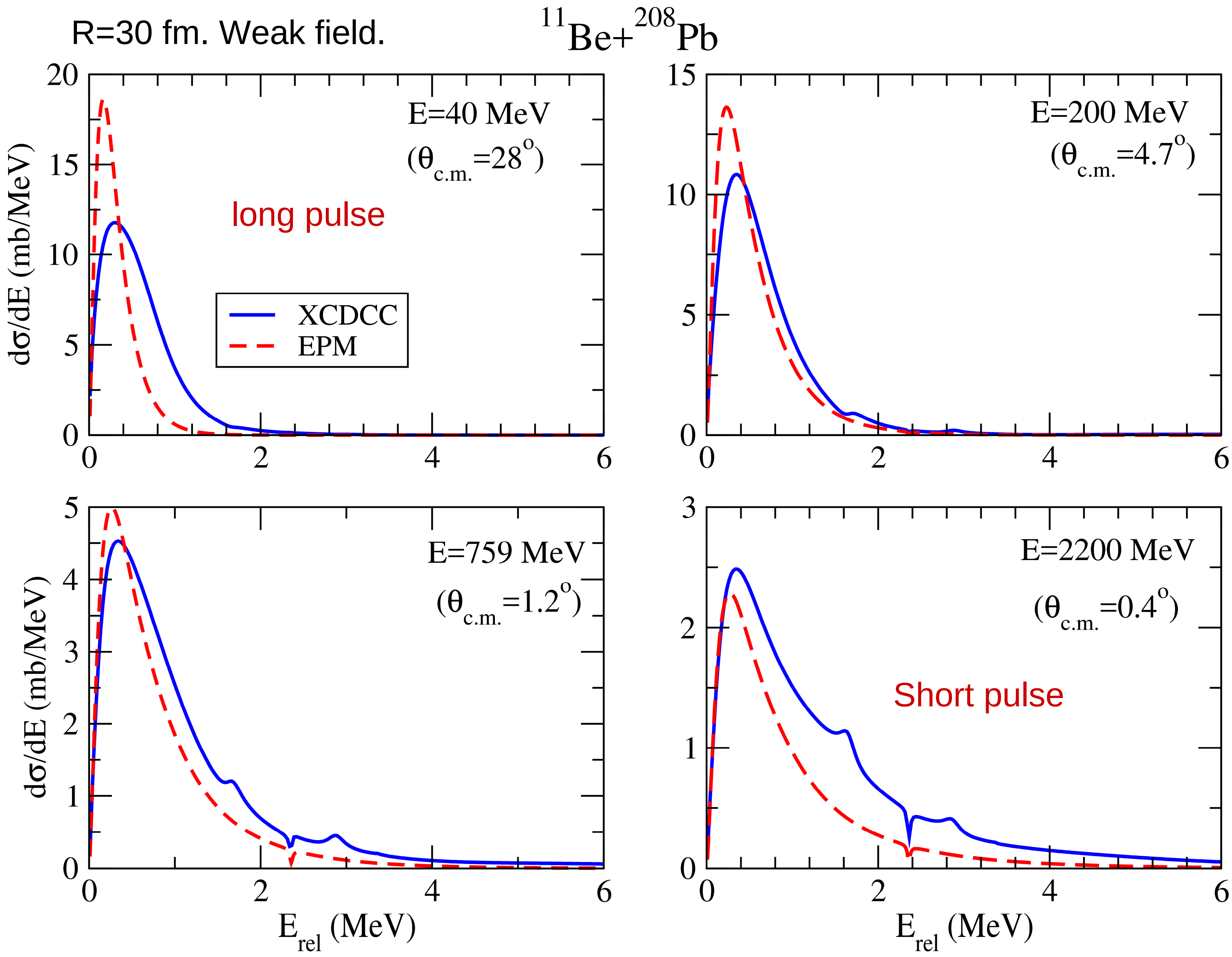
- Is EPM accurate?



^{11}Be+^{208}Pb @ 69 MeV/u
Fukuda *et al.*
XCDCC: j=1/2$^+$ - 7/2$^-$
XCDCC: j=1/2$^+$ - 7/2$^-$ (convoluted)
(E_{rel}=0-5 MeV)
3/2$^-$
5/2$^+$
3/2$^+$
1/2$^+$
1/2$^-$
c.m.
$\theta_{c.m.}$ (deg)

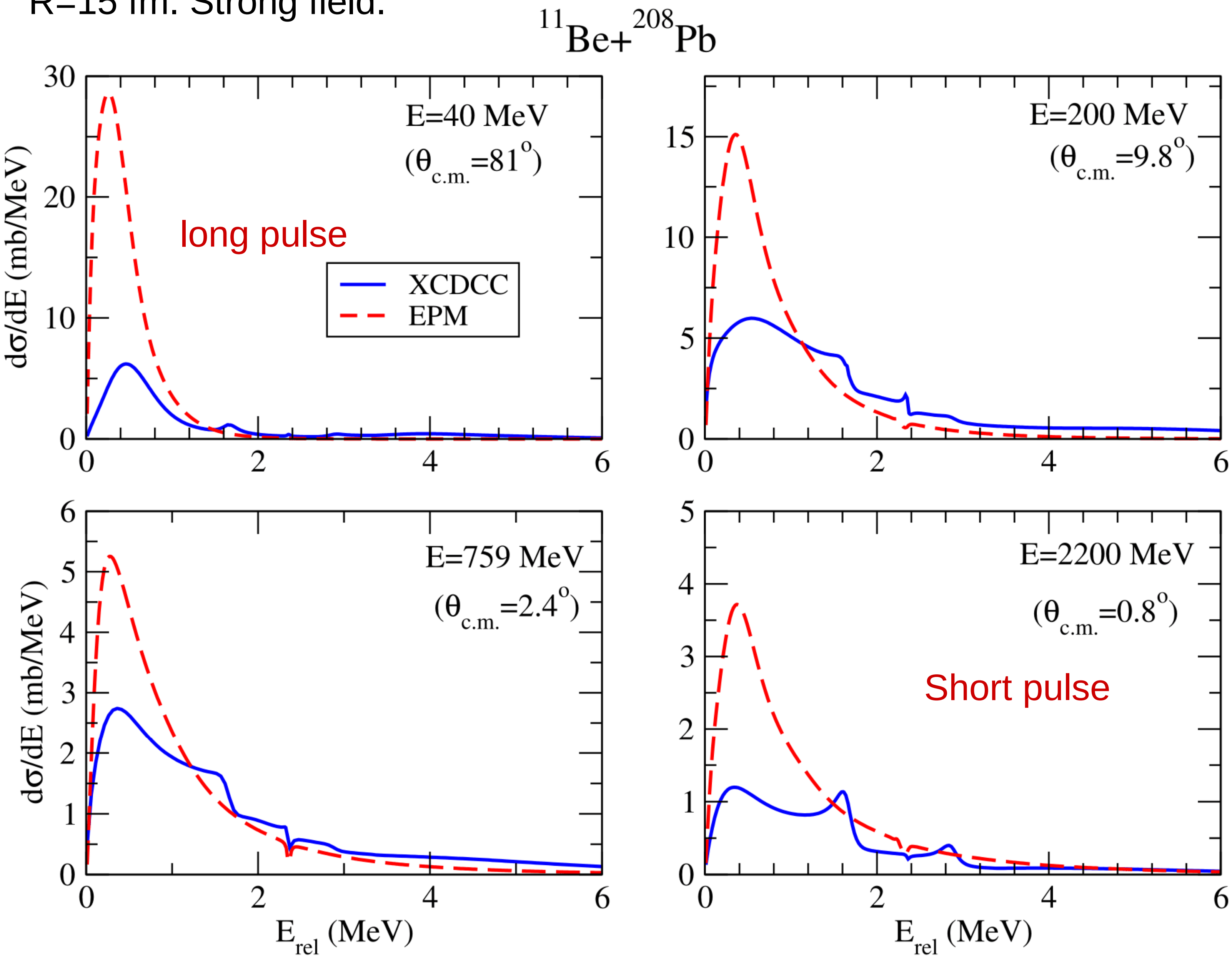


^{11}Be+^{208}Pb
E=40 MeV
E=200 MeV
E=759 MeV
E=2000 MeV
EPM
XCDCC
dσ/dΩ (mb/sr)
θ$_{c.m.}$ (deg)



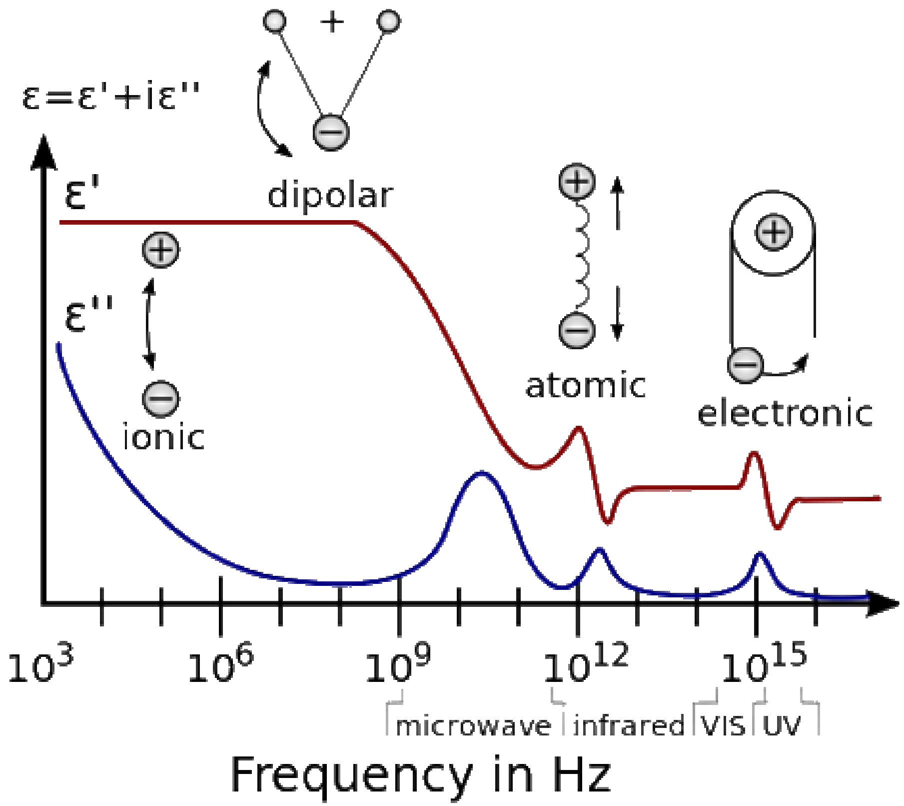
R=30 fm. Weak field.
^{11}Be+^{208}Pb
E=40 MeV
($\theta_{c.m.}$=28^o)
long pulse
XCDCC
EPM
E=200 MeV
($\theta_{c.m.}$=4.7^o)
E=759 MeV
($\theta_{c.m.}$=1.2^o)
E=2200 MeV
($\theta_{c.m.}$=0.4^o)
Short pulse
dσ/dE (mb/MeV)
E_{rel} (MeV)

R=15 fm. Strong field.



Conclusions

- We can tune the strenght (angle) and the time scale (energy) of the electric field
- EPM is not accurate. (X)CDCC should be used to analyze data.
- High order coupling effects are important, specially at low energies
- Opportunity: Study electric susceptibility of nuclear media as a function of collision time

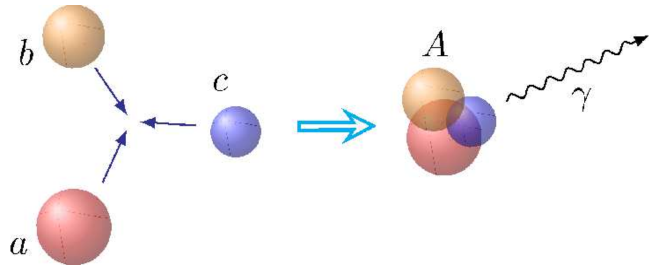


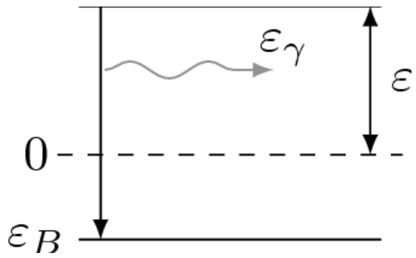
Inclusive Coulomb break-up as a tool for astrophysics

- Astrophysical photoemission reaction rates are a thermal average of the B(E1) distribution, governed by the temperature T.
- Inclusive Coulomb break-up (In the EPM) is an exponential average of the B(E1) distribution, governed by the collision time t.
- When kT= 1/t, both observables are strongly correlated.

- Can we directly measure Astrophysical reaction rates, from the adequate inclusive Coulomb break-up?

Radiative capture





Reaction rates depends on electromagnetic transition probability distributions

At first order:

$$\langle R_{abc}(\varepsilon)\rangle(T) \simeq \mathcal{N}_1(T) \int_{|\varepsilon_B|}^{\infty} d\varepsilon_\gamma \; \varepsilon_\gamma^3 \frac{dB(E1)}{d\varepsilon} e^{-\frac{\varepsilon_\gamma}{k_B T}}$$

Reduced breakup probability in the EPM:

$$P_r(t) = \int_{|\varepsilon_B|}^{\infty} d\varepsilon_\gamma \; \varepsilon_\gamma \frac{dB(E1)}{d\varepsilon} e^{-t\varepsilon_\gamma} t^2$$

Collision time:

$$t = \frac{a_0}{\hbar v}\left(\pi + \frac{2}{\sin(\theta/2)}\right)$$

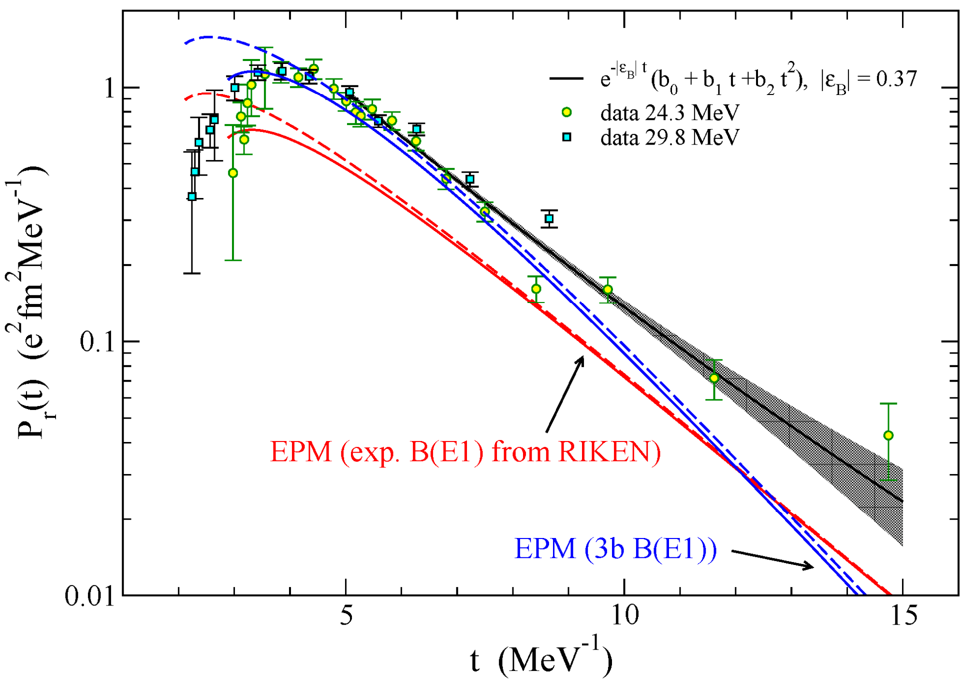
Both observables strongly correlated when $t=1/(k_B\,T)$

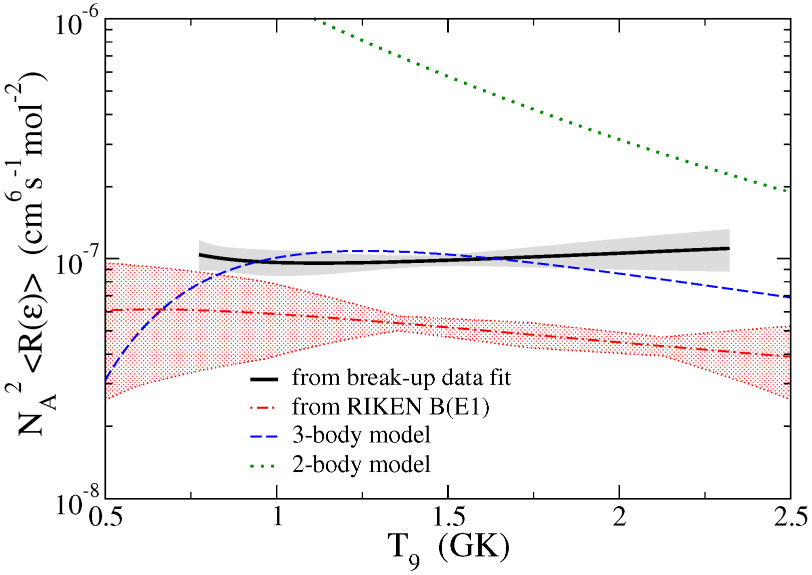
$$\langle R_{abc}(\varepsilon)\rangle(T) = \mathcal{C}\; t^3 e^{|\varepsilon_B| t} \frac{d^2}{dt^2}\left(\frac{1}{t^2} P_r(t)\right)$$

PRC 93 (2016) 041602
J. Casal et al.

Explore astrophysical temperatures by measuring inclusive Coulomb breakup at energies below the barrier and forward angles

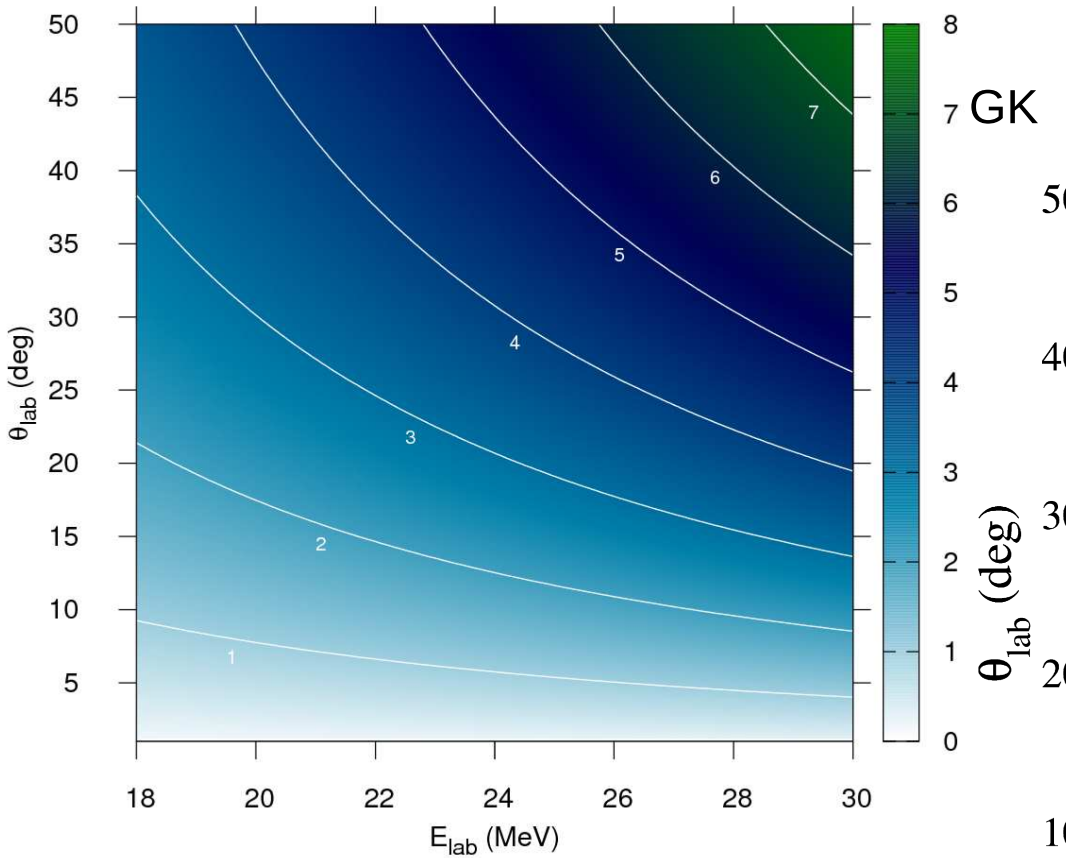
Application to $^{11}Li \to {}^{9}Li+2n$



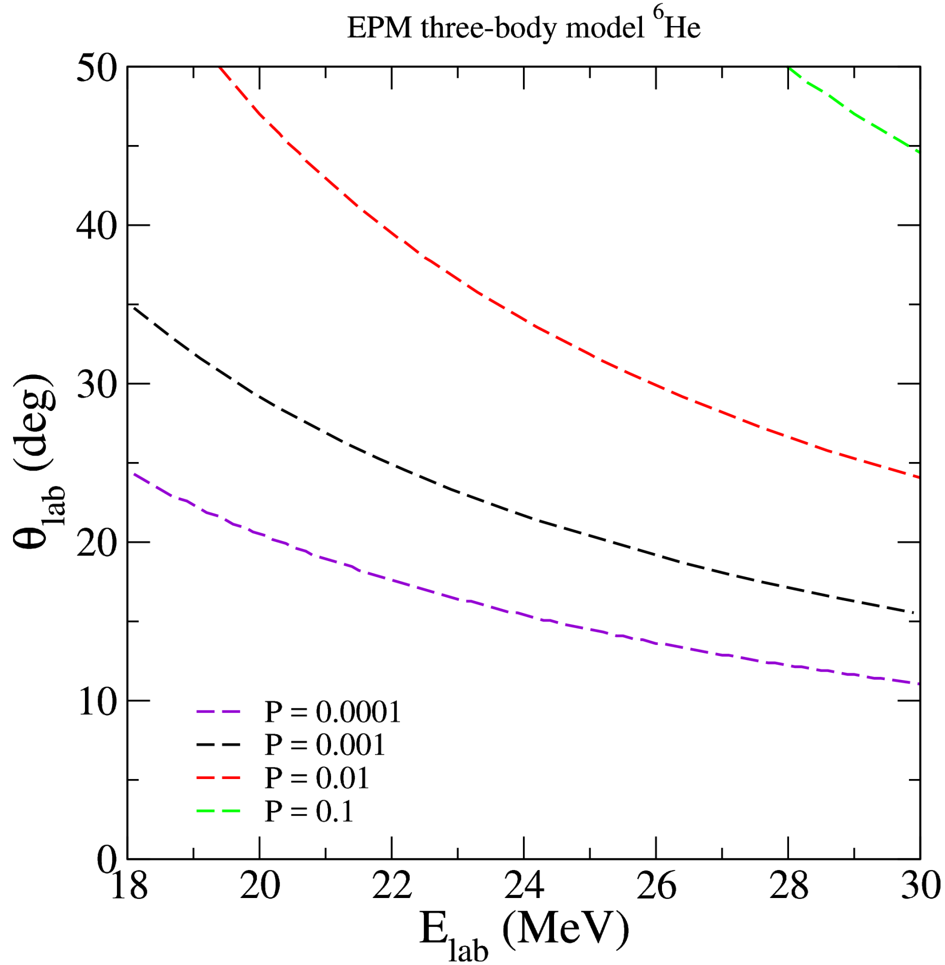


Astrophysics question: In a neutron star environment, what is the rate for alpha particles to absorb 2 neutrons, to form 6He?

^{6}He on ^{208}Pb



$$P(\theta) = P_r(t)\frac{16\pi^2\left(Z_t e\right)^2 \sin^4\left(\theta/2\right)}{9t^2(\hbar v)^3 a_0}$$



Can we directly measure Astrophysical reaction rates, from the adequate inclusive Coulomb break-up?

- We could reach temperatures as low as 2 GK, but:
- We need to separate 1 B.U. on 10000 elastic
- EPM may not be accurate.
- Non-Elastic Break-up shuold be taken into account

“Solid” He targets for exotic beam experiments

- In material science, magnetron sputtering is an effective procedure to produce thin films of Si and other metals.
- The films contain a large fraction of the inert gas (4He).
- ENSAF facilities (i.e. CNA) routinely analyze thin films by IBA techniques (PIXE, RBS)
- 4He is an ideal probe to investigate other nuclei by scattering.
- For exotic nuclei, 4He would make an ideal target (Inert, spin 0, Isospin 0).
- However, 4He is a gas and does not form solid molecules.

- Can we use thin films, rich in 4He, as targets for exotic nuclei?

V. Godinho, F.J. Ferrer, B. Fernández, J. Caballero-Hernández, J. Gómez-Camacho, A. Fernández

Amorphous-Si:He targets with He trapped in closed porosity

- **Magnetron Sputtering to produce a-Si:He, with homogeneously distributed throughout the film thickness**
  - **high He/Si low O/Si content**
- **Reproducibility and stability (fluence, temperature & aging) of the targets**
- **Targets deposited over a variety of substrates or Self-supported targets**

	Present work	Vanderbist et al.	Raabe et al.	Ujic et al.
Technique	Magnetron sputtering	Ion implantation	Ion implantation	Ion implantation
Metal ($\times 10^{15}$ at/cm^2)	(Si) 9250	(Al) 1100	(Al) 4200	(Al) 1200
He ($\times 10^{15}$ at/cm^2)	4060	275	270	130
O ($\times 10^{15}$ at/cm^2)	700	60	100	Not mentioned
He/M	0.44	0.25	0.06	0.11
O/He	0.17	0.22	0.37	Not mentioned

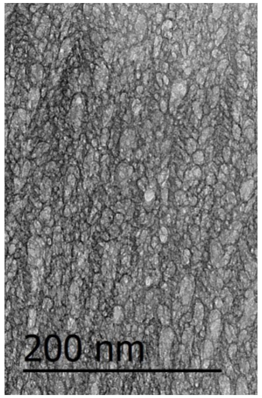
Solid He targets for Nuclear Physics Experiments

V. Godinho, F.J. Ferrer, B. Fernández, J. Caballero-Hernández, J. Gómez-Camacho, A. Fernández

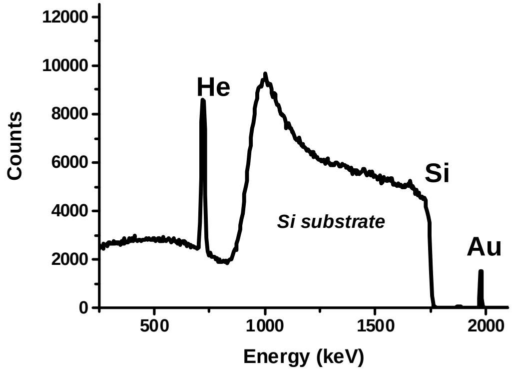
Supported (over Si) *a-Si:He target*

^{4}He(^{1}H,^{1}H) ^{4}He Elastic scattering

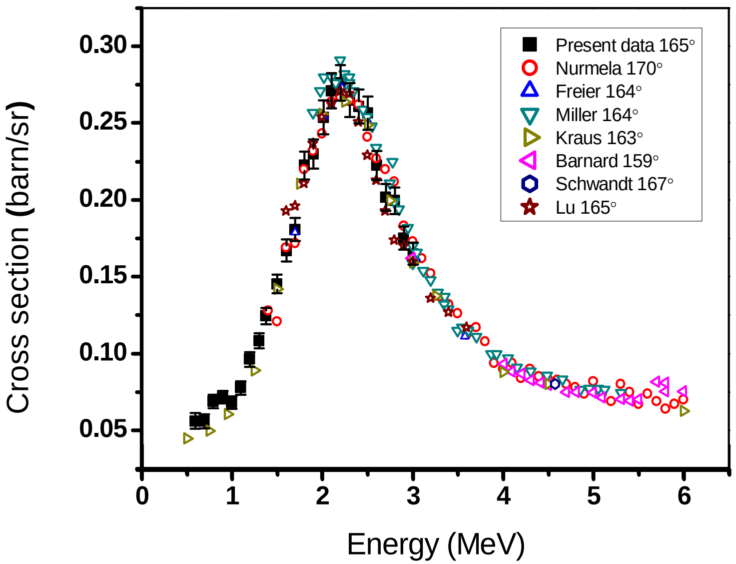
Backscattering (θ > 90°)



TEM cross-setional view



p-EBS Ep = 2000 keV; θ = 165 °



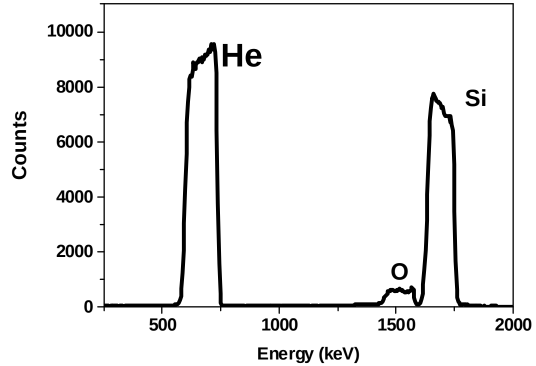
Differential scattering cross-section ^{4}He(^{1}H,^{1}H)^{4}He; θ = 165 °

Self-supported a-Si:He target

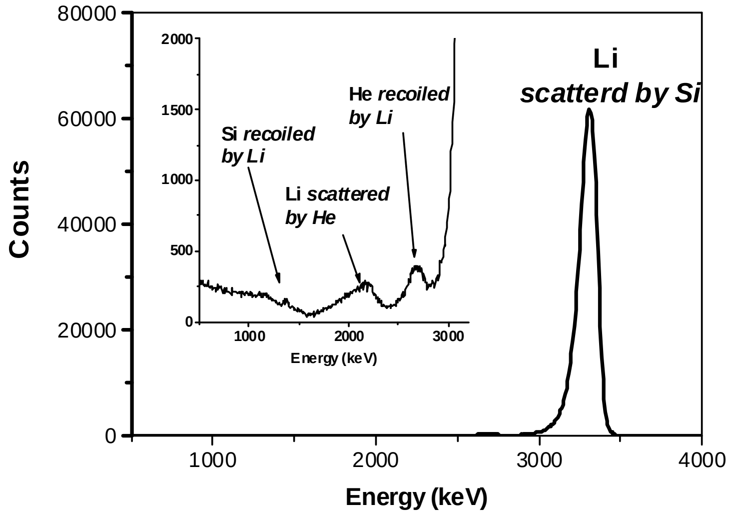
^{4}He(^{6}Li, ^{6}Li) ^{4}He Elastic scattering

Forward scattering (θ < 90°).

Self-supported thin film mounted on the holder for measurements



p-EBS Ep = 2000 keV; θ = 165 °



Scattering spectrum ^{4}He(^{6}Li, ^{6}Li)^{4}He; θ = 30 °

Can we use thin films, rich in 4He, as targets for exotic nuclei?

- Yes!
- In progress: changing the substrate by heavier nuclei, building thicker targets, ...

One physics case:

(4He, 6He) to check long range n-n correlation, complementary to (p,t).

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