Studying the Nuclear Pairing Force Through $^{18}O(^{26}Mg,^{28}Mg)^{16}O$

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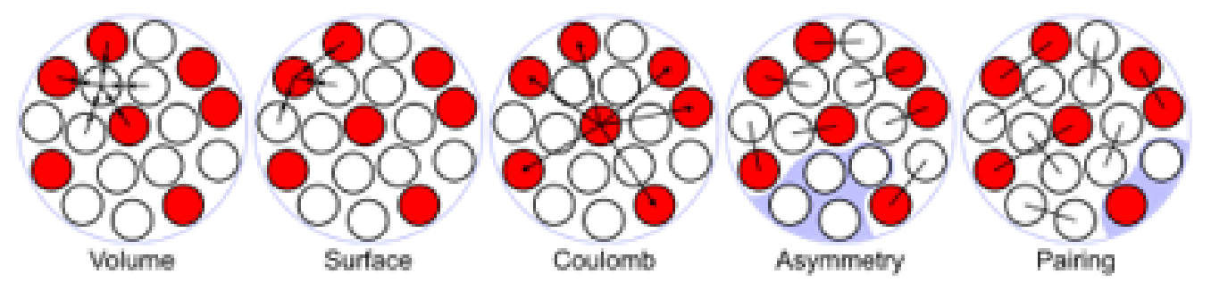
Abstract

Weizsaecker Formula

- Nuclear Binding energy
- Two strong force terms, one electrostatic, one asymmetry and one pairing term

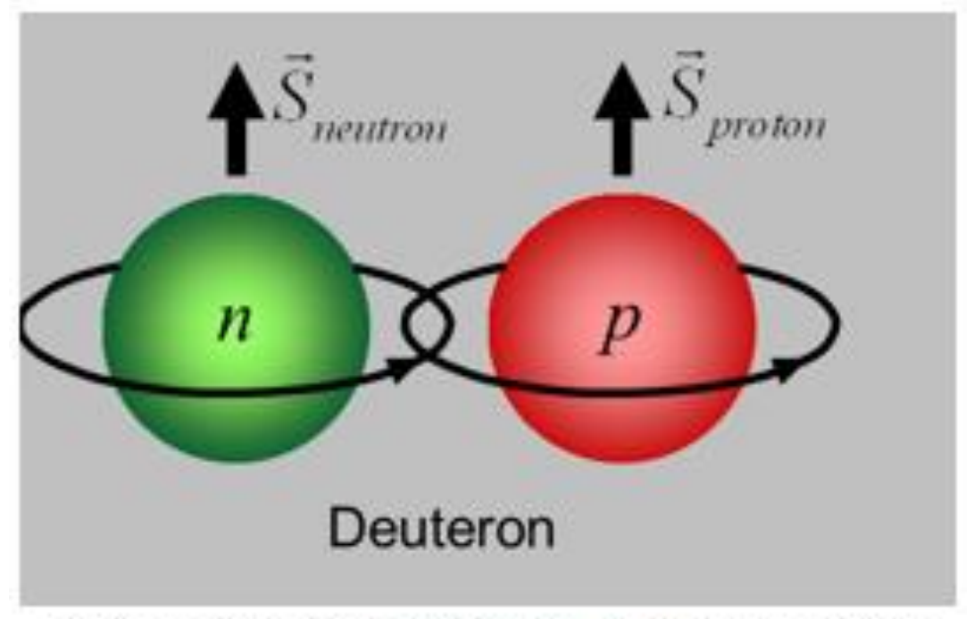
$$E_b(MeV) = a_V A - a_S A^{\frac{2}{3}} - a_C \frac{Z^2}{A^{\frac{1}{3}}} - a_A \frac{(A-2Z)^2}{A} \pm \delta(A,Z)$$

$$\delta(A,Z) = \begin{matrix} +\delta_0 \; for\; Z,N\; even \\ 0 \\ -\delta_0 \; for\; Z,N\; odd \end{matrix}$$



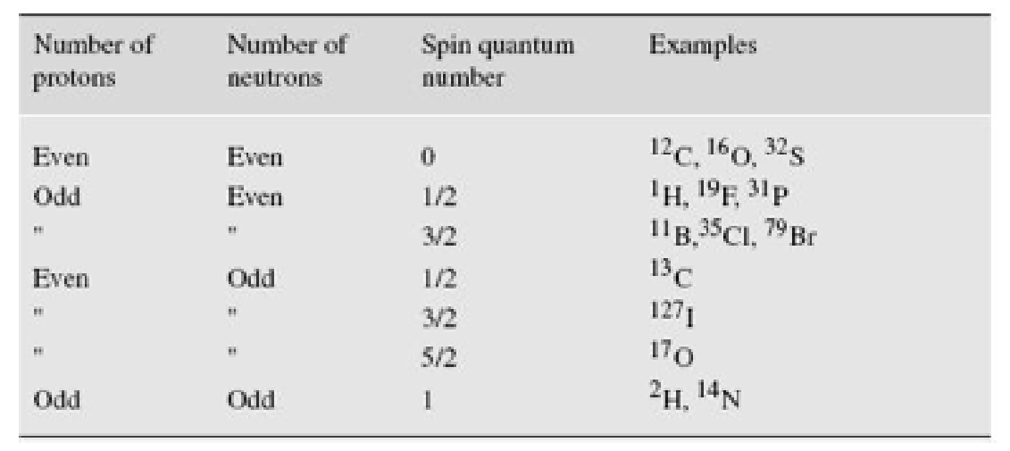
Semi-empiracal Mass Formula. Digital image. *Wikipedia*. N.p., n.d. Web. 22 July 2016

Paired Spin



Deuteron. Digital image. *Skyblue*. N.p., n.d. Web. 22 July 2016

- Half integral spins
- Usually spin pairing between proton-proton, neutron-neutron but also proton-neutron
- Asymmetry term based on Pauli so some neutrons must be in higher energy state
- Even-even number of protons and neutrons are favorable
- Same number of protons and neutrons have larger binding energy because they have paired spin



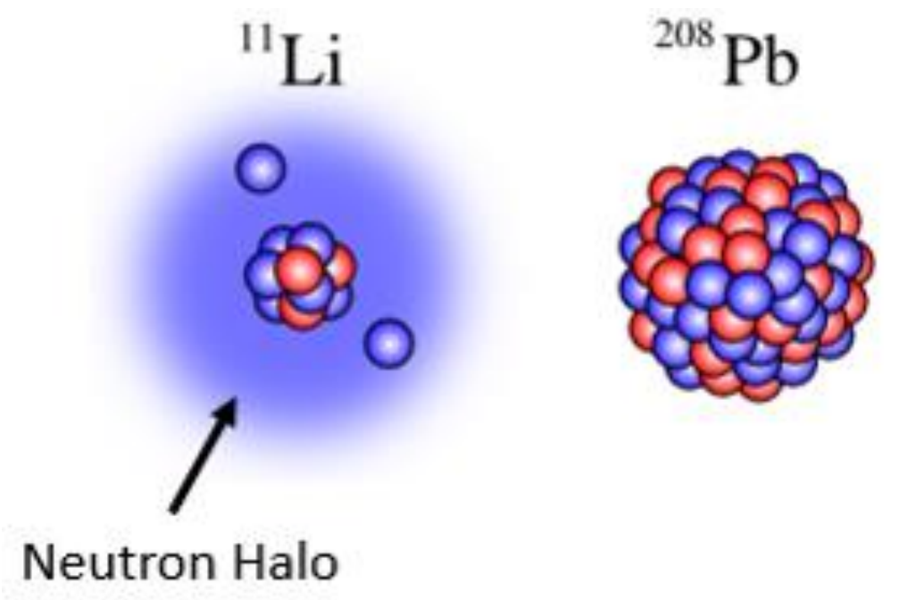
Number of protons	Number of neutrons	Spin quantum number	Examples
Even	Even	0	^{12}C, ^{16}O, ^{32}S
Odd	Even	1/2	^{1}H, ^{19}F, ^{31}P
"	"	3/2	^{11}B, ^{35}Cl, ^{79}Br
Even	Odd	1/2	^{13}C
"	"	3/2	^{127}I
"	"	5/2	^{17}O
Odd	Odd	1	^{2}H, ^{14}N

Nucleus Spin. Digital image. *Nucleonica*. N.p., n.d. Web. 22 July 2016.

Halo Neutrons

- Very weakly bound
- Predicted Li-11 size 2.74 fm, Actual Li-11 size ~ 7.29 fm
- Wave function has small overlap with protons in nucleus

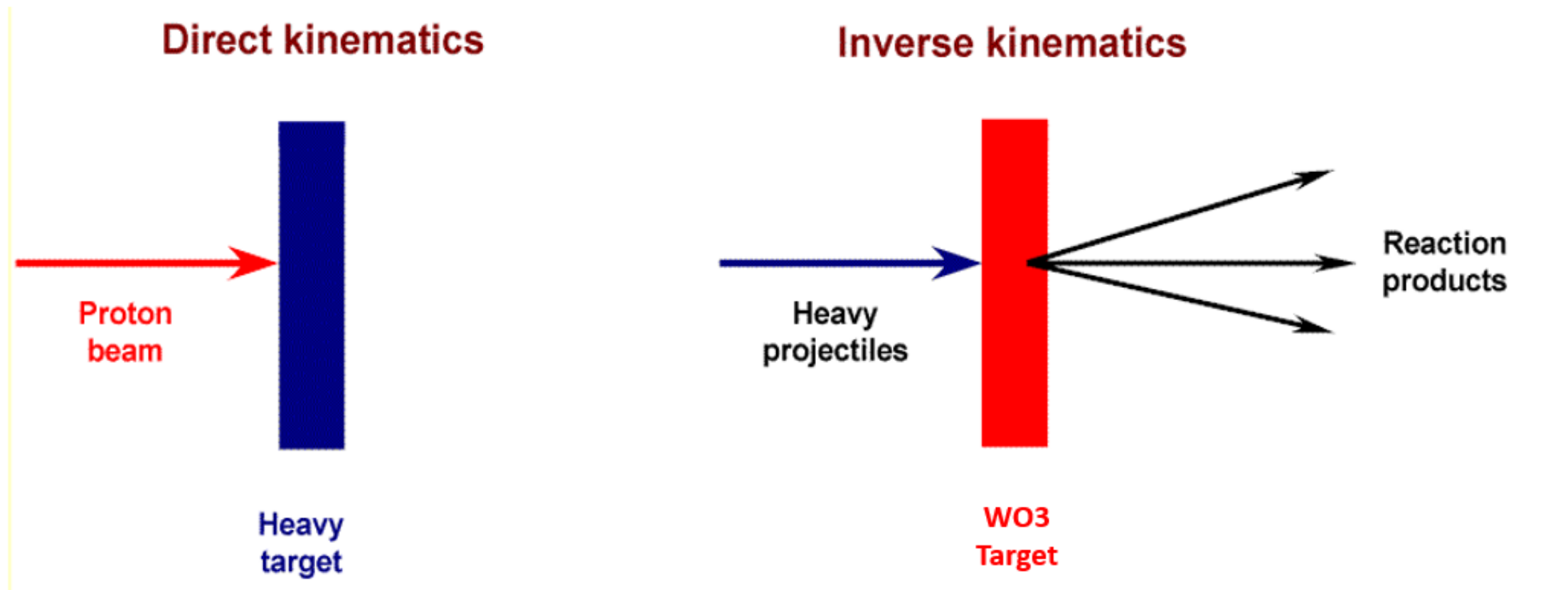
$R = r_0 A^{1/3}$
$R = nuclear\ size$
$r_0 = 1.23\ fm$
A = mass number



Lithium 11 Nucleus. Digital image. *Triumf*. N.p., n.d. Web. 22 July 2016.

Inverse Kinematics

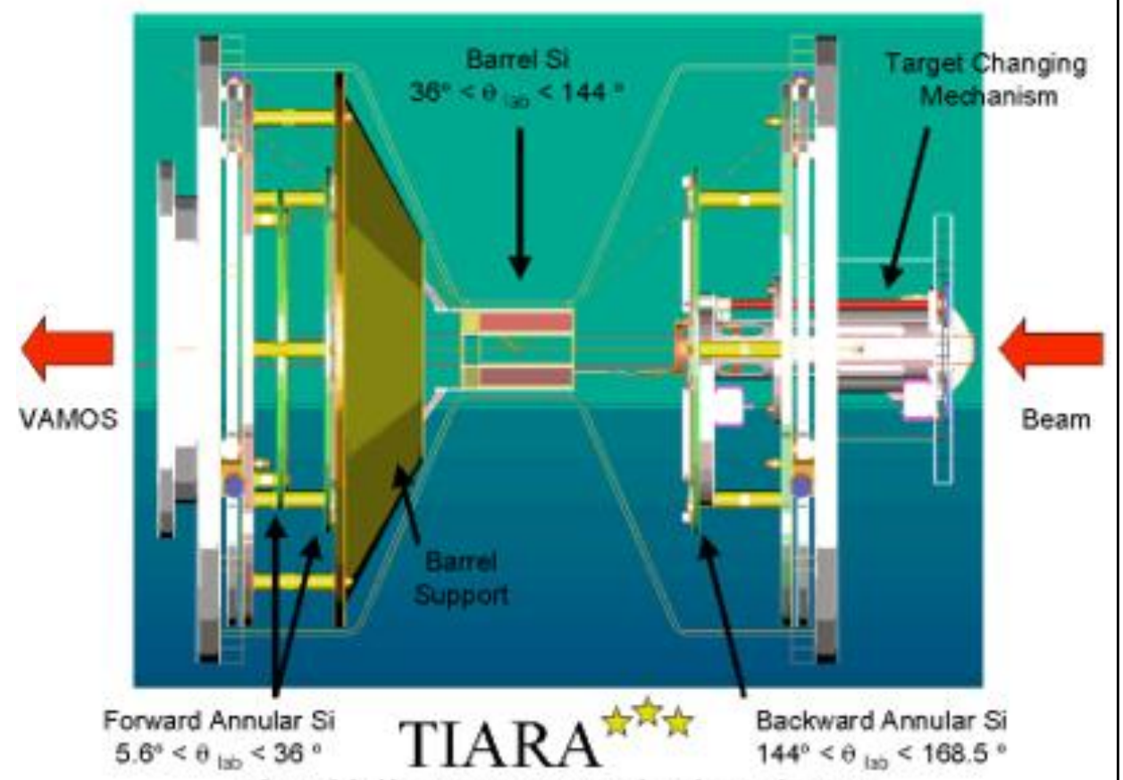
- Forward kinematics beam probes target
- Inverse target probes beam
- Can use rare isotope and radioactive beam that wouldn't be able to use with forward kinematics



Inverse Kinematics. Digital image. *Win.gsi.de*. N.p., n.d. Web. 27 July 2016

TIARA

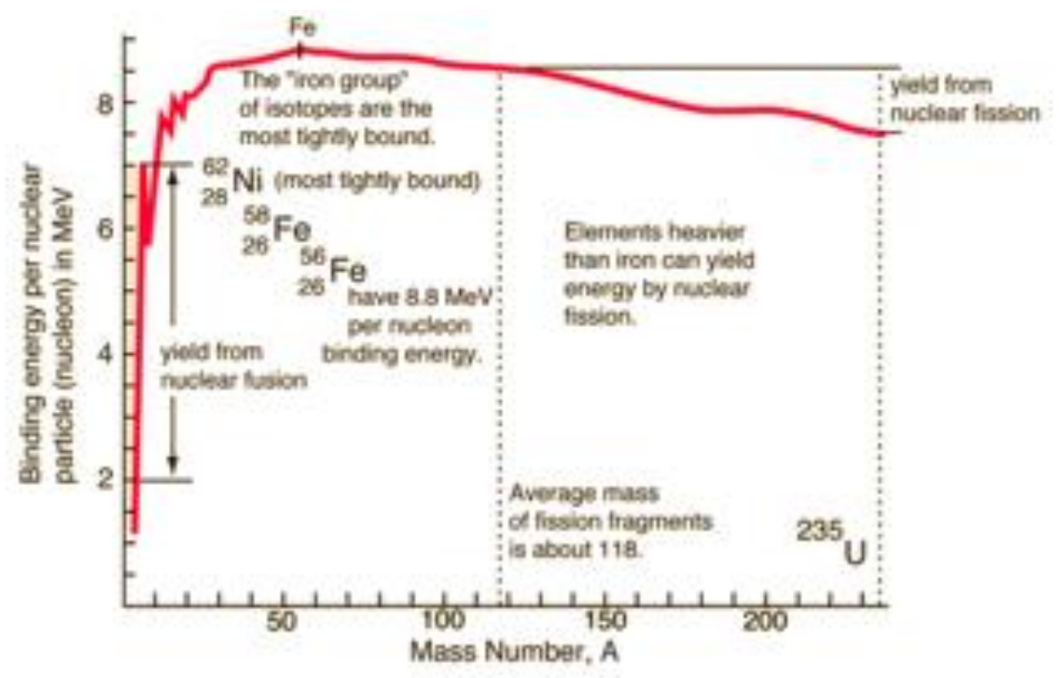
- Silicon detectors measure energy and angle of recoiling Oxygen
- MDM uses dipole magnet to measure angle and energy of heavy Magnesium
- Germanium detectors measure gamma ray energy



Tiara. Digital image. *Surrey*. N.p., n.d. Web. 22 July 2016.

My Project

- WO3 target .1 $^{mg}/_{cm^2}$
- Test viability of inverse kinematics
- Test by transferring two neutrons to unstable nucleus
- Higher cross section stronger pairing force
- O-16 is doubly magic



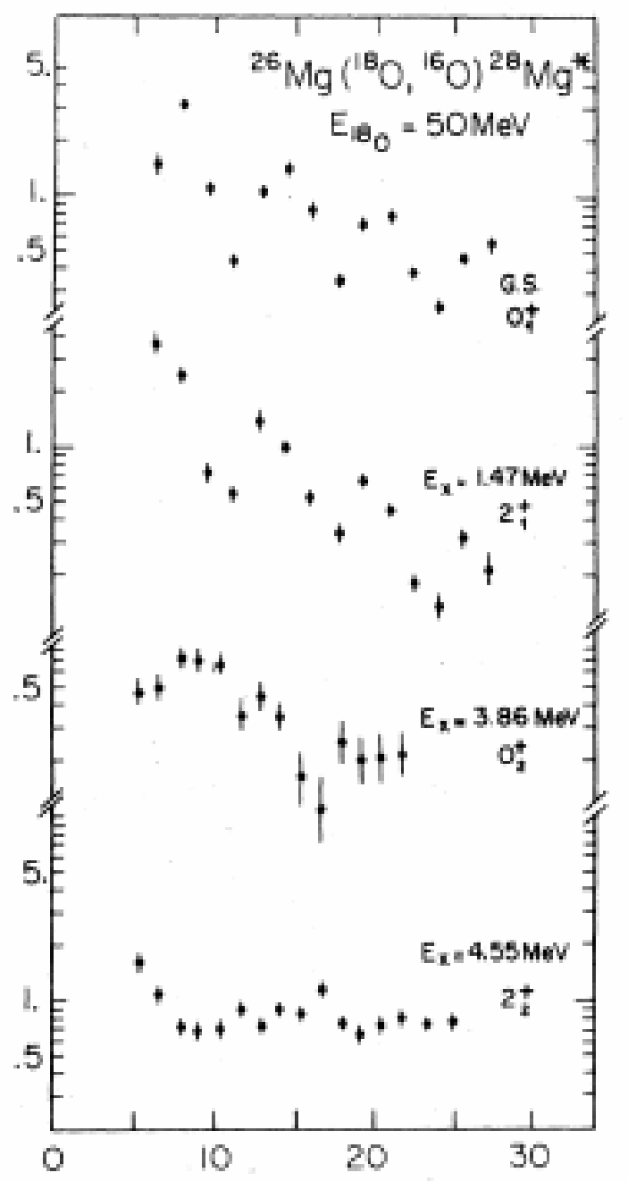
Binding Energy. Digital image. *Hyperphysics*. N.p., n.d. Web. 22 July 2016.

Methods

Finding Cross Section

- Gate for single excitation energy
- Divide out detector efficiency
- Integrate over solid angle
- Plot frequency of ThetaCM

Differential cross section vs center of mass angle

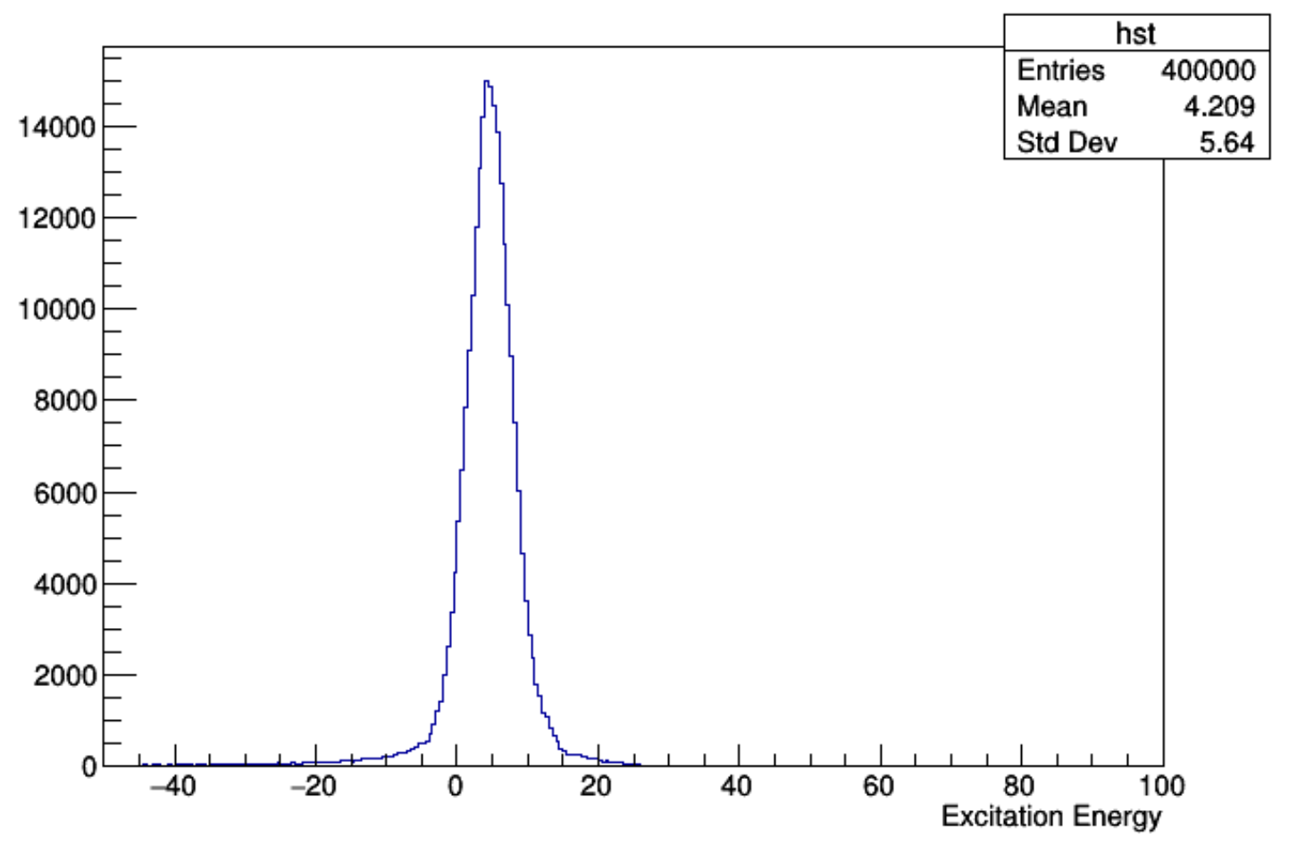


Angular Distribution for First Four Excitation Energies. Digital image. *Aps*. N.p., n.d. Web. 22 July 2016.

Simulations

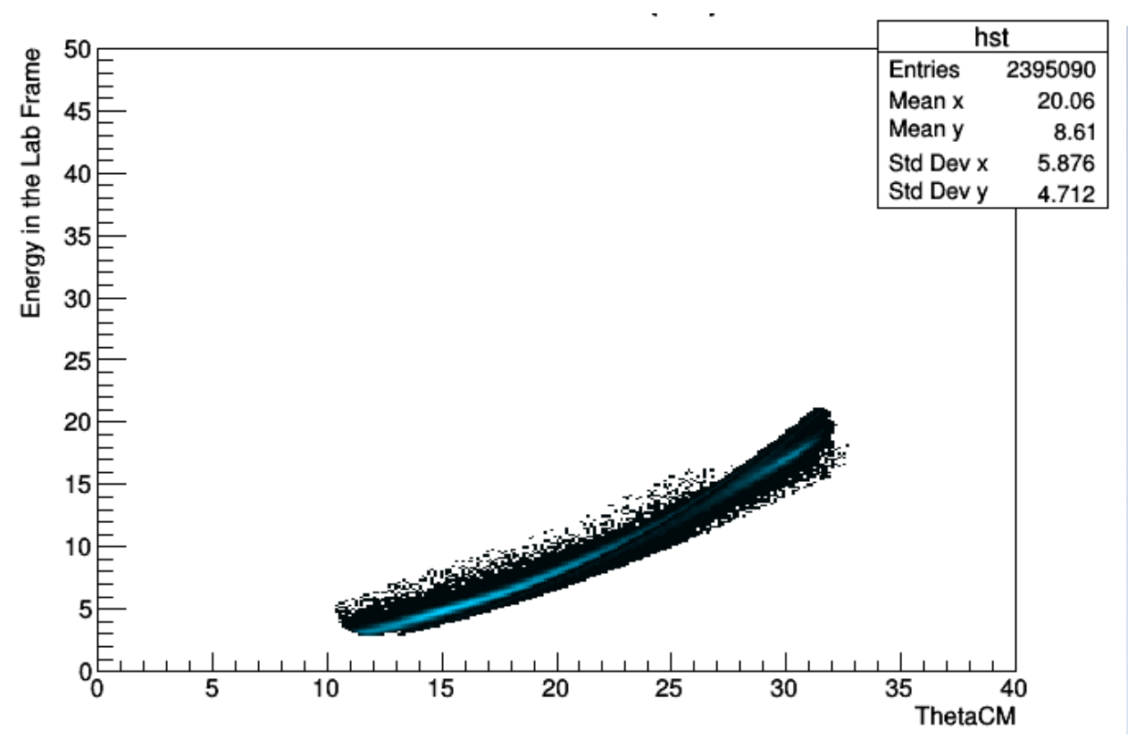
Excitation Energy

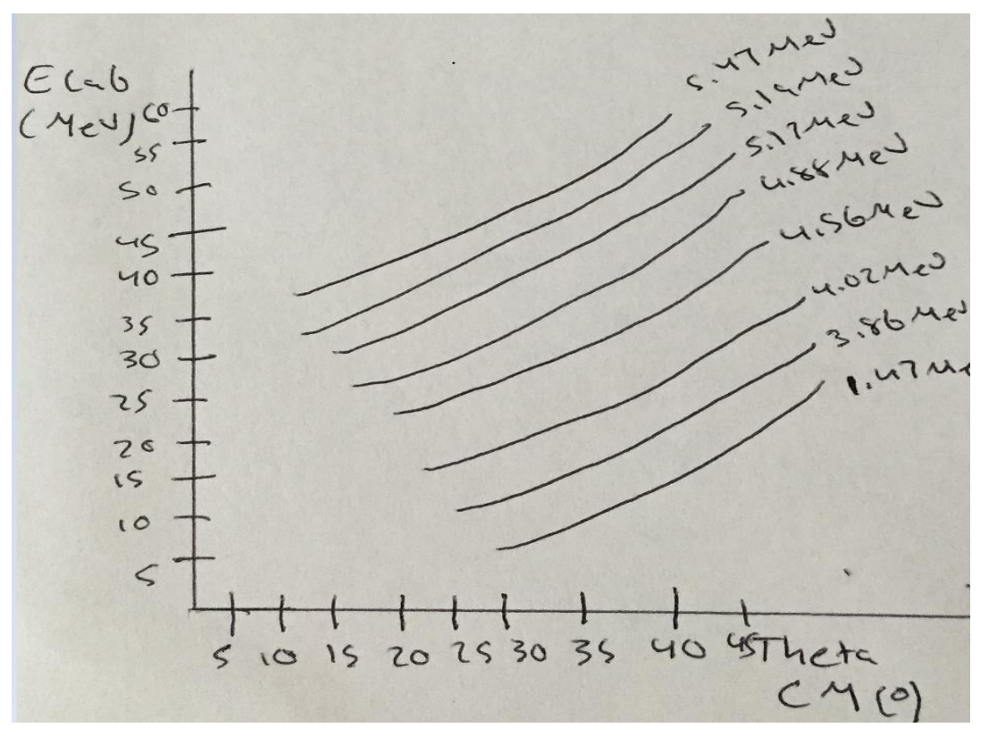
- Cannot pick out specific peaks
- Mean Excitation energy around 2 MeV



Elab vs ThetaCM curves

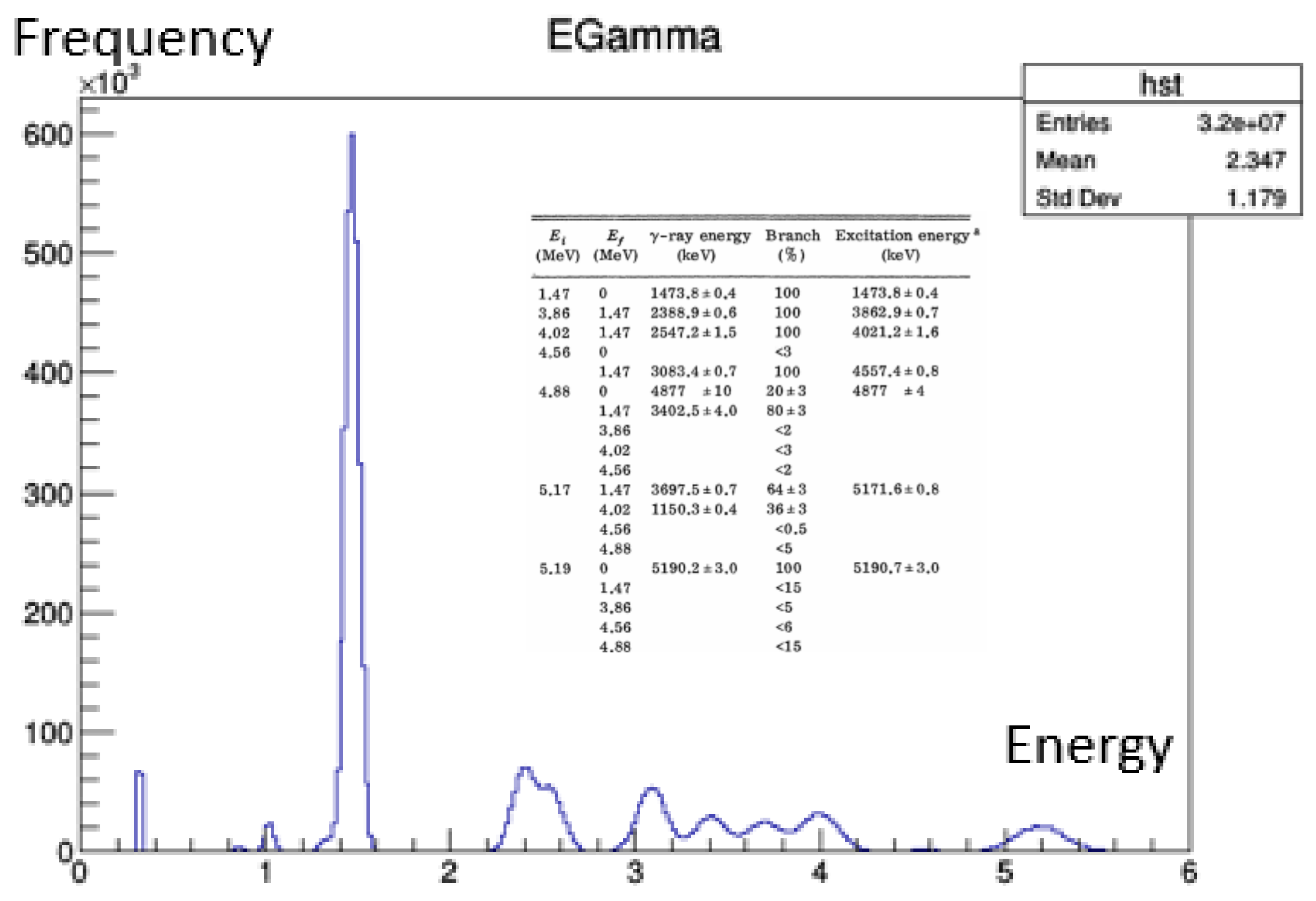
- Run Simulations of $^{18}O(^{26}Mg,^{28}Mg)^{16}O$
- To get cross section we analyze Elab vs ThetaCM curves
- Shape of angular distribution tells you the transferred orbital angular momentum.





Gamma Rays

- Reaction emits gamma rays because it is an excited state
- Each state has unique branching ratios which give us a gamma cascade



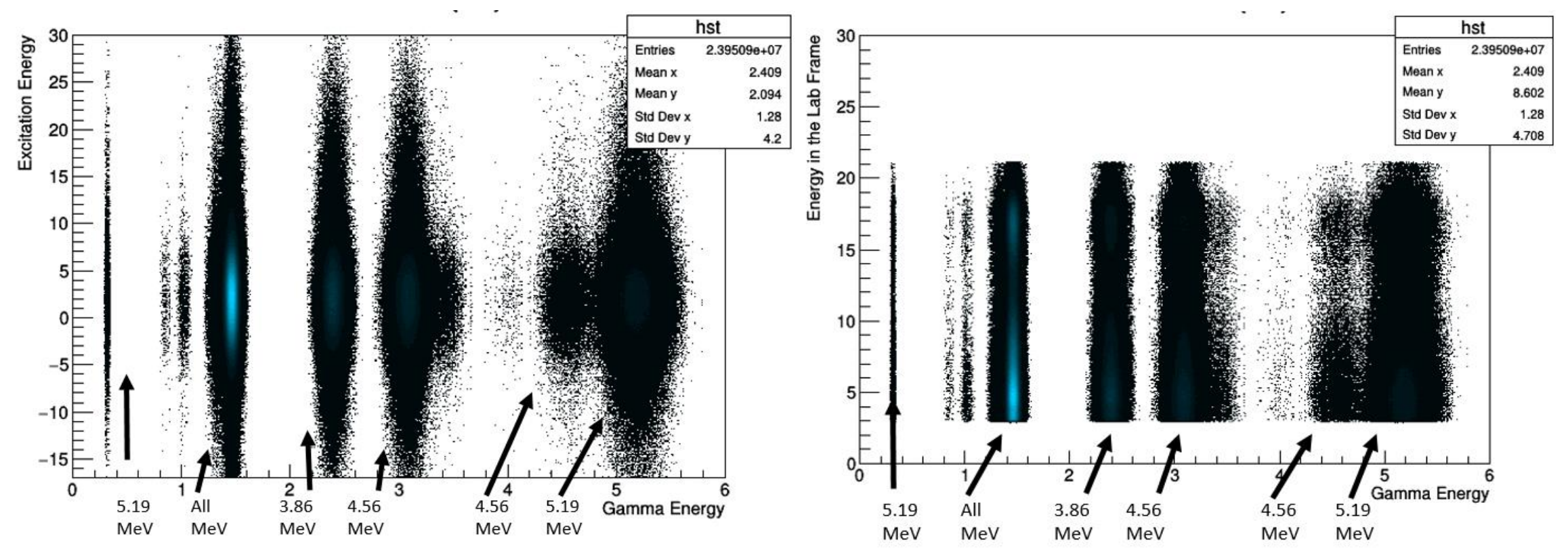
E_i (MeV)	E_f (MeV)	γ-ray energy (keV)	Branch (%)	Excitation energy^a (keV)
1.47	0	1473.8 ± 0.4	100	1473.8 ± 0.4
3.86	1.47	2388.9 ± 0.6	100	3862.9 ± 0.7
4.02	1.47	2547.2 ± 1.5	100	4021.2 ± 1.6
4.56	0		<3	
	1.47	3083.4 ± 0.7	100	4557.4 ± 0.8
4.88	0	4877 ± 10	20 ± 3	4877 ± 4
	1.47	3402.5 ± 4.0	80 ± 3	
	3.86		<2	
	4.02		<3	
	4.56		<2	
5.17	1.47	3697.5 ± 0.7	64 ± 3	5171.6 ± 0.8
	4.02	1150.3 ± 0.4	36 ± 3	
	4.56		<0.5	
	4.88		<5	
5.19	0	5190.2 ± 3.0	100	5190.7 ± 3.0
	1.47		<15	
	3.86		<5	
	4.56		<6	
	4.88		<15	

Fisher, T. R et. al. (1973). Gamma-Ray Spectroscopy of Low-Lying Levels in Mg 28.*Phys. Rev. C Physical Review C, 7*(5), 1878-1885. doi:10.1103/physrevc.7.1878

Simulation and Results

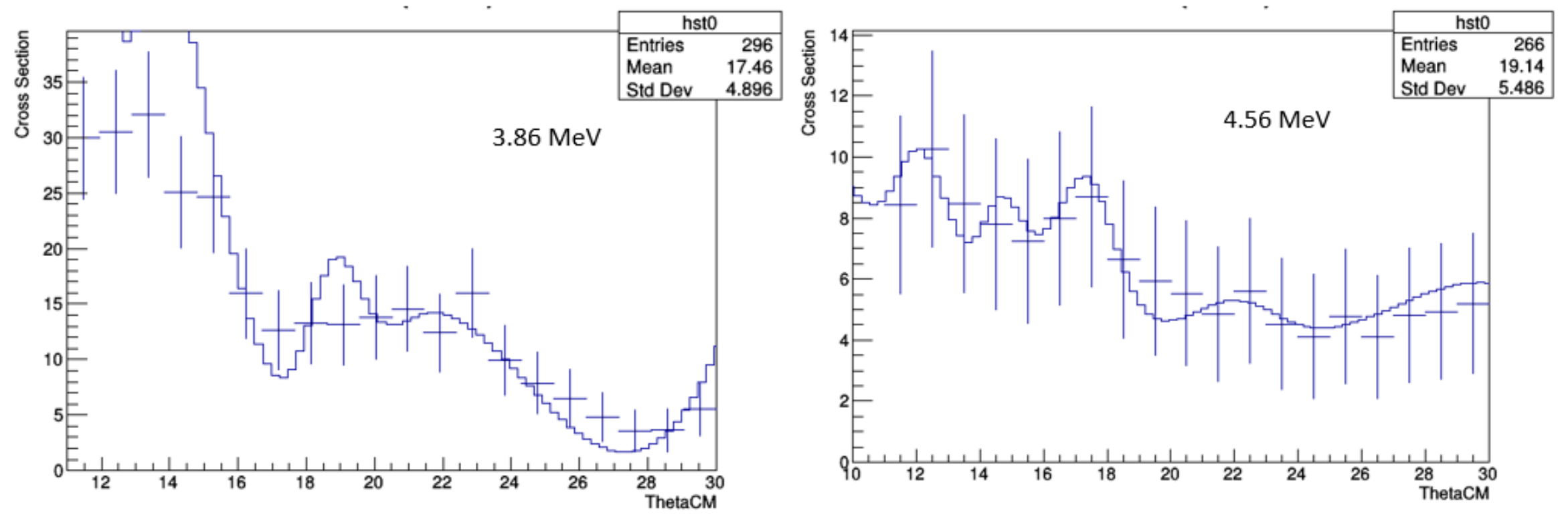
Elab and Ex vs EGamma

- Individual Excitation energies
- Different excitation energies emit different Gamma rays
- Pick out gamma rays specific to an excitation energy
- Gate around those areas



Conclusions

- $^{18}O(^{26}Mg,^{28}Mg)^{16}O$ reaction can study nuclear pairing force
- Reaction suitable for inverse kinematics
- Low statistics and not having the ability to find 1.47 MeV state



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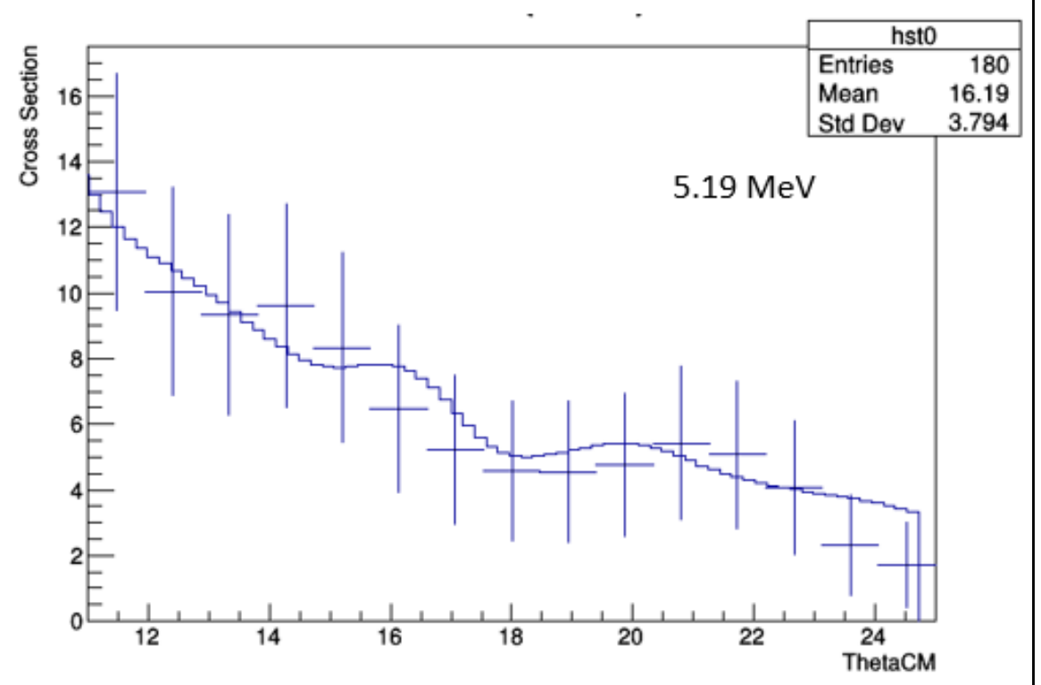

References

Fisher, T. R et. al. (1973). Gamma-Ray Spectroscopy of Low-Lying Levels in Mg 28.*Phys. Rev. C Physical Review C, 7*(5), 1878-1885. doi:10.1103/physrevc.7.1878

Margerin, V. et al. (2015). Inverse Kinematic Study of the Al 26 g (d , p) Al 27 Reaction and Implications for Destruction of Al 26 in Wolf-Rayet and Asymptotic Giant Branch Stars. *Phys. Rev. Lett. Physical Review Letters, 115*(6). doi:10.1103/physrevlett.115.062701

Pain, S. D et al. (2015). Constraint of the Astrophysical Al 26 g (p , γ) Si 27 Destruction Rate at Stellar Temperatures. *Phys. Rev. Lett. Physical Review Letters, 114*(21). doi:10.1103/physrevlett.114.212501

Labiche, M., et al. (2010). TIARA: A large solid angle silicon array for direct reaction studies with radioactive beams. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment,614*(3), 439-448. doi:10.1016/j.nima.2010.01.009

Bernas, M., et al. (1979). Mechanism of the Mg 26 (O 18 , O 16) Mg 28 reaction at E O 18 = 50 MeV and the energy levels of Mg 28. *Phys. Rev. C Physical Review C, 19*(6), 2246-2258. doi:10.1103/physrevc.19.2246