

CRUCIAL MEASUREMENTS FOR HADRONTHERAPY

- ❑ Recommended beams : H, C, **O**
- ❑ Recommended targets: **H, C**, O, N

CRUCIAL MEASUREMENTS FOR RADIOPROTECTION

- ❑ Recommended beams : H, He, C, **O**, Si, Fe
- ❑ Recommended targets: H, Al (Z=13), **low Z materials (Z<13)**

GSII DATA TAKING

- ❑ Beam : ^{16}O (200 – 400 – 800 MeV/n)
- ❑ Targets: C (2mm) , C_2H_4 (5 mm)
- ❑ Beam Energy: 200 – 400 – 800 MeV/u
- ❑ Detection: H, He, Li, Be, B, C, N → only charge measurements

POSSIBLE MEASUREMENTS

- ❑ Charge changing cross sections: $^{16}\text{O} + \text{Target} \rightarrow \text{something} \neq ^{16}\text{O}$, $\Delta Z \geq 1$
- ❑ Elemental σ (charge) cross section
- ❑ Differential Angular $d\sigma/d\Omega$ charge cross section

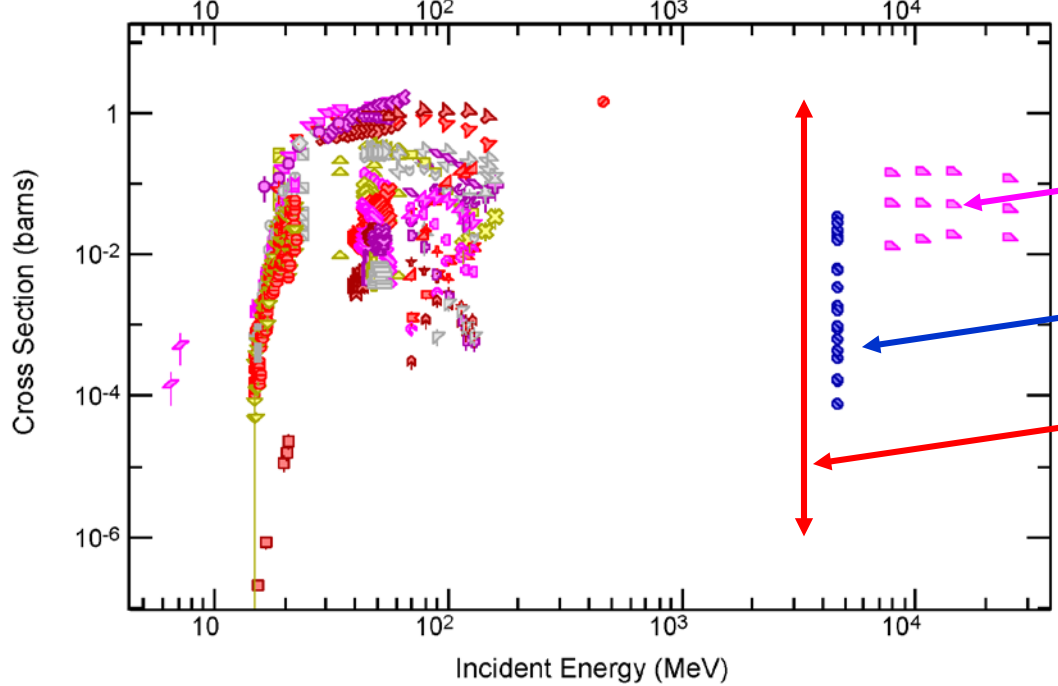
- ❑ Radiation Measurements 47 (2012) 315-363 «Nuclear data for space radiation» J.W.Norbry et al.
- ❑ EXFOR Database

σ on Carbon target: $^{16}\text{O} + \text{C} \rightarrow \text{X}$ in $[0-10]$ GeV

Total σ : $^{16}\text{O} + ^{12}\text{C} \rightarrow \text{X}$

6-C-12(8-O-16,X)2-HE-4
EXFOR Request: 3416/1, 2019-Feb-14 14:55:16

Energy is total (not per nucleon)

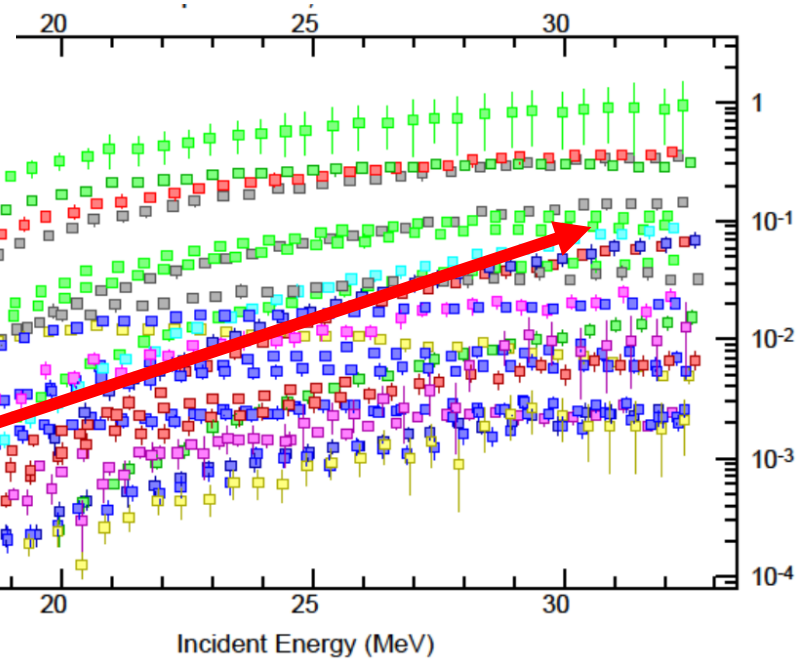


550-1625 MeV/n

290 MeV/n

200 MeV/n

Total σ : $^{16}\text{O} + ^{13}\text{C} \rightarrow \text{X}$



ISOTOPIC IDENTIFICATION (NOT FOR US)

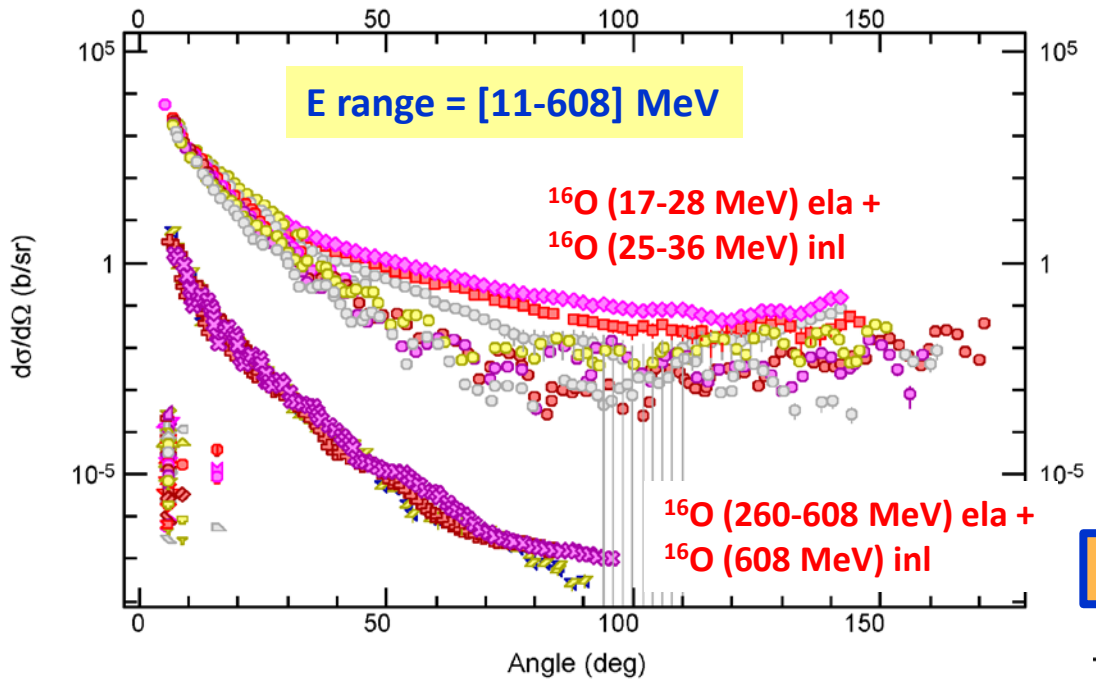
No measurements in our energy range

different final states

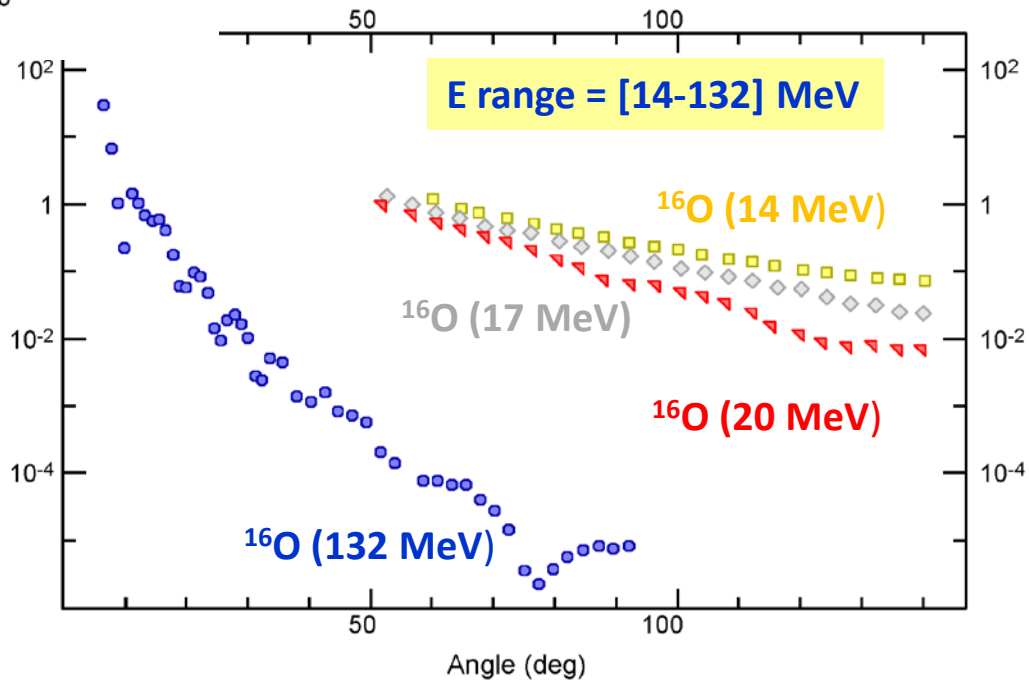
$d\sigma/d\Omega$ on Carbon target: $^{16}\text{O} + \text{C} \rightarrow X$ in [0-10] GeV

$d\sigma/d\Omega: ^{16}\text{O} + ^{12}\text{C} \rightarrow X$

Energy is total (not per nucleon)



$d\sigma/d\Omega: ^{16}\text{O} + ^{13}\text{C} \rightarrow$ elastic scattering



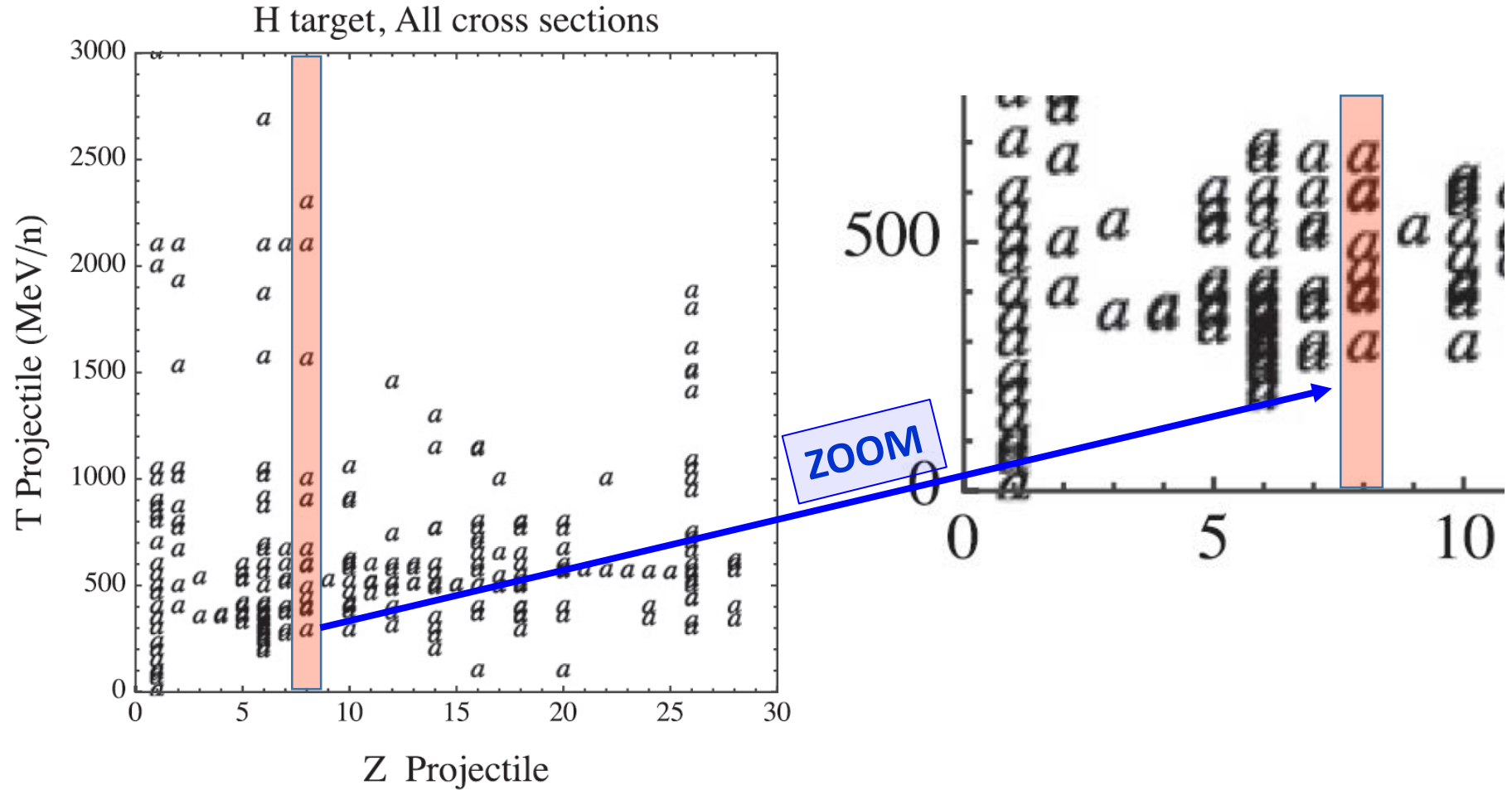
ISOTOPIC IDENTIFICATION (NOT FOR US)

No measurements in our energy range

$\sigma: ^{16}\text{O} + ^{14}\text{C} \rightarrow$ only ela scatt

Total σ on hydrogen target: $^{16}\text{O} + \text{H} \rightarrow \text{X}$ in [0-10] GeV

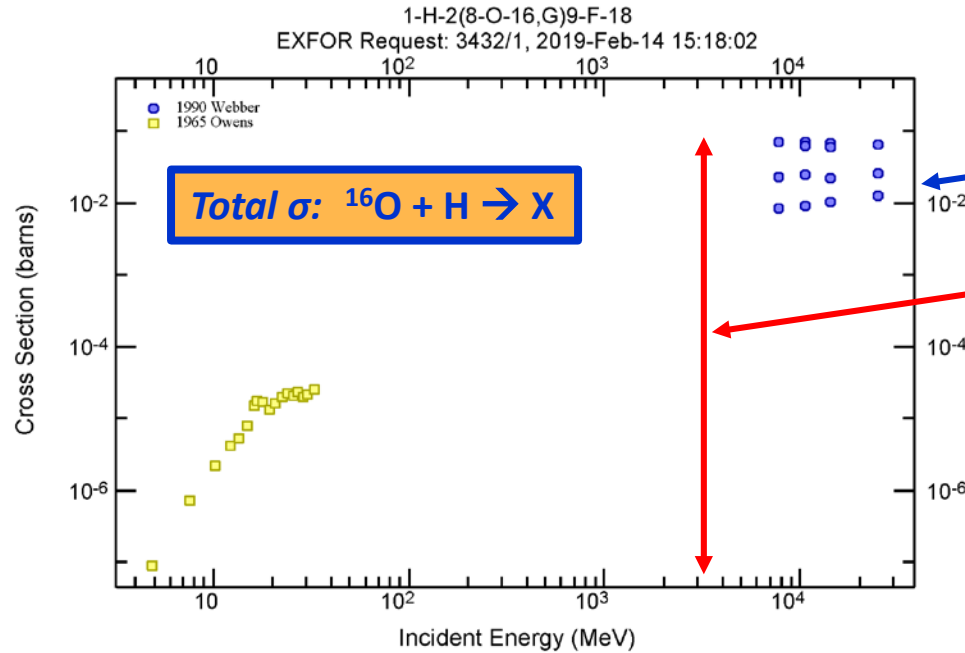
Energy per nucleon



Measurements at ~300 – 400 – 450 – 500 – 600 – 680 MeV/u

Total σ and $d\sigma/d\Omega$ on hydrogen target: $^{16}\text{O} + \text{H} \rightarrow \text{X}$ in [0-10] GeV

Energy is total (not per nucleon)

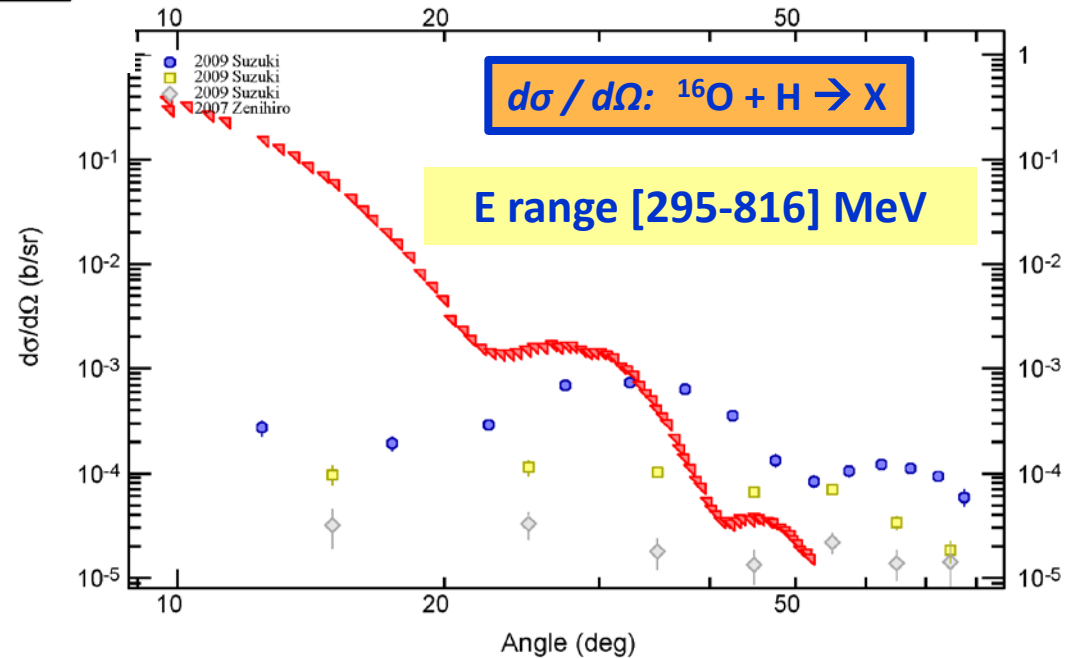


490-1560 MeV/n

200 MeV/n

No measurements in our energy range

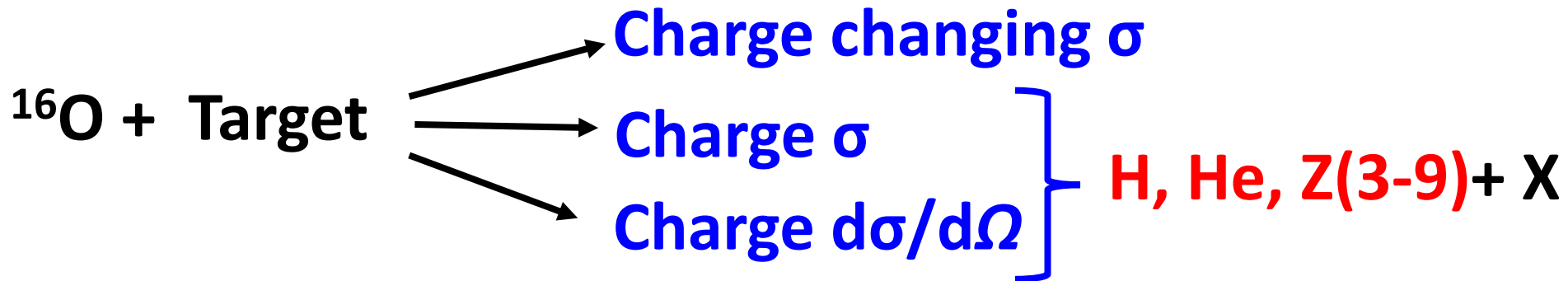
1-H-1(8-O-16,T)8-O-14,PAR,DA Ei=8.16e+8 Lv=0



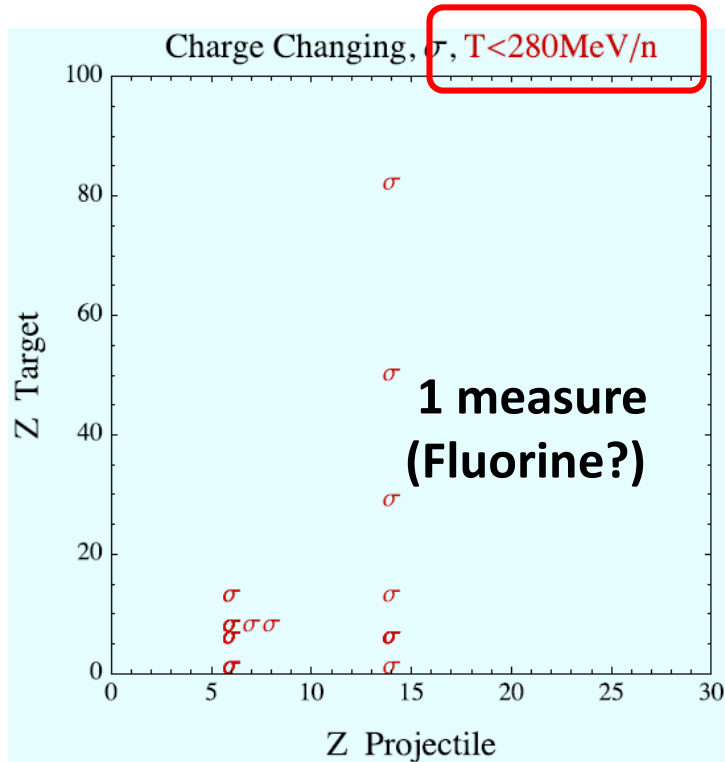
Experimental Panorama with final state visible at GSI

POSSIBLE MEASUREMENTS

- Charge changing cross sections: $^{16}\text{O} + \text{Target} \rightarrow \text{something} \neq ^{16}\text{O}, \Delta Z \geq 1$
- Elemental σ (charge) cross section
- Differential Angular $d\sigma/d\Omega$ charge cross section



Charge Changing Cross Section



Charge changing Cross Section

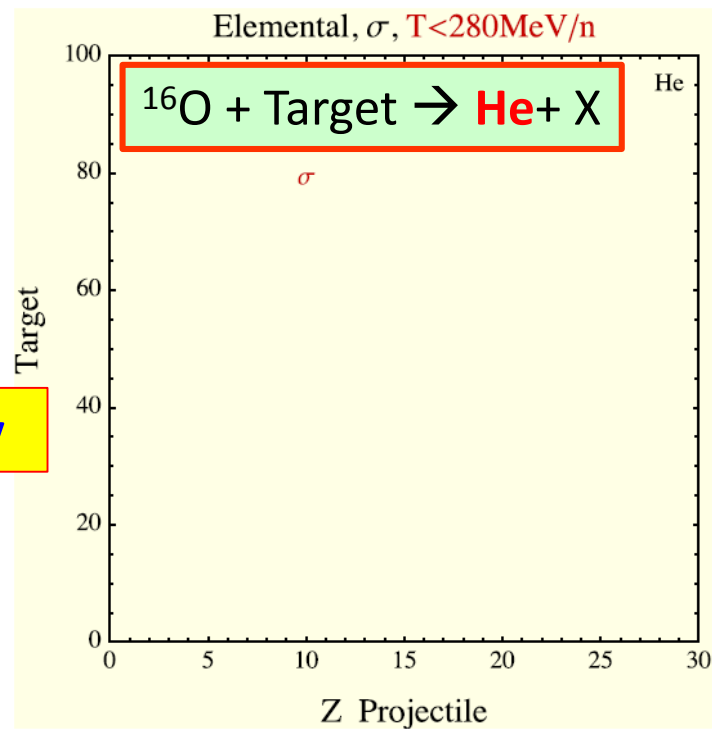
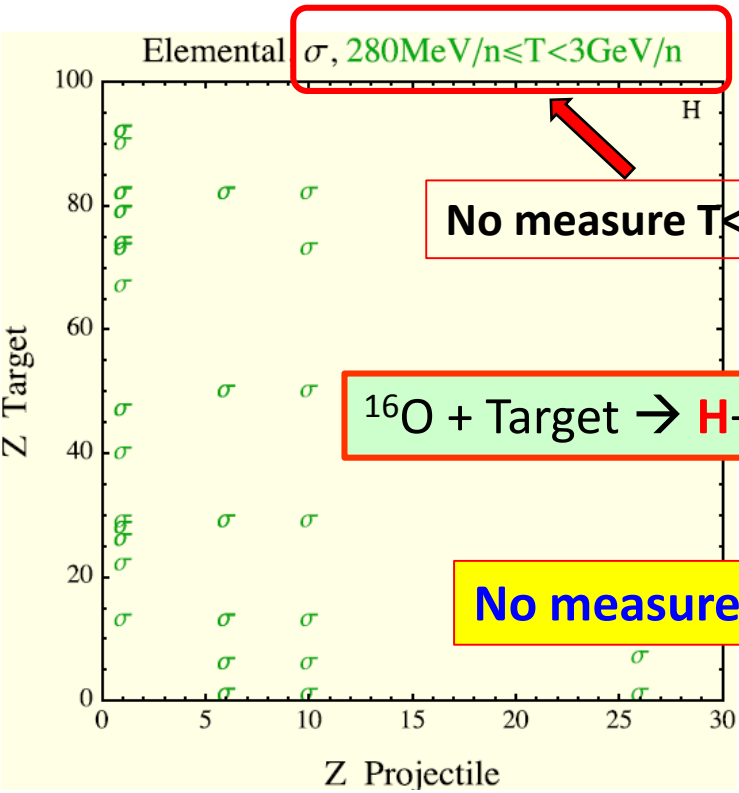
$^{16}\text{O} + \text{Target} \rightarrow \text{something} \neq ^{16}\text{O} (\Delta Z \geq 1)$

Now and in the following
Research focalize on $T < 280 \text{ MeV/u}$

Recommendation to make measurements with O

Cross-section	Below $< \pi$ threshold projectile	Low energy projectile	Medium energy projectile	High energy projectile
σ	O, Fe	—	C, Fe(T)	C, Fe

σ (charge):
Cross Section: H, He production



Recommendations

H elemental and ^{1,2,3}H isotopic fragment measurement recommendations. "All" projectiles signify He, C, O, Si, Fe. Projectiles needed for *only* H targets are listed with (H). Projectiles needed for a range of targets, *except* H, are listed with (H). No parentheses indicates that a range of targets, including H, is needed. The notation (T) means that only a few additional targets are required. H projectiles are not considered.

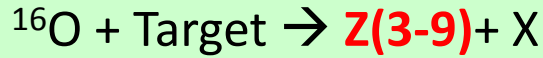
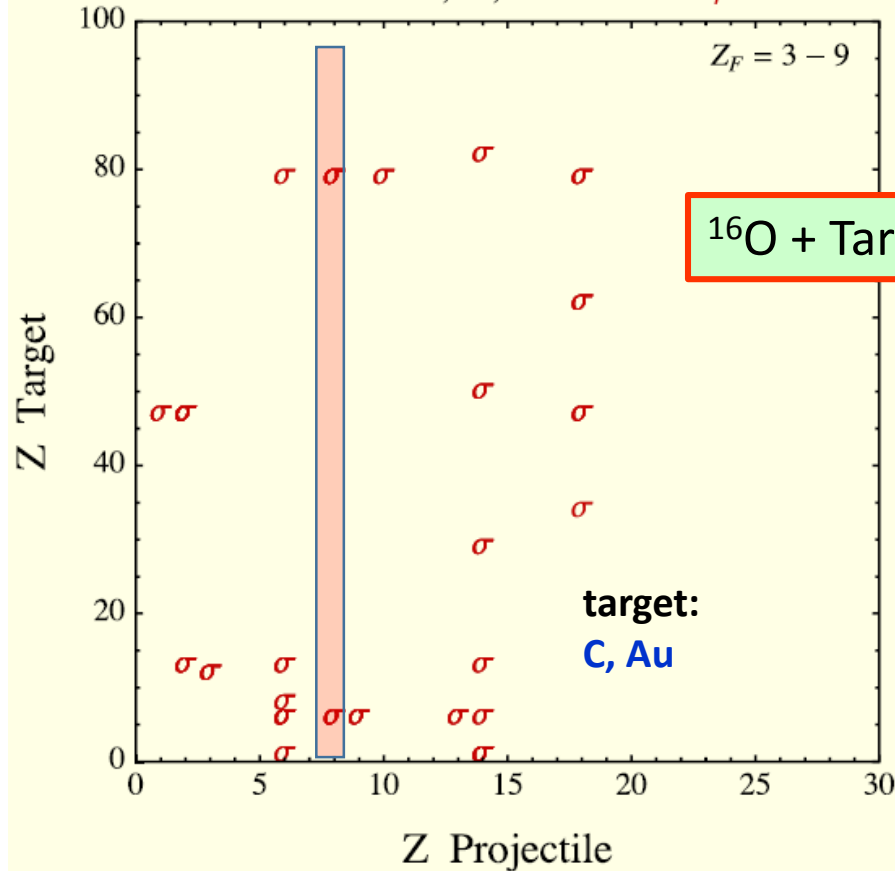
Cross-section	Fragment	Below π threshold projectile	Low energy projectile	Medium energy projectile	High energy projectile
σ	H	All	He,O,Si,Fe(T)	All	All
	^{1,2,3} H	He(T),C,O(H),Si,Fe	He(H),O(T),Si,Fe	He(H),C(H),O,Si,Fe	All

Table 7
 He elemental and ^{3,4,6}He isotopic fragment measurement recommendations. "All" projectiles signify He, C, O, Si, Fe. Projectiles needed for *only* H targets are listed with (H). Projectiles needed for a range of targets, *except* H are listed with (H). No parentheses indicates that a range of targets, including H, is needed. The notation (T) indicates that only a few additional targets are required.

Cross-section	Fragment	Below π threshold projectile	Low energy projectile	Medium energy projectile	High energy projectile
σ	He	All	He,O,Si,Fe(T)	All	All

σ (charge): Total Cross Section light ion ($3 \leq Z \leq 9$) production

Elemental, σ , $T < 280 \text{ MeV/n}$



Measurements in C and Au

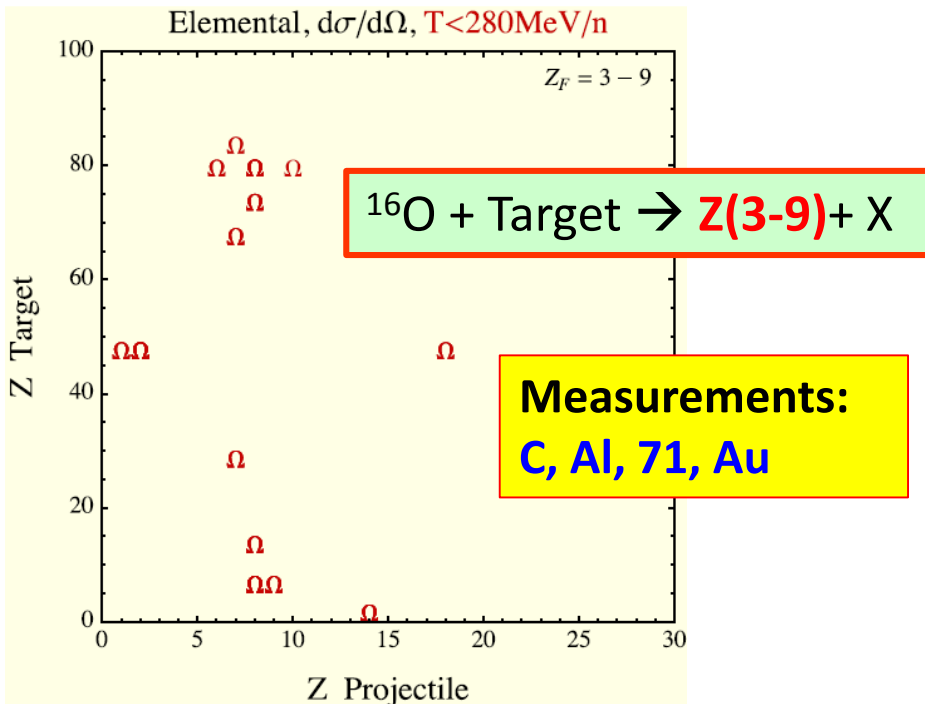
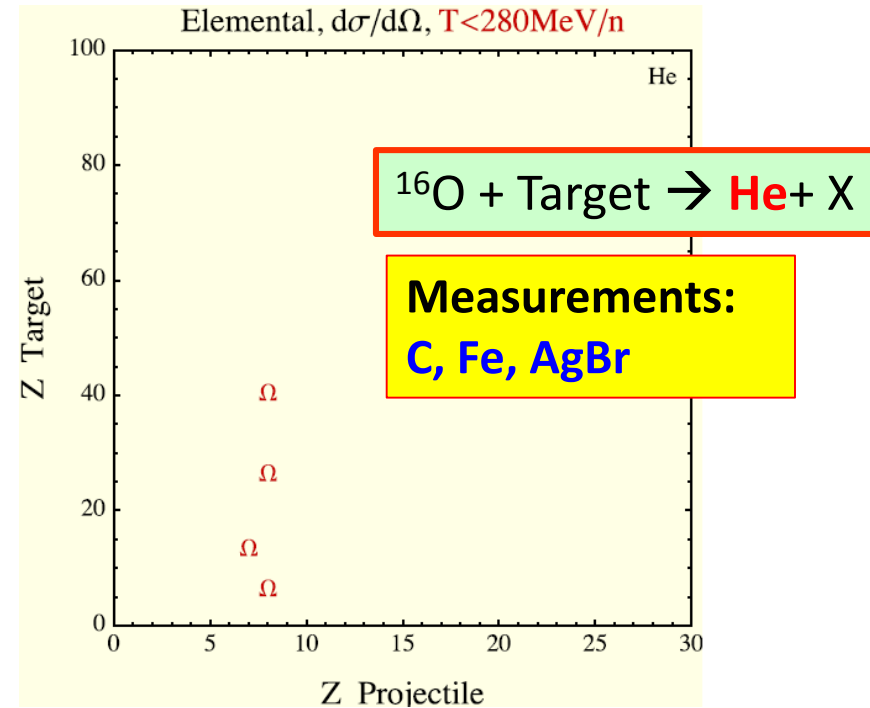
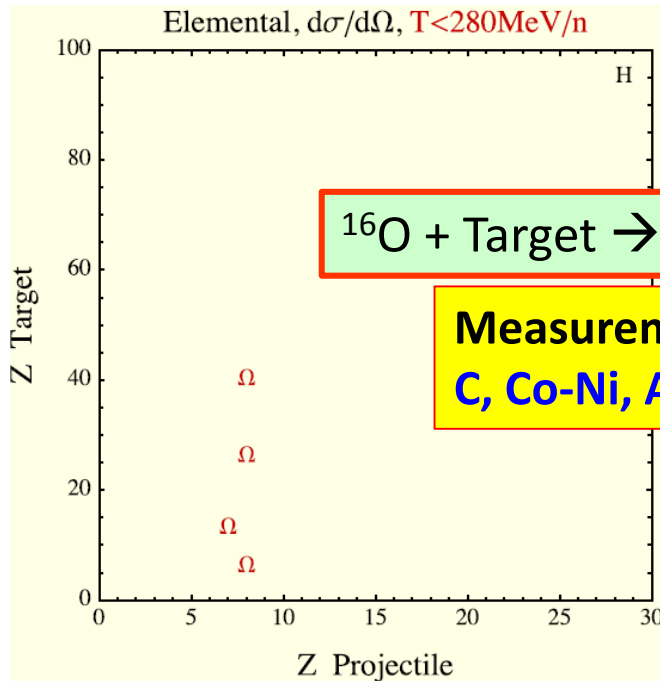
important to compare

Recommendations

Medium-light ($Z_F = 3-9$) elemental and isotopic fragment measurement recommendations. A complete measurement set for C, O, Si and Fe projectiles would be required to fill this gap. Projectiles needed for *only* H targets are listed with (H). Projectiles needed for a range of targets, *except* H, are listed with (#). No parentheses indicates that a range of targets, including H, is needed. H and He projectiles are not considered, because projectile fragmentation will not produce medium-light fragments.

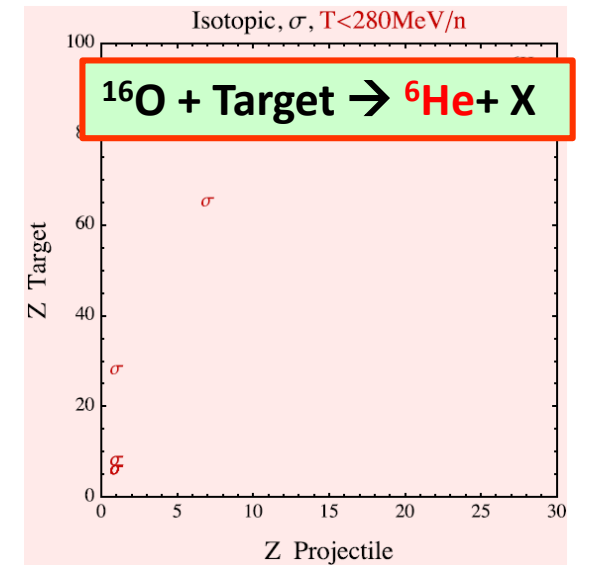
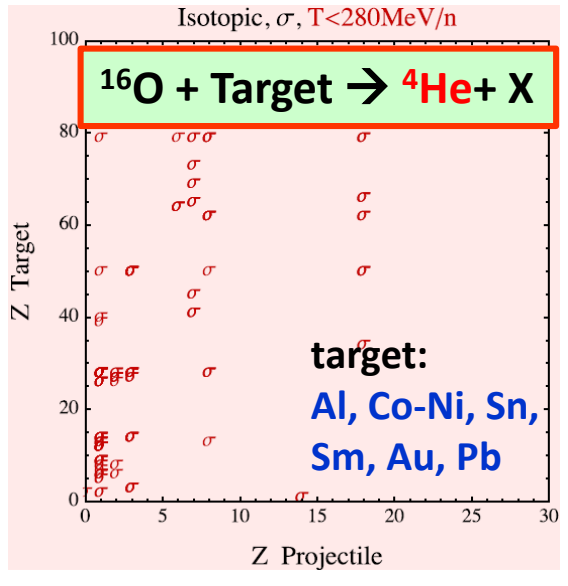
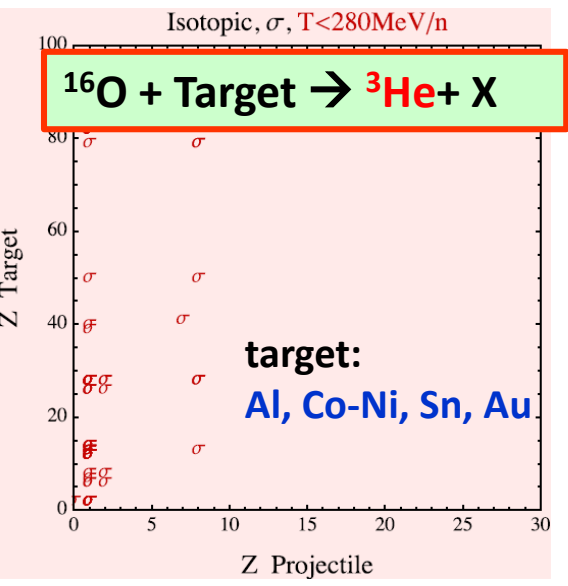
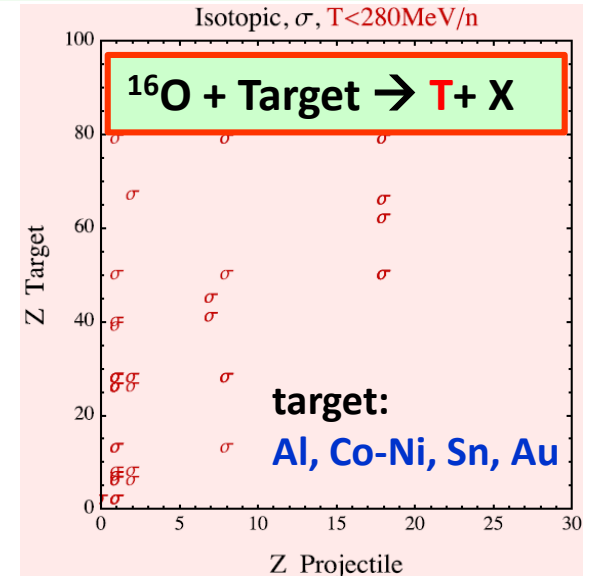
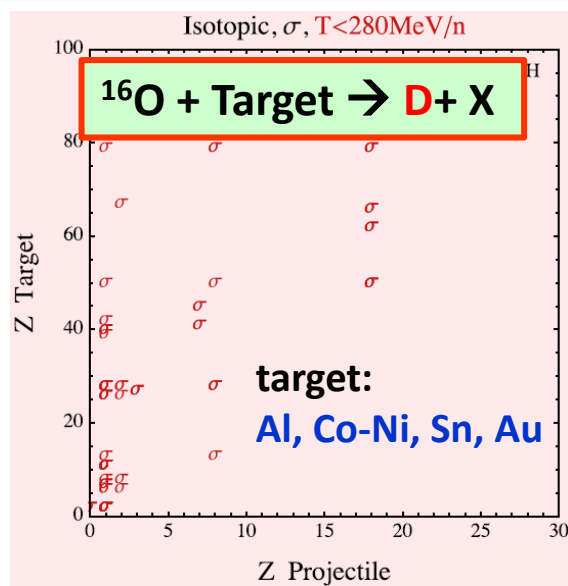
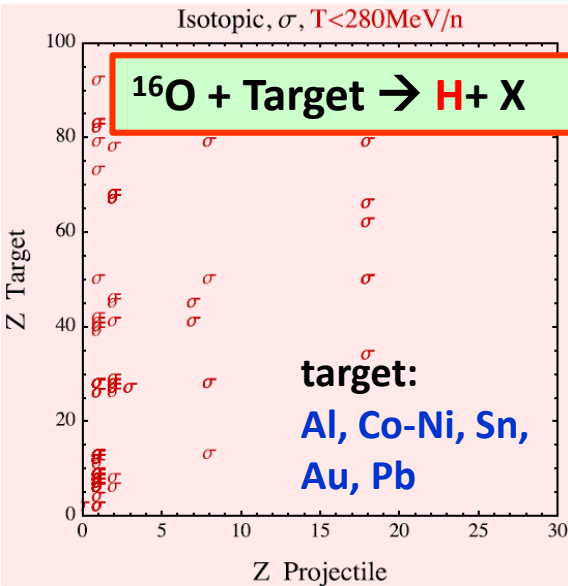
Cross-section	Fragment	Below π threshold projectile	Low energy projectile	Medium energy projectile	High energy projectile
σ	Elemental	C(T), O, Fe	—	C(#), O(H), Fe	C, Fe
	Isotopic	C(H), O, Si, Fe	Fe(#)	C(#), O, Si(H), Fe	C, O, Si, Fe
$dE/d\Omega$	Elemental	C, O, Si, Fe	C, O, Si, Fe	C, O, Si, Fe	C, O, Si, Fe
	Isotopic	C, O, Si, Fe	C, O, Si, Fe	C, O, Si, Fe	C, O, Si, Fe

$d\sigma(\text{charge})/d\Omega$: Differential Charge Cross Section



Measurements with C target:
important test

σ : Isotopic Total Cross Section: H, He production

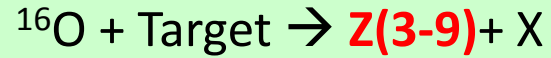
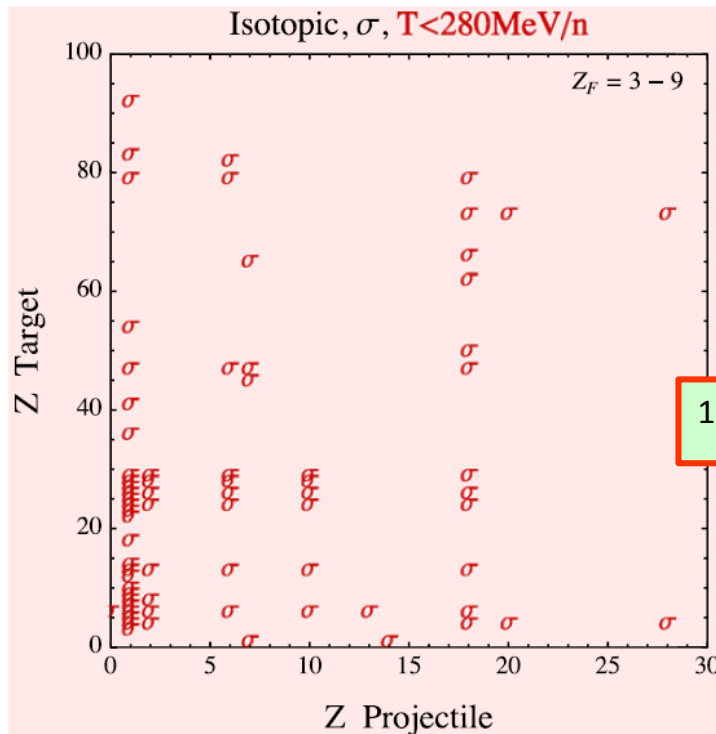


Adding σ (H, D, T or ${}^3\text{He}$, ${}^4\text{He}$, ${}^6\text{He}$) \rightarrow elemental cross section

No measurements on C and C_2H_4 targets

σ :

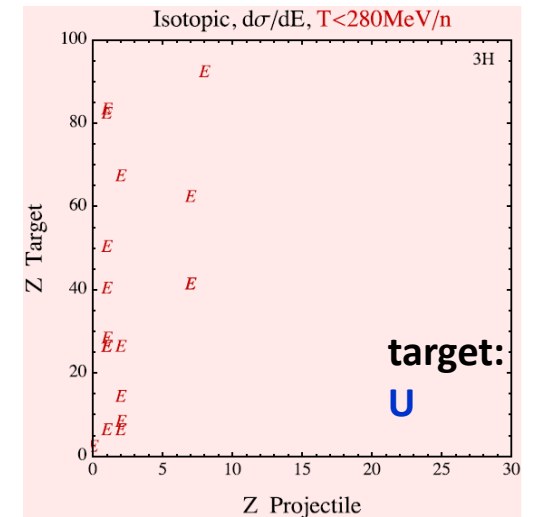
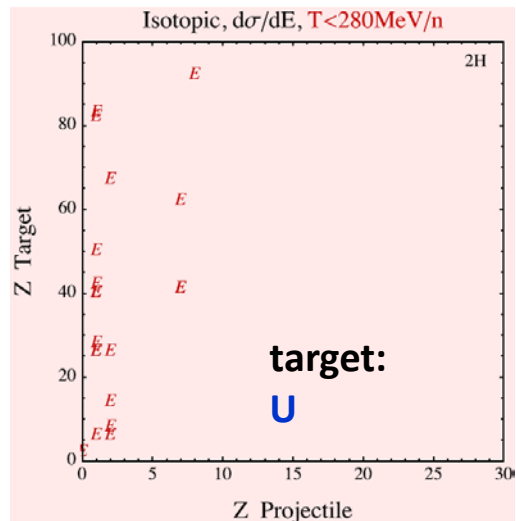
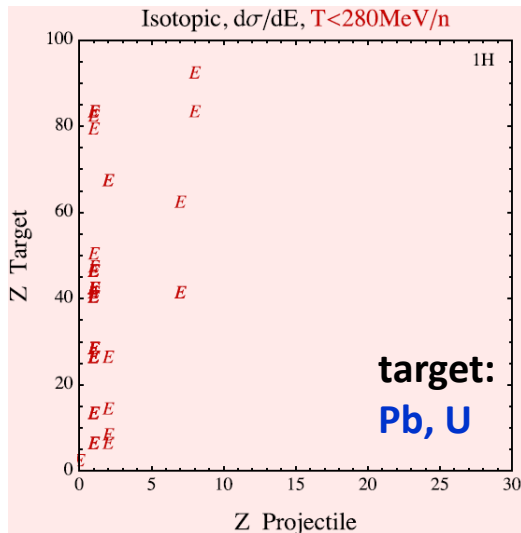
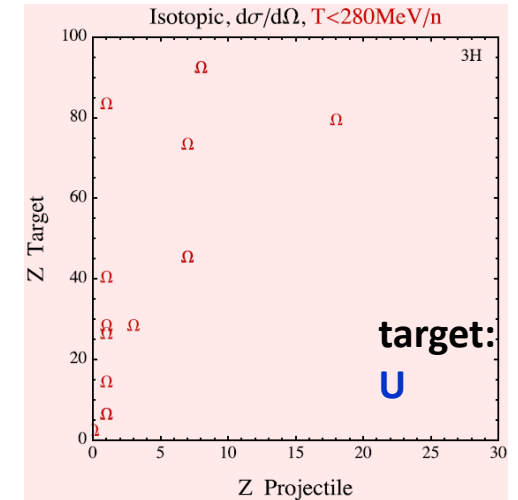
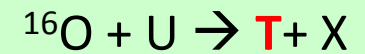
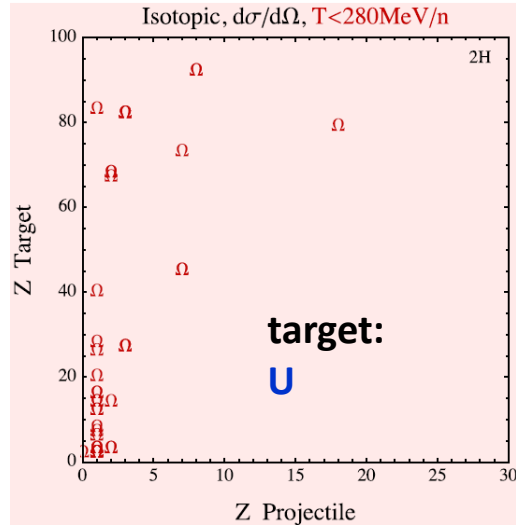
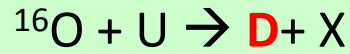
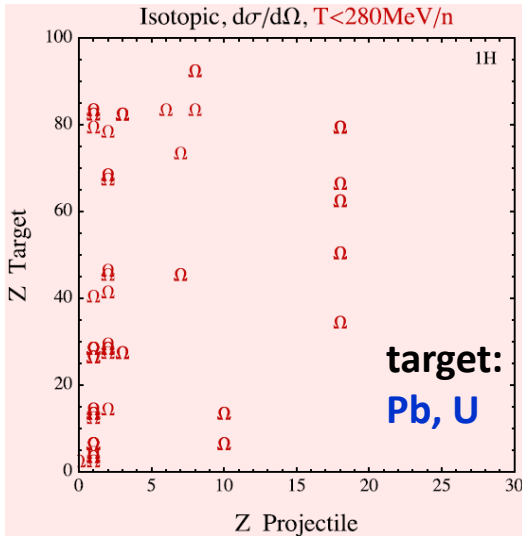
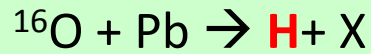
Isotopic Total Cross Section: ($3 \leq Z \leq 9$) production



No measurements of isotopic cross section with ^{16}O

$d\sigma/d\Omega$, $d\sigma/dE$:

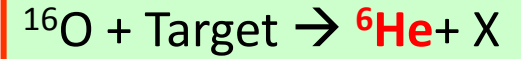
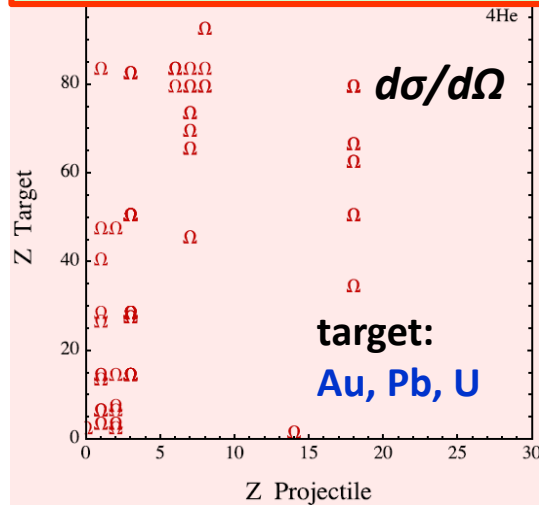
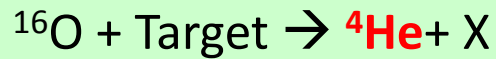
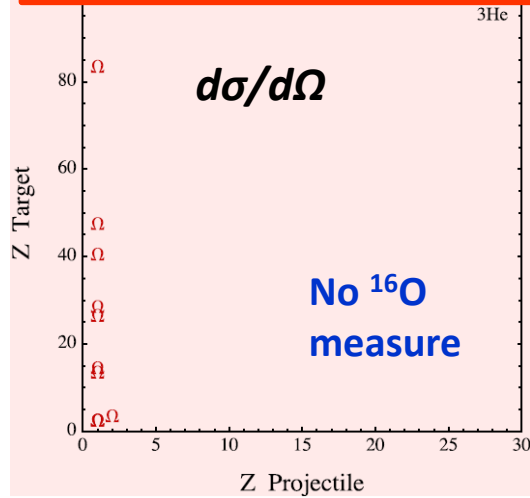
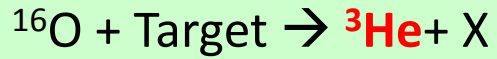
Differential Isotopic Cross Section: H production



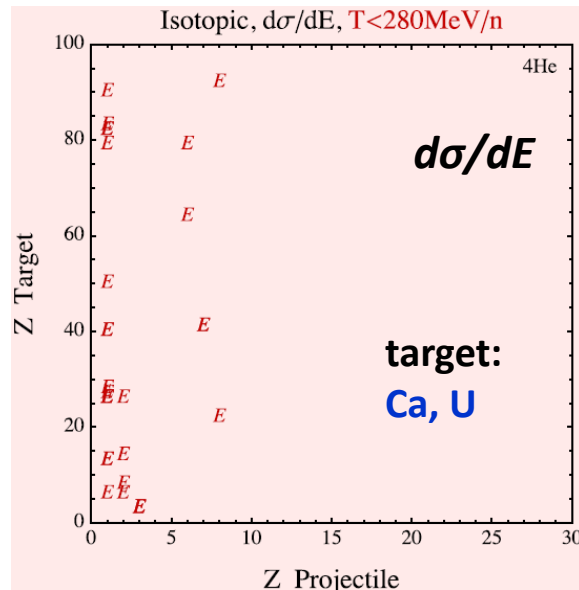
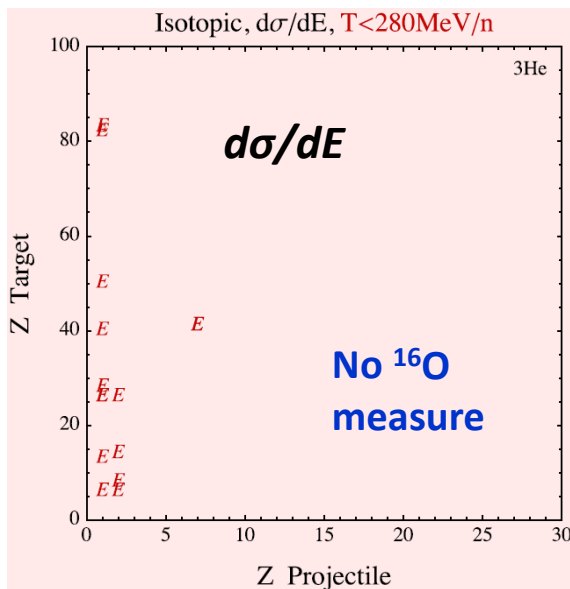
Exist also the differential cross section wrt momentum ($p_{//}$ and p_{\perp})

$d\sigma/d\Omega$, $d\sigma/dE$

Differential Isotopic Cross Section: He production



No measurements

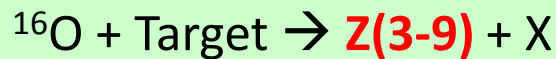
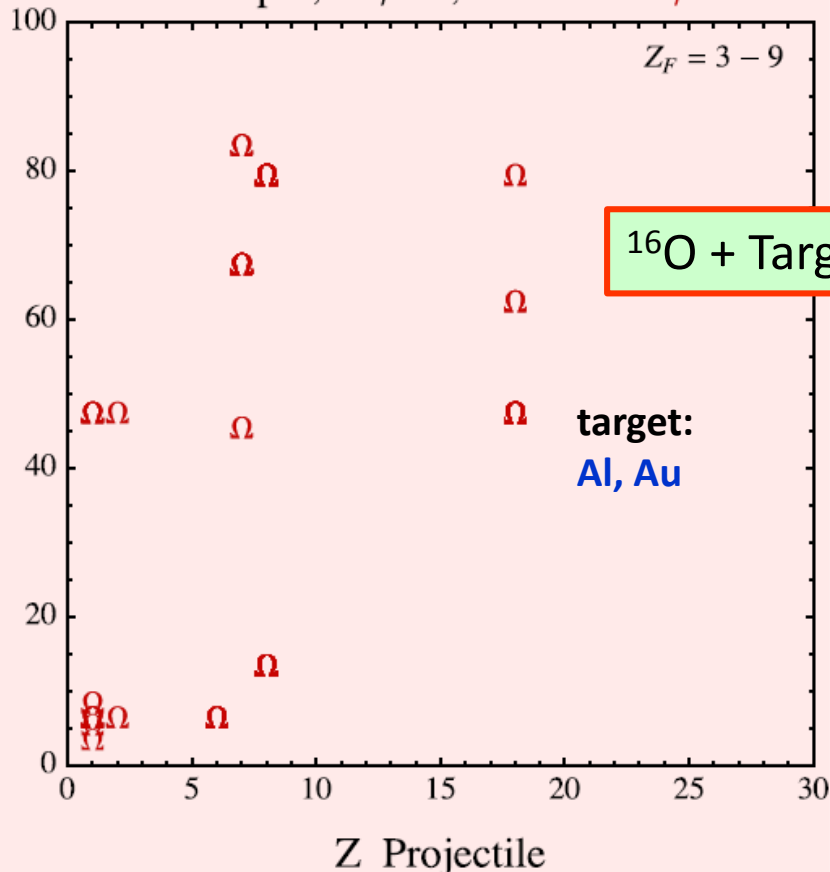


No measurements

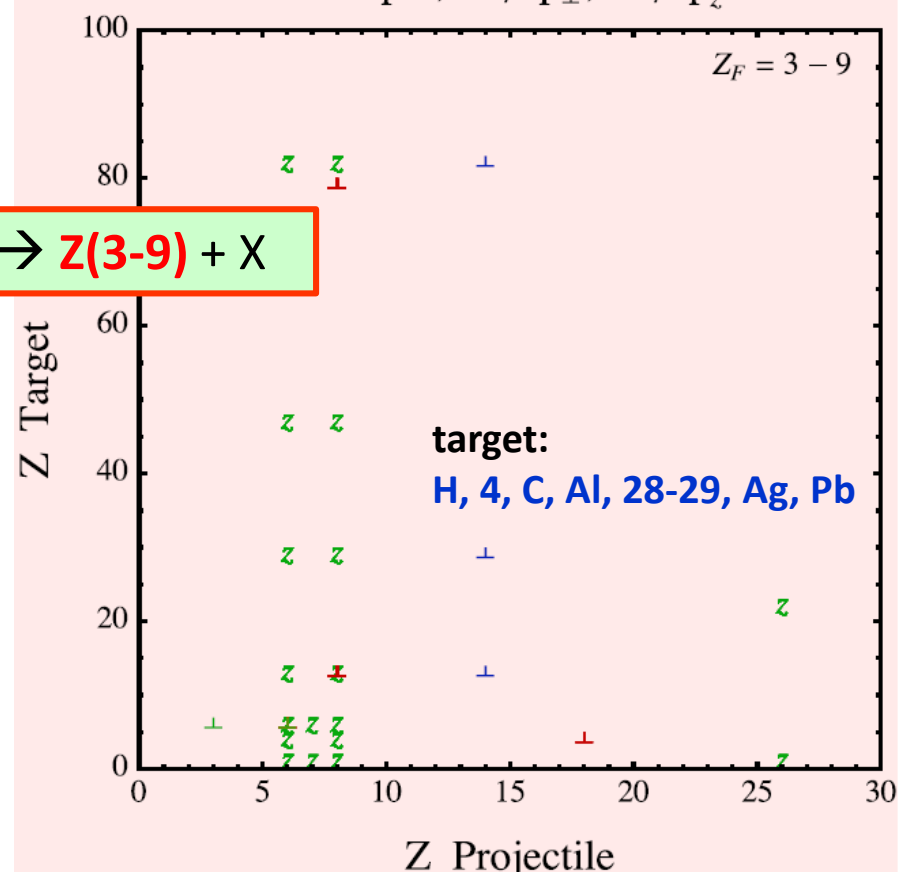
$d\sigma/d\Omega$, $d\sigma/dp$

Differential Isotopic Cross Section: : ($3 \leq Z \leq 9$) production

Isotopic, $d\sigma/d\Omega$, $T < 280 \text{ MeV/n}$



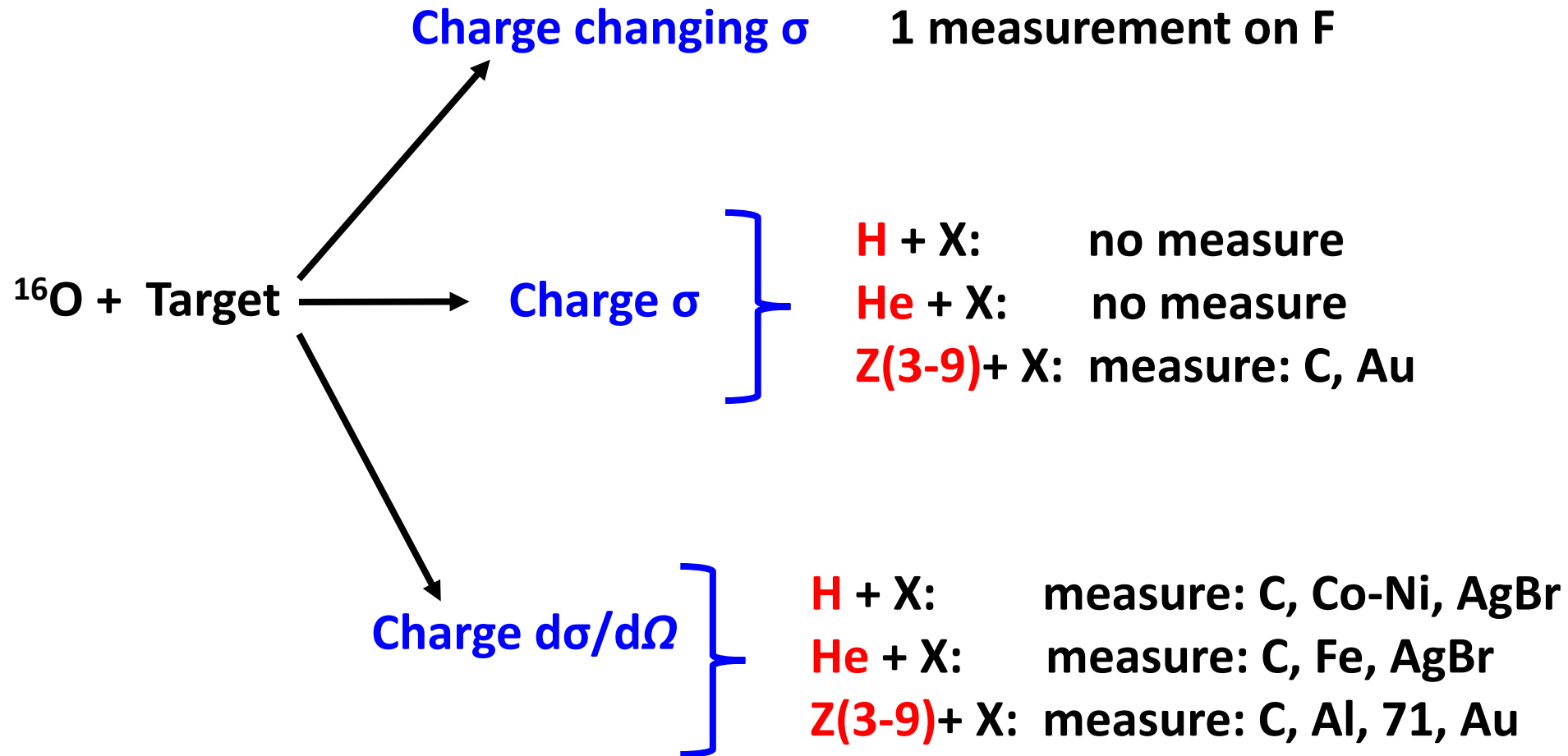
Isotopic, $d\sigma/dp_{\perp}$, $d\sigma/dp_z$



No measurements of $d\sigma/dE$

Short summary of the experimental panorama

^{16}O beam with $T < 280$ MeV/n



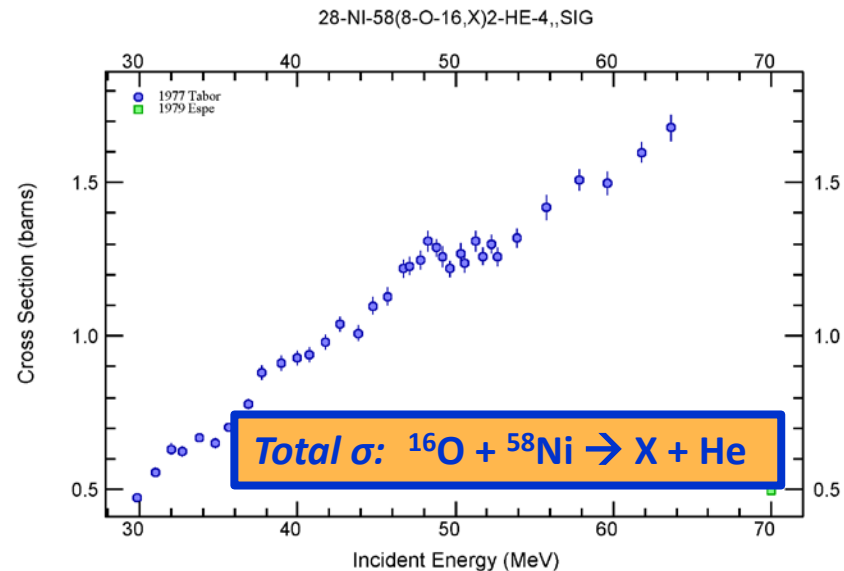
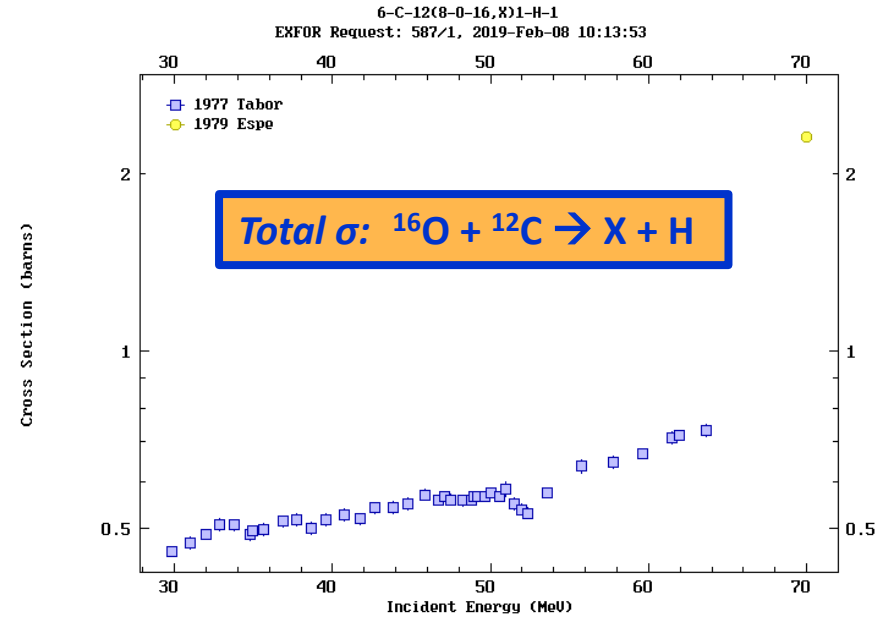
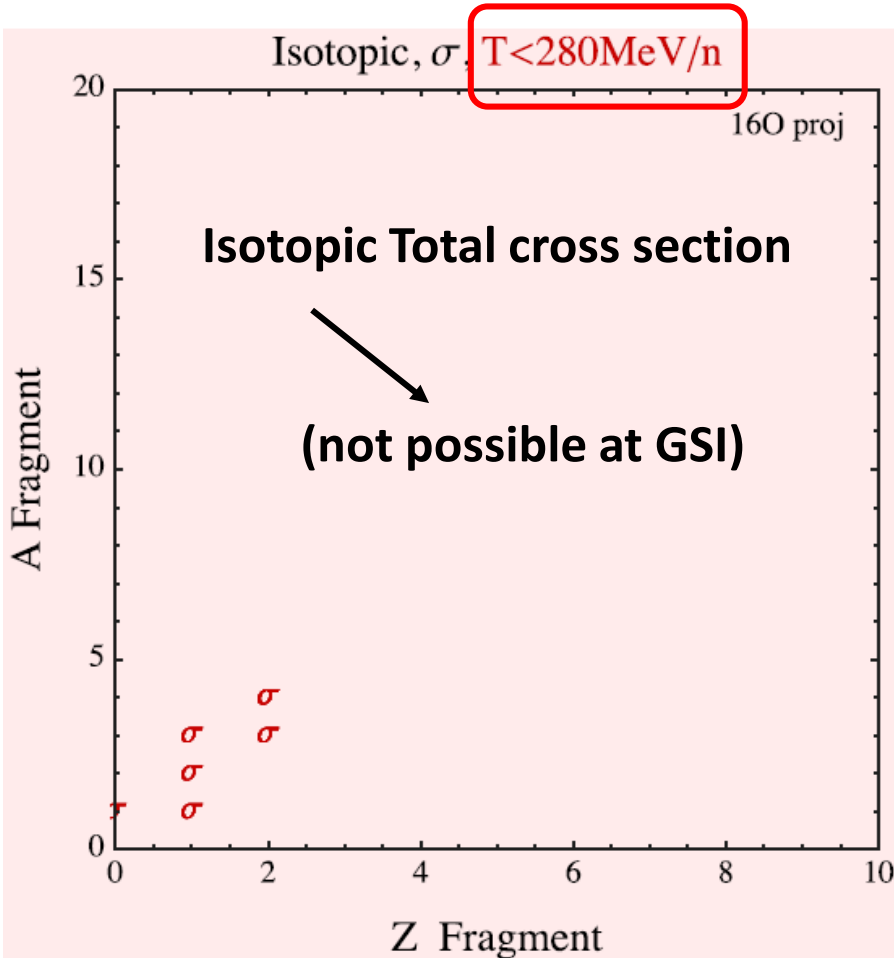
Isotopic total σ and $d\sigma/d\Omega \rightarrow$ no measure on C and C_2H_4

Backup slides

σ :

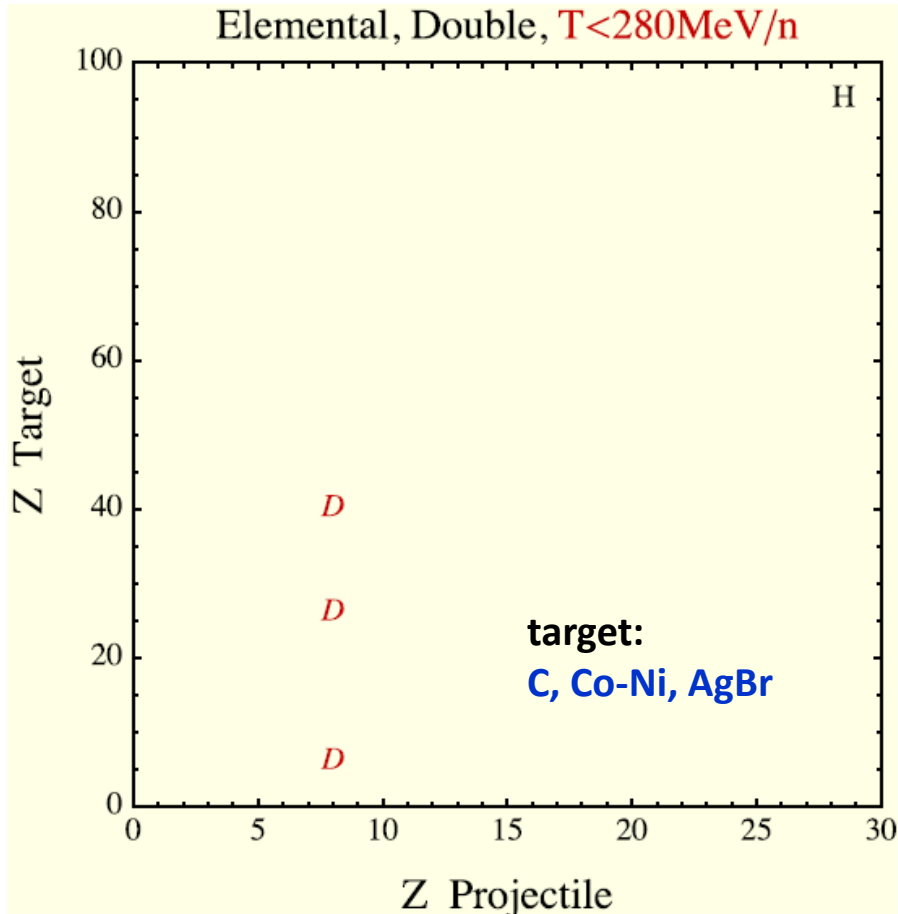
Isotopic Total Cross Section with ^{16}O projectile

Radiation Measurements 47 (2012) 315-363
«Nuclear data for space radiation» J.W.Norbry et al.



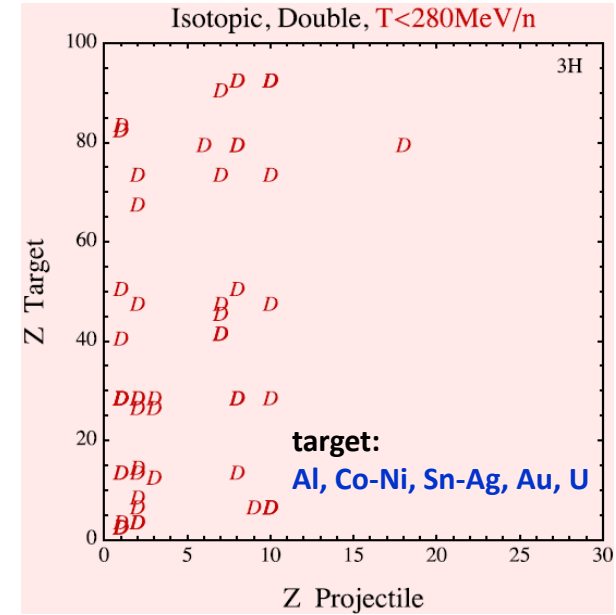
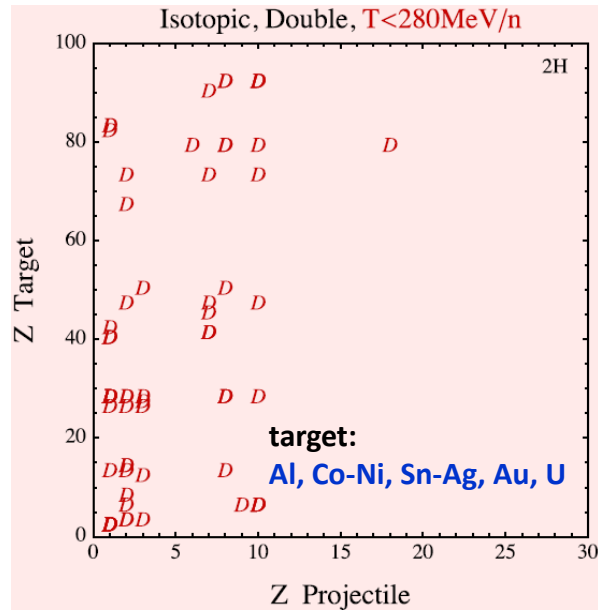
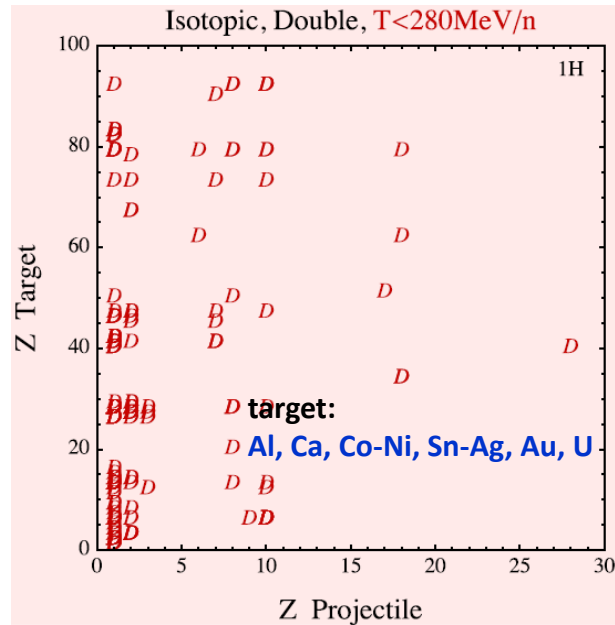
$$D^2\sigma(\text{charge})/dE d\Omega :$$

Double Differential elemental Cross Section: H production



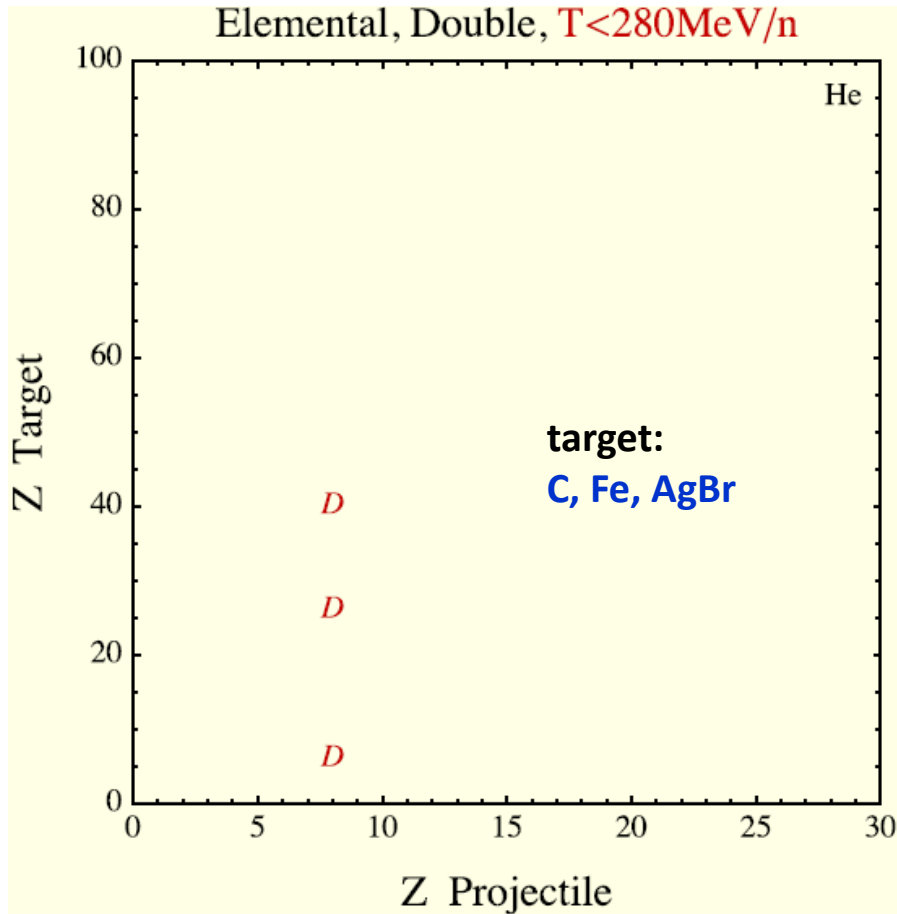
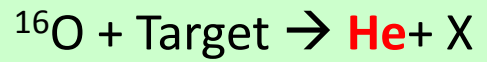
$$d^2\sigma/dE d\Omega :$$

Double Differential Isotopic Cross Section: H production



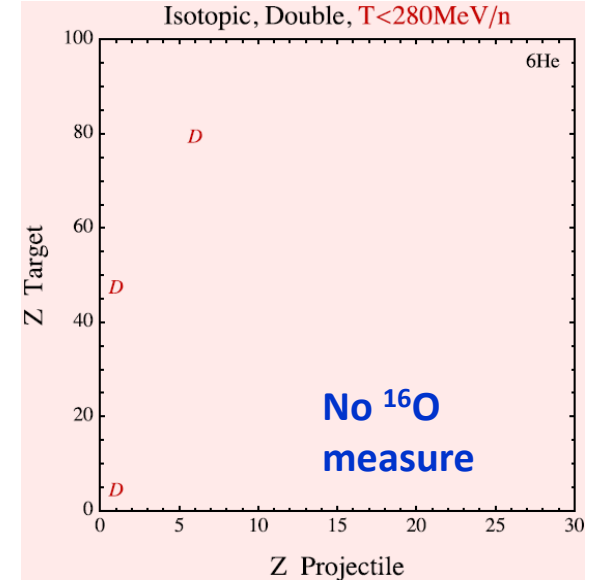
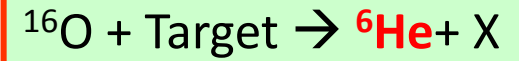
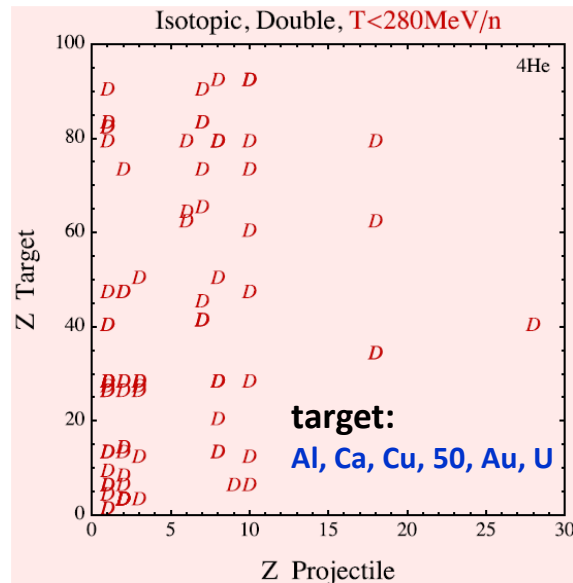
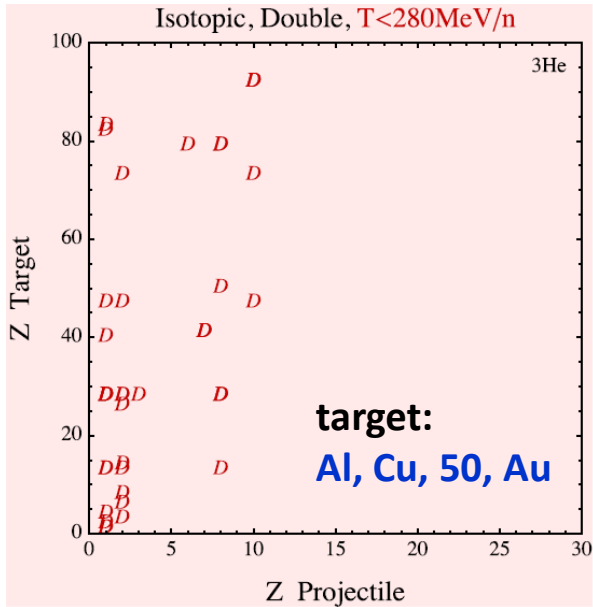
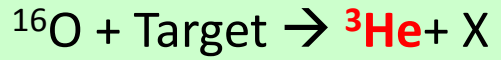
$$D^2\sigma(\text{charge})/dE d\Omega :$$

Double Differential elemental Cross Section: He production



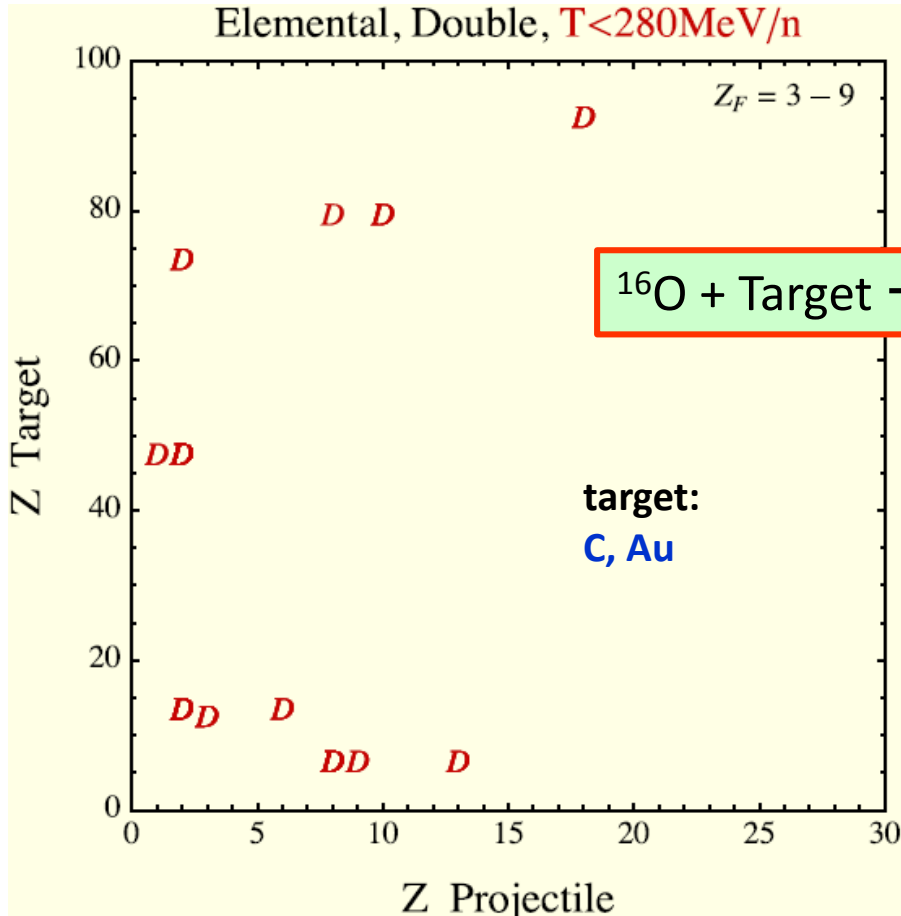
$$d^2\sigma/dE d\Omega :$$

Double Differential Isotopic Cross Section: He production



$D^2\sigma(\text{charge})/dE d\Omega$:

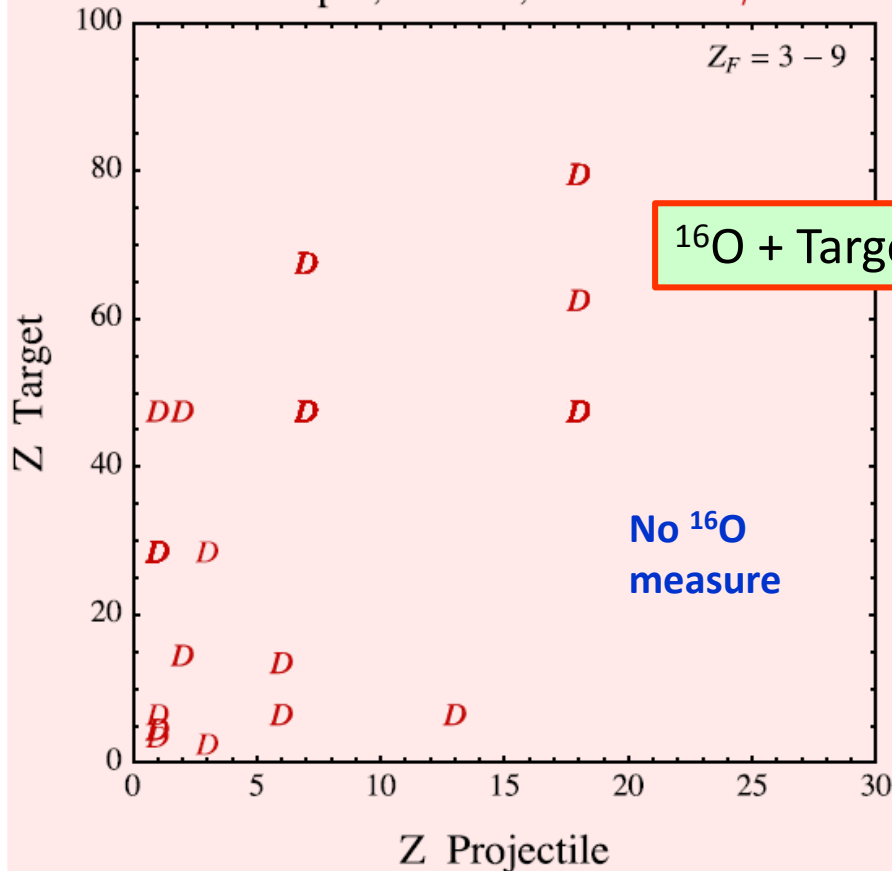
Double Differential elemental Cross Section: ($3 \leq Z \leq 9$) production



$$d^2\sigma/dE d\Omega :$$

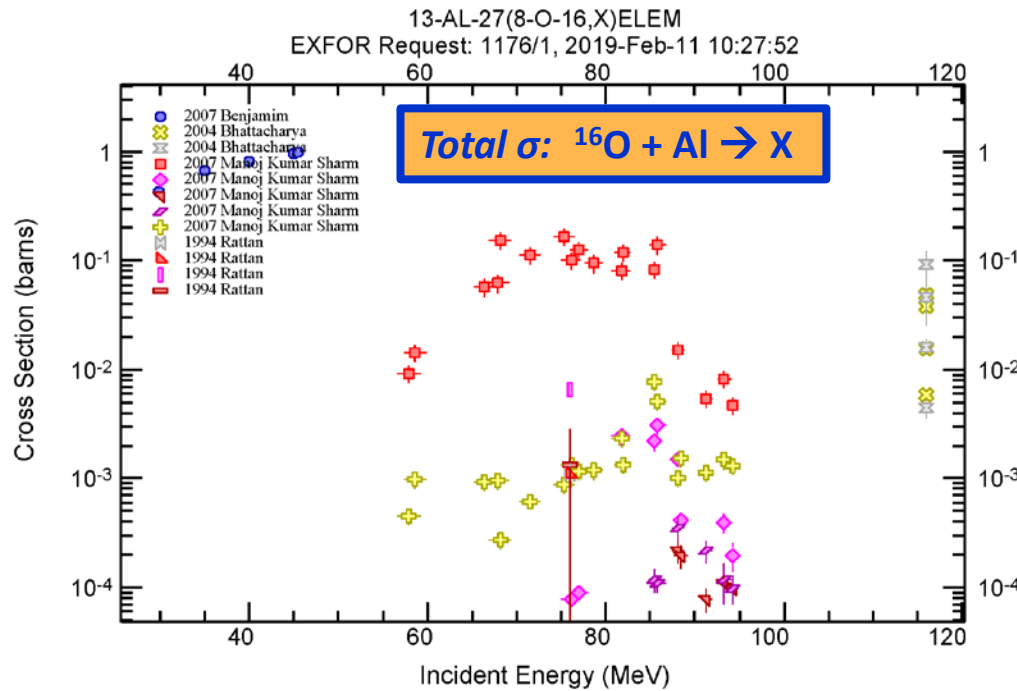
Double Differential Isotopic Cross Section: ($3 \leq Z \leq 9$) production

Isotopic, Double, $T < 280 \text{ MeV/n}$



Total σ and $d\sigma/d\Omega$ on Aluminium: $^{16}\text{O} + \text{Al} \rightarrow X$ in [0-10] GeV

Energy is total (not per nucleon)



$d\sigma/d\Omega$: $^{16}\text{O} + \text{Al} \rightarrow X$

13-AL-27(8-O-16,INL)13-AL-27,PAR,DA Ei=2.8e+8

No measurements in our energy range

Also measurements of $d^2\sigma/d\Omega dE$ at 88 MeV of ^{16}O

