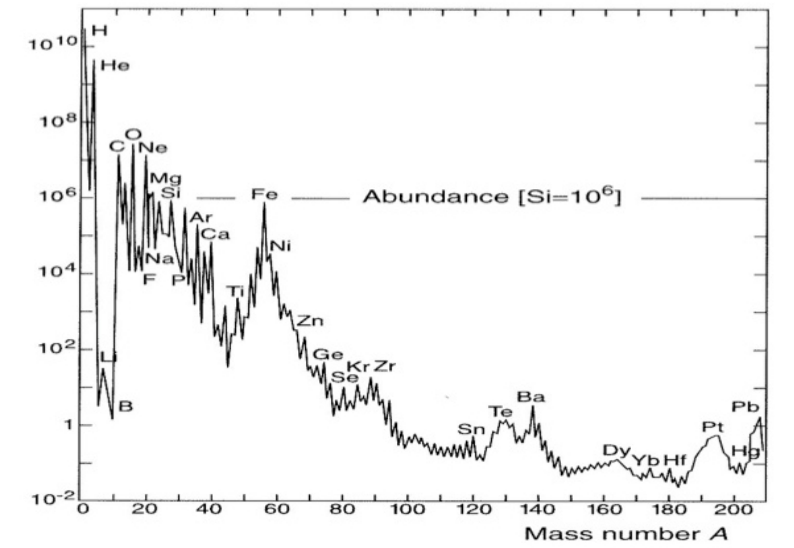
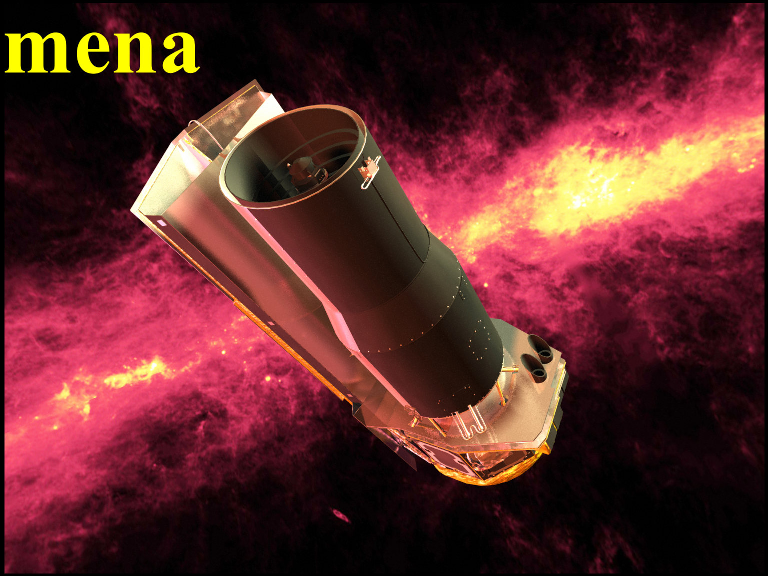
Experimental Studies of Explosive Stellar Phenomena





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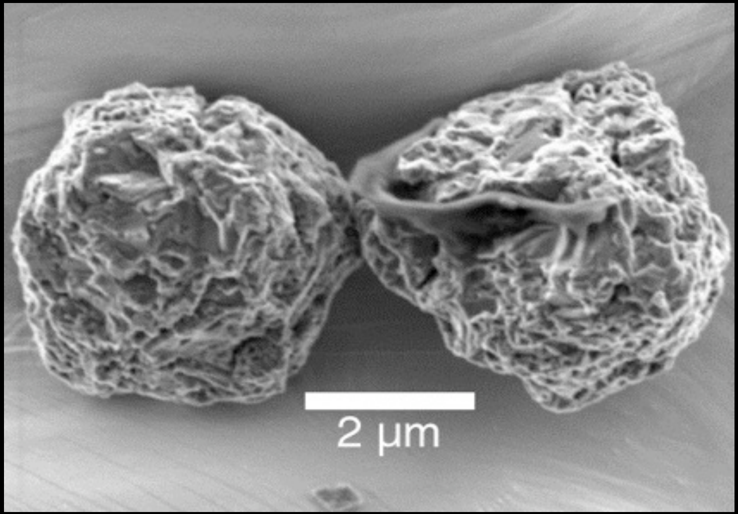


Explosive Nuclear Astrophysics

Overview

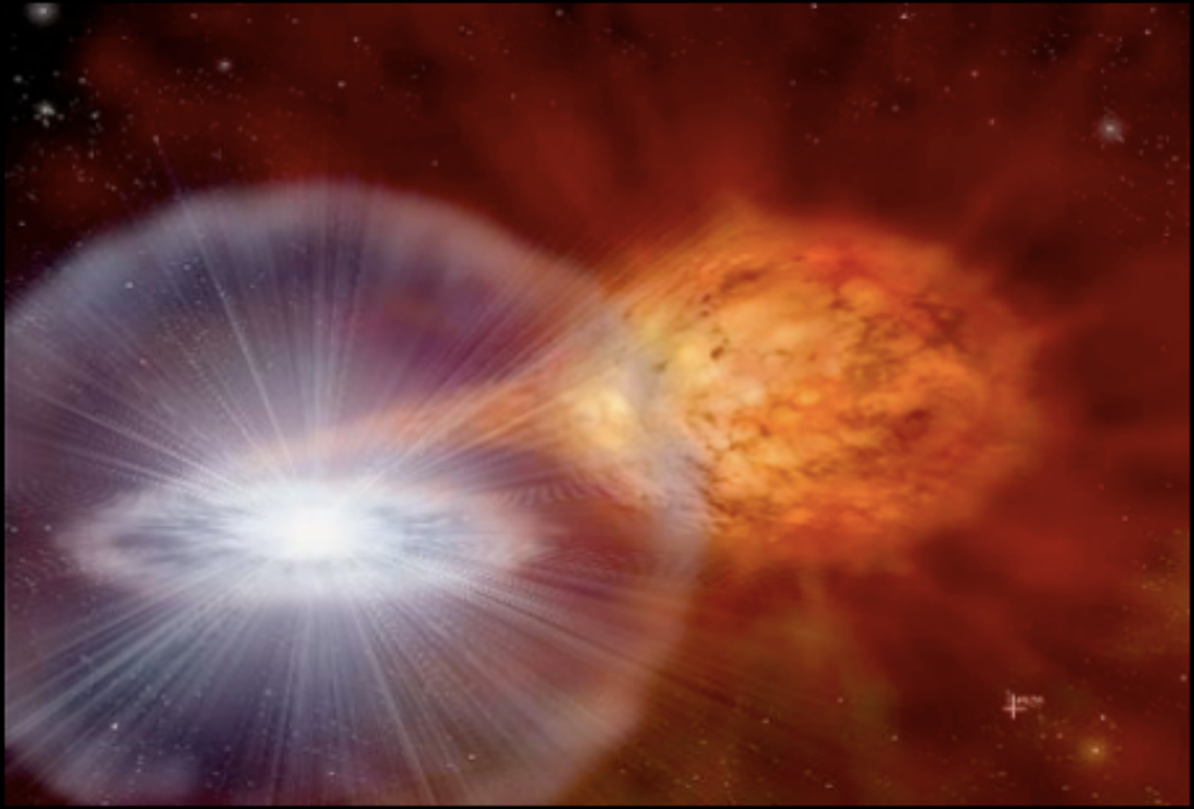
- **Lecture 1 – Background and Theory (Today)**

  - Explosive Astrophysical Environments
  - Experimental Quantities of Interest
  - Designing Experiments – gamma-ray spectroscopy and particle transfer
  - Some ‘textbook’ examples

- **Lecture 2 – State-of-the-Art and Future Experimental work (Thursday)**

  - Learning about Explosive Environments from Nuclear Structure
  - State-of-the-Art work
  - Future investigations with stable and radioactive beams

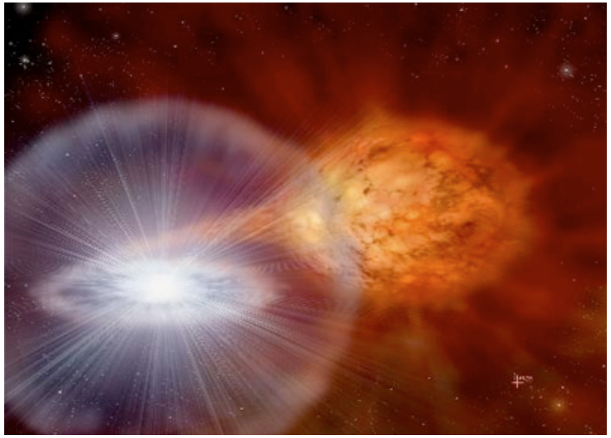
Explosive Stellar Phenomena – Classical Novae

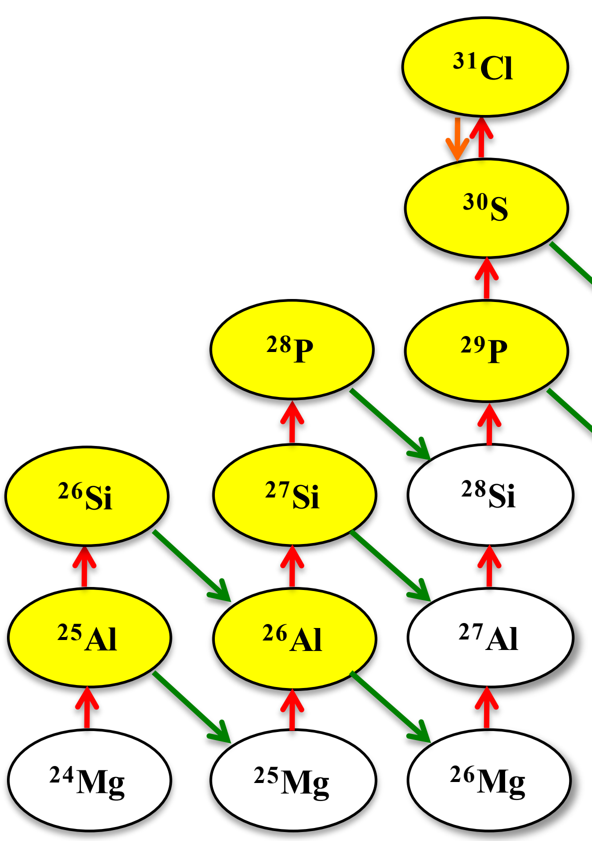
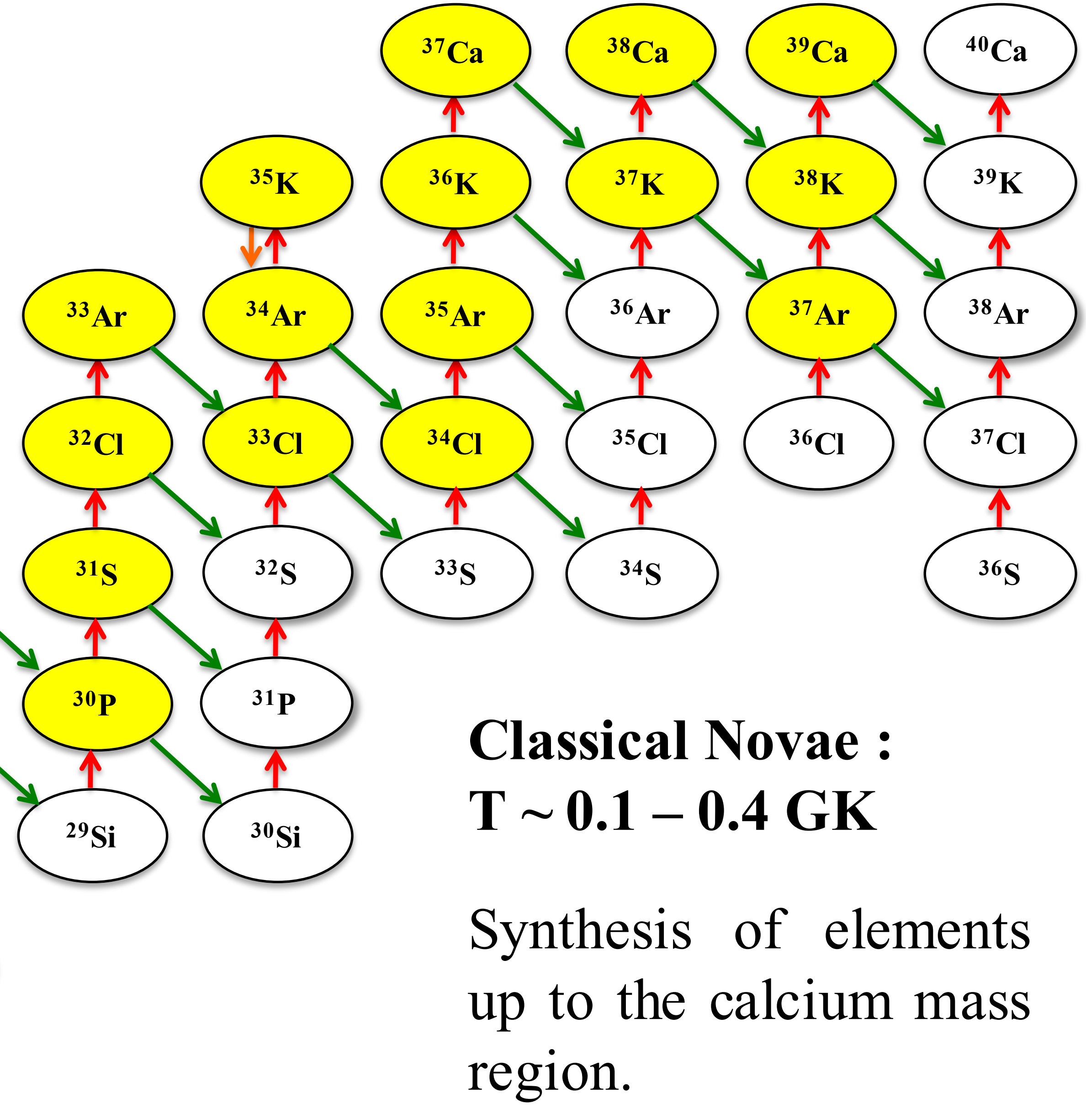


Among the most frequent and violent stellar explosions to occur in the Milky Way

Isaac Newton, Principia Mathematica (1687):
'from this fresh supply of new fuel those old stars, acquiring new splendour, may pass for new stars'

Explosive Stellar Phenomena – Classical Novae

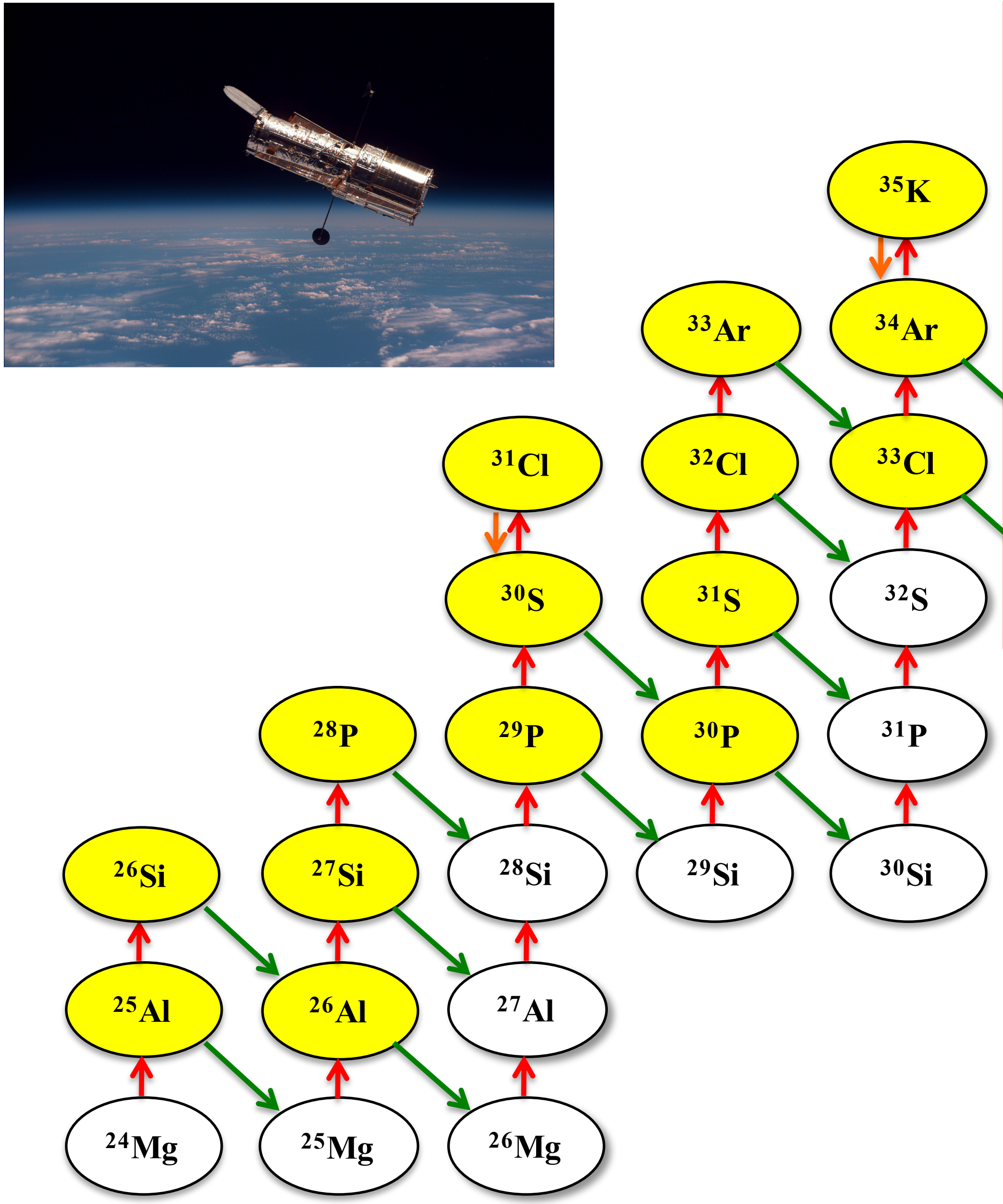


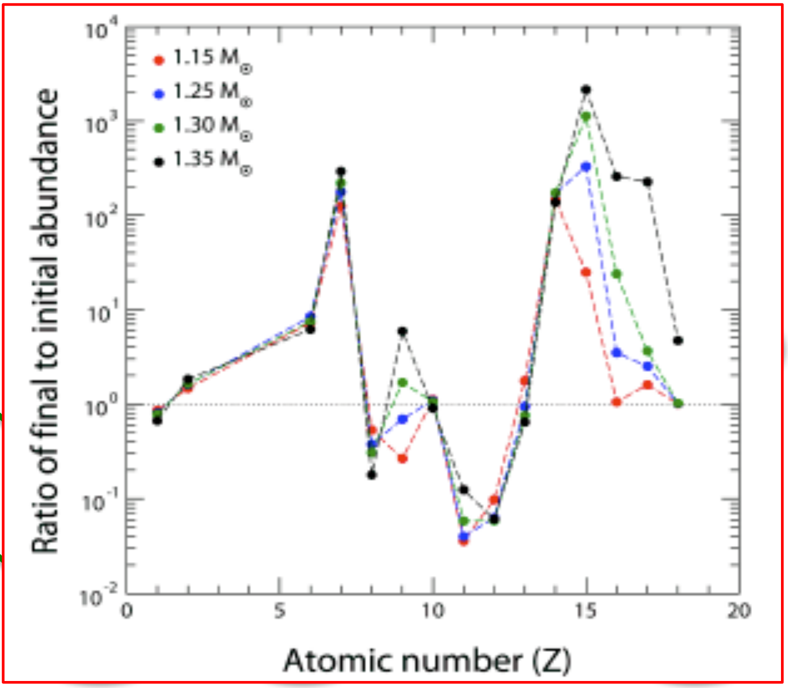


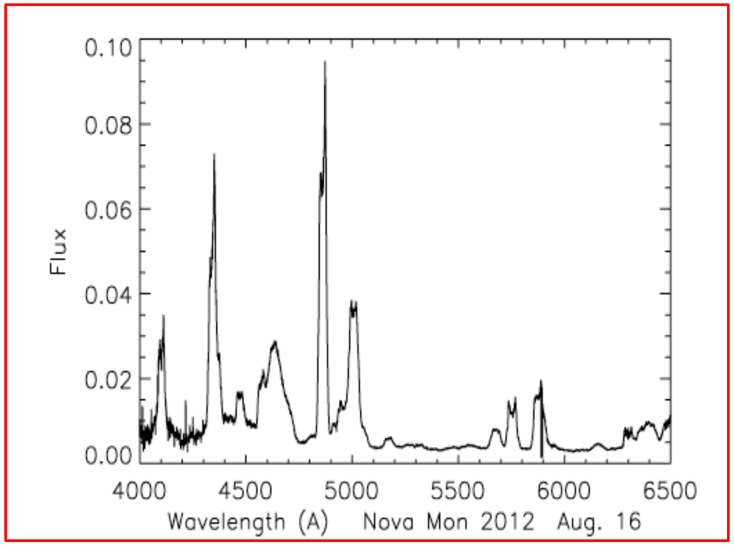
Classical Novae :
T ~ 0.1 – 0.4 GK

Synthesis of elements up to the calcium mass region.

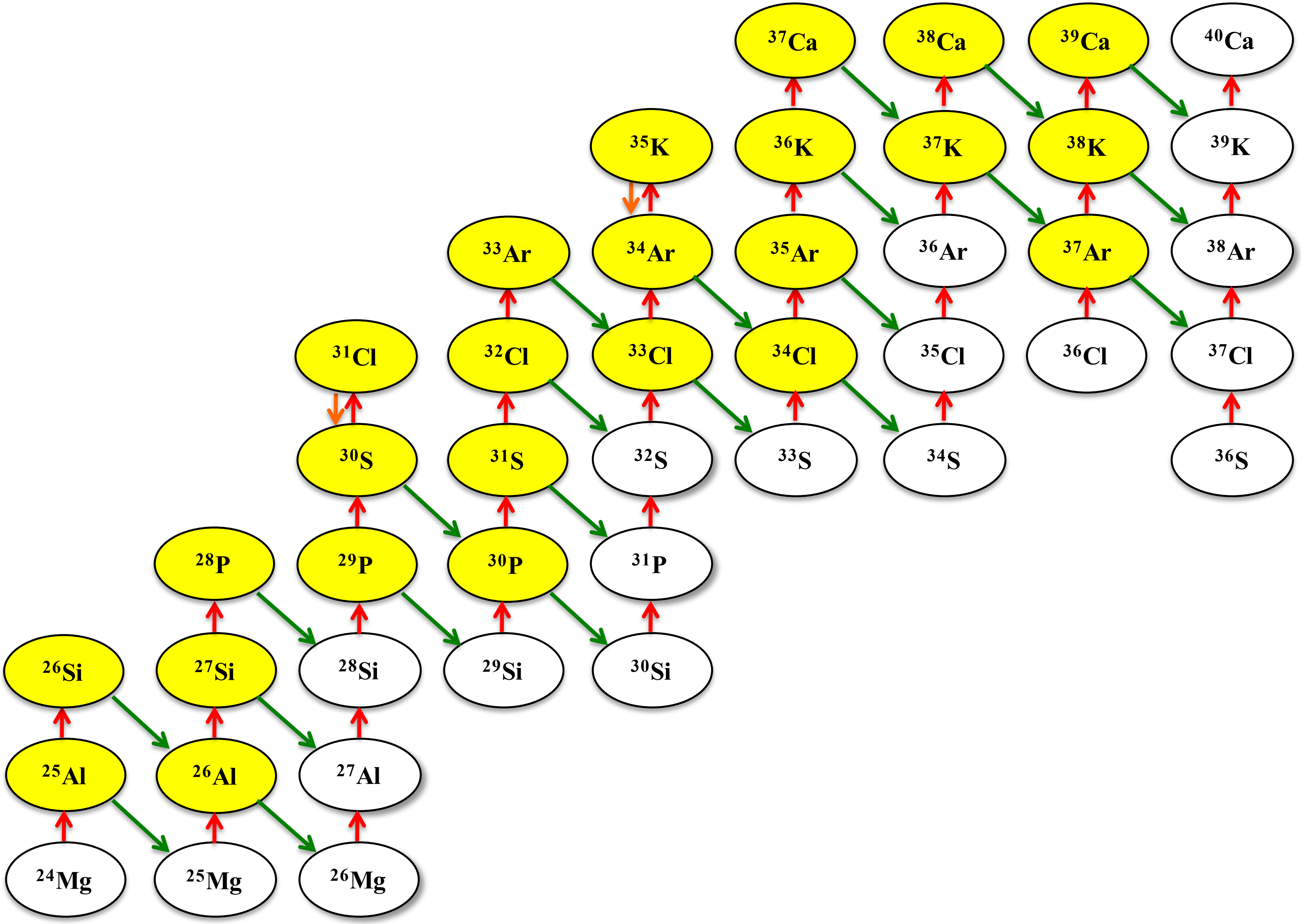
Explosive Stellar Phenomena – Classical Novae







Explosive Stellar Phenomena – Classical Novae



^{37}Ca ^{38}Ca ^{39}Ca ^{40}Ca

^{35}K ^{36}K ^{37}K ^{38}K ^{39}K

^{33}Ar ^{34}Ar ^{35}Ar ^{36}Ar ^{37}Ar ^{38}Ar

^{31}Cl ^{32}Cl ^{33}Cl ^{34}Cl ^{35}Cl ^{36}Cl ^{37}Cl

^{30}S ^{31}S ^{32}S ^{33}S ^{34}S ^{36}S

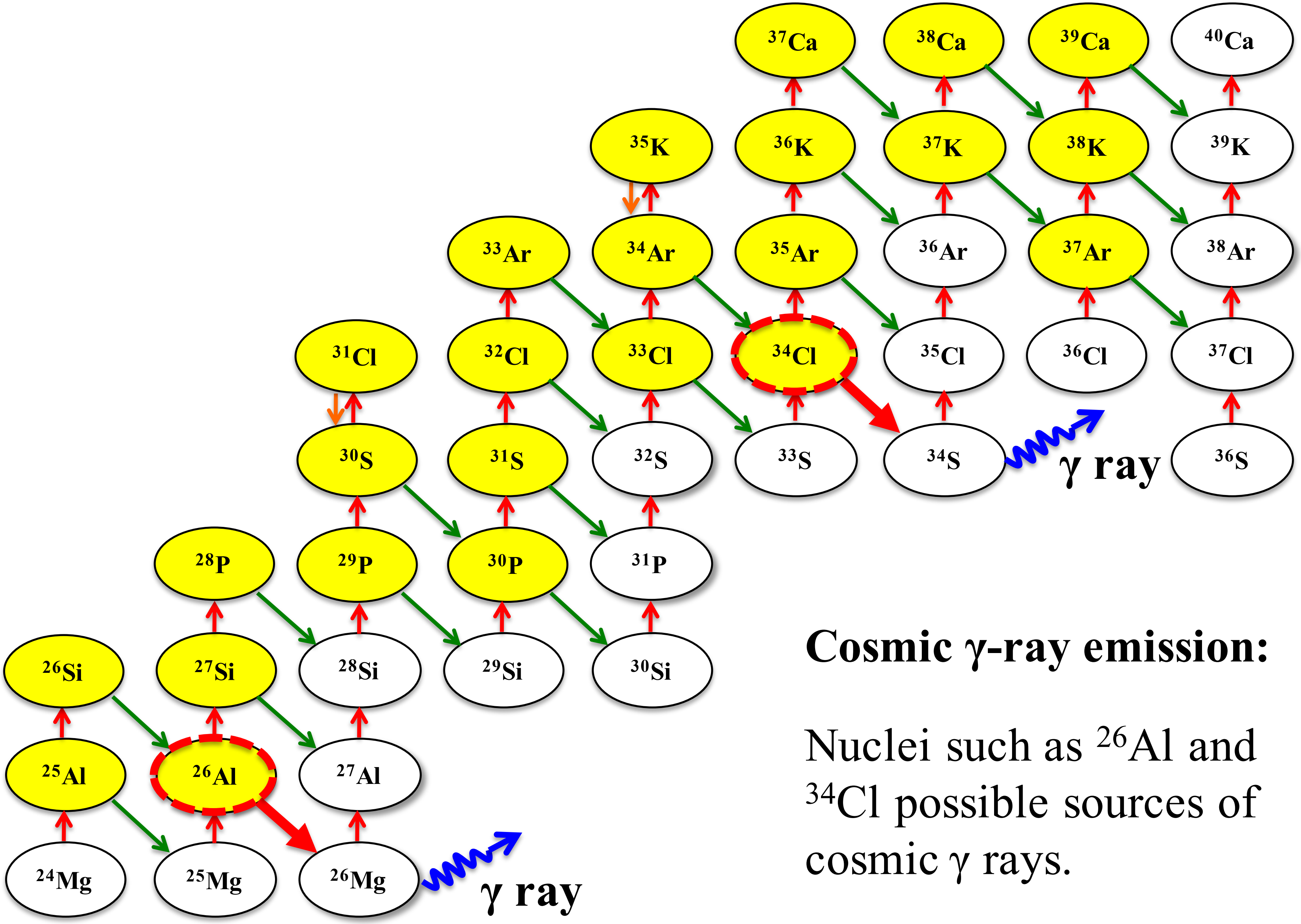
^{28}P ^{29}P ^{30}P ^{31}P

^{26}Si ^{27}Si ^{28}Si ^{29}Si ^{30}Si

^{25}Al ^{26}Al ^{27}Al

^{24}Mg ^{25}Mg ^{26}Mg

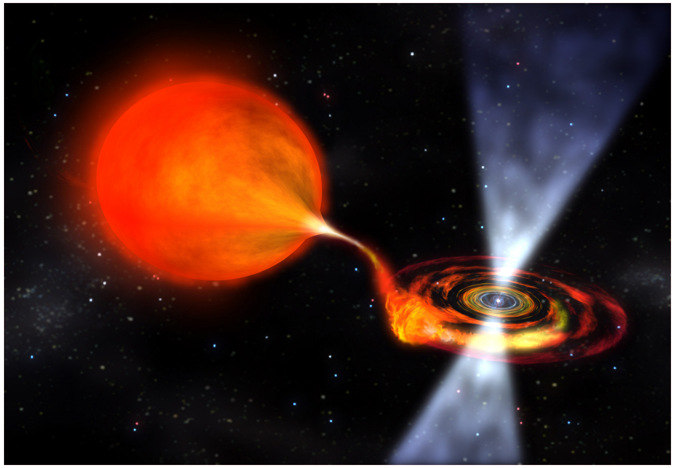
Explosive Stellar Phenomena – Classical Novae

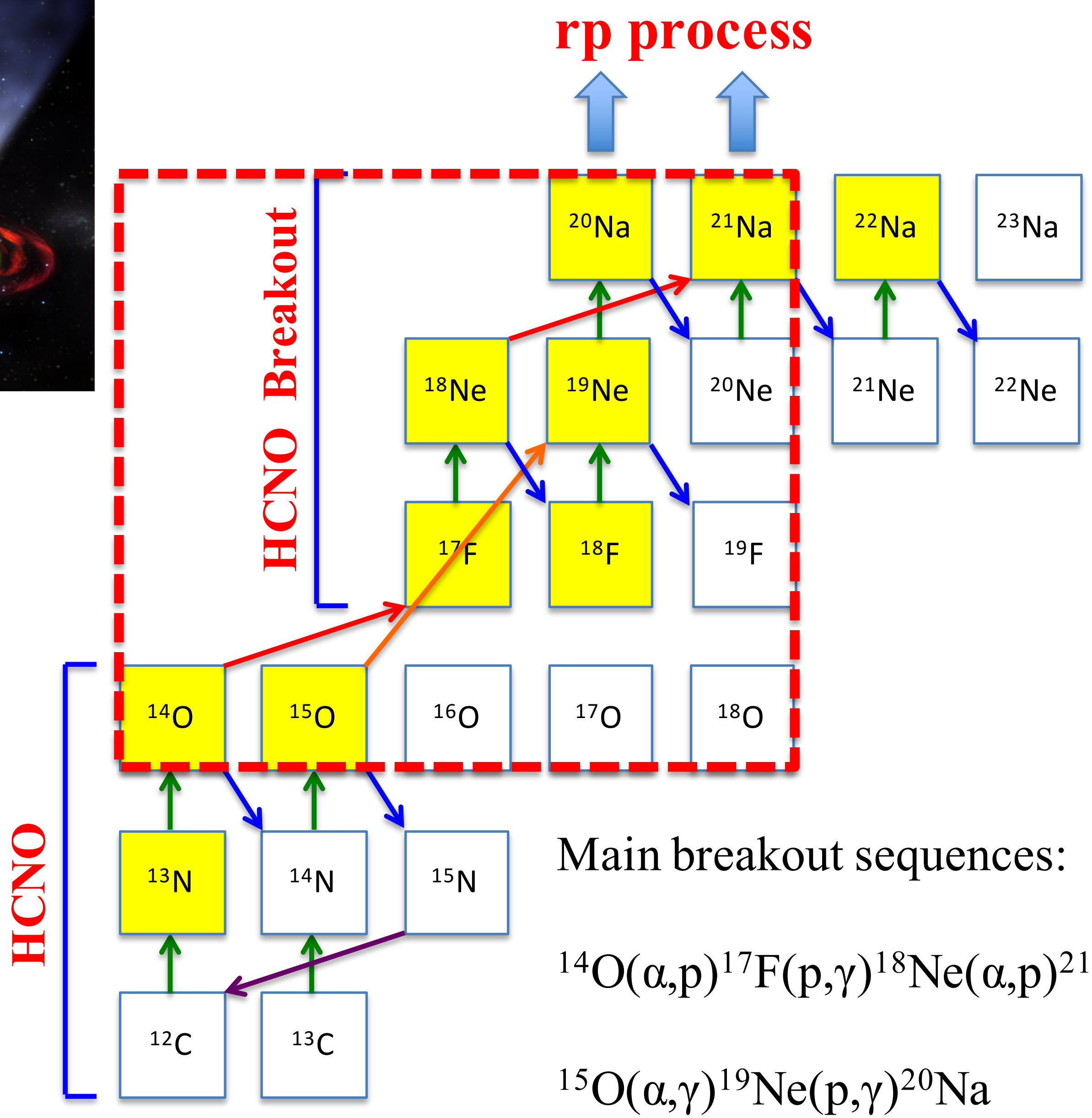


Cosmic γ-ray emission:

Nuclei such as ^{26}Al and ^{34}Cl possible sources of cosmic γ rays.

Explosive Stellar Phenomena – X-ray bursts





X-ray bursts:
T ~ 0.8 – 1.5 GK

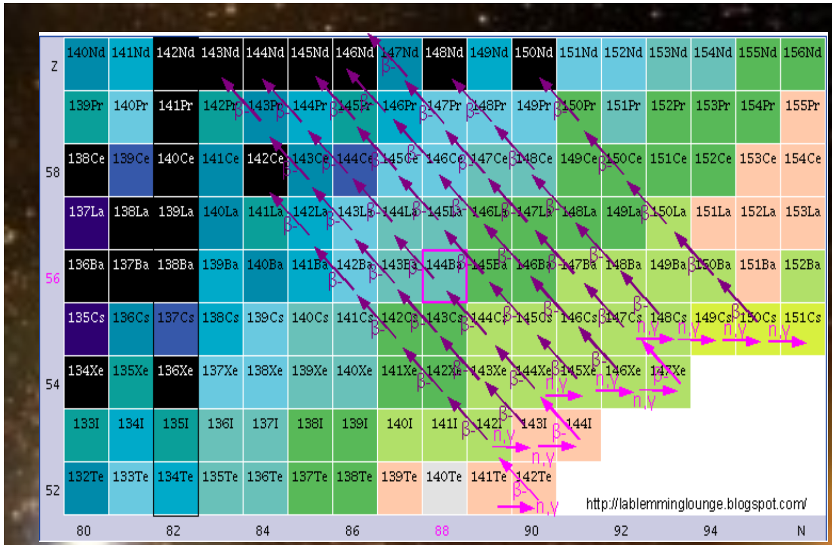
Synthesis of elements up to the tin - tellurium mass region.

Main breakout sequences:

^{14}O(α,p)^{17}F(p,γ)^{18}Ne(α,p)^{21}Na

^{15}O(α,γ)^{19}Ne(p,γ)^{20}Na

Explosive Stellar Phenomena - CCSN



Z	140Nd	141Nd	142Nd	143Nd	144Nd	145Nd	146Nd	147Nd	148Nd	149Nd	150Nd	151Nd	152Nd	153Nd	154Nd	155Nd	156Nd
	139Pr	140Pr	141Pr	142Pr	143Pr	144Pr	145Pr	146Pr	147Pr	148Pr	149Pr	150Pr	151Pr	152Pr	153Pr	154Pr	155Pr
58	138Ce	139Ce	140Ce	141Ce	142Ce	143Ce	144Ce	145Ce	146Ce	147Ce	148Ce	149Ce	150Ce	151Ce	152Ce	153Ce	154Ce
	137La	138La	139La	140La	141La	142La	143La	144La	145La	146La	147La	148La	149La	150La	151La	152La	153La
56	136Ba	137Ba	138Ba	139Ba	140Ba	141Ba	142Ba	143Ba	144Ba	145Ba	146Ba	147Ba	148Ba	149Ba	150Ba	151Ba	152Ba
	135Cs	136Cs	137Cs	138Cs	139Cs	140Cs	141Cs	142Cs	143Cs	144Cs	145Cs	146Cs	147Cs	148Cs	149Cs	150Cs	151Cs
54	134Xe	135Xe	136Xe	137Xe	138Xe	139Xe	140Xe	141Xe	142Xe	143Xe	144Xe	145Xe	146Xe	147Xe			
	133I	134I	135I	136I	137I	138I	139I	140I	141I	142I	143I	144I					
52	132Te	133Te	134Te	135Te	136Te	137Te	138Te	139Te	140Te	141Te	142Te						
	80		82		84		86		88		90		92		94		N

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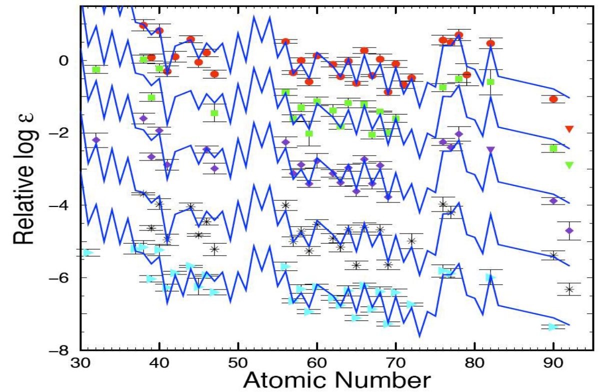

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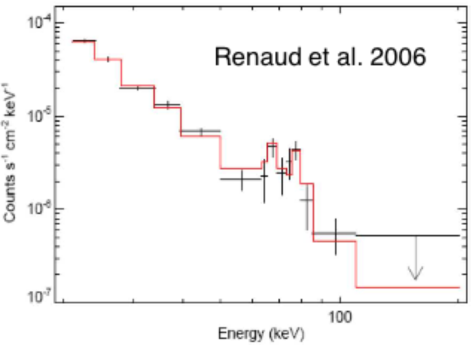
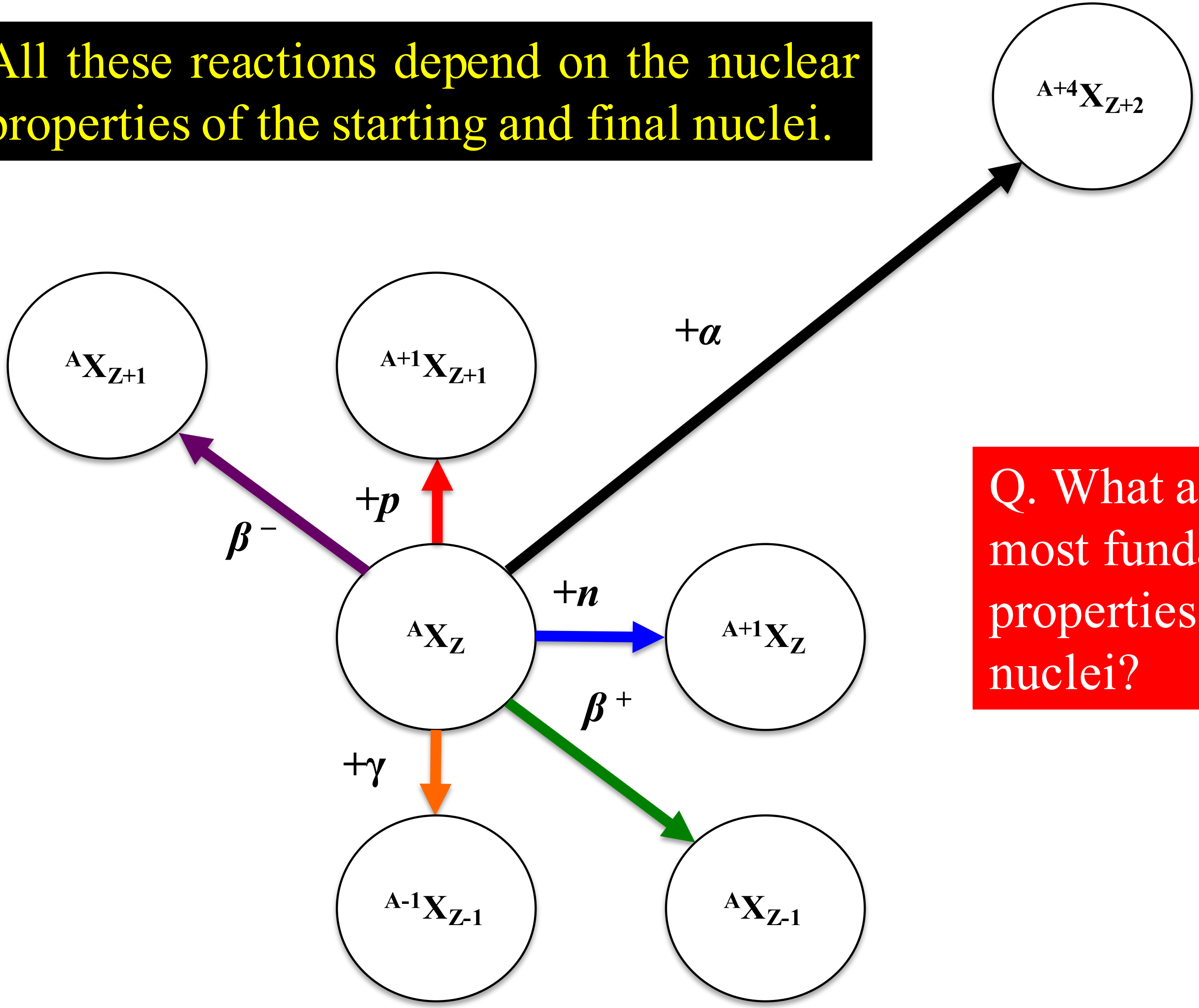


Type – II Supernovae:
T > 3 GK

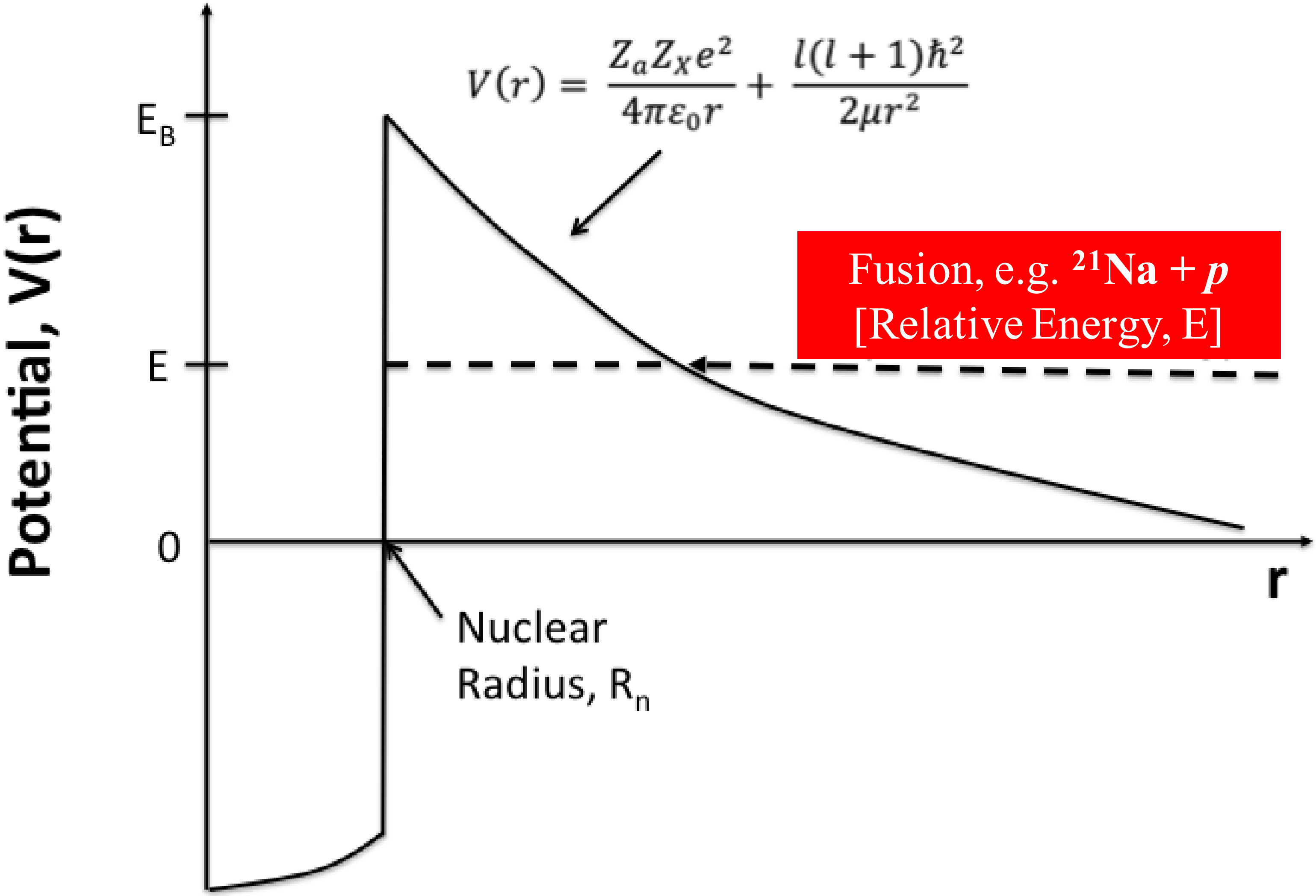
Nuclear Processes in Explosive Environments

All these reactions depend on the nuclear properties of the starting and final nuclei.



Q. What are the most fundamental properties of nuclei?

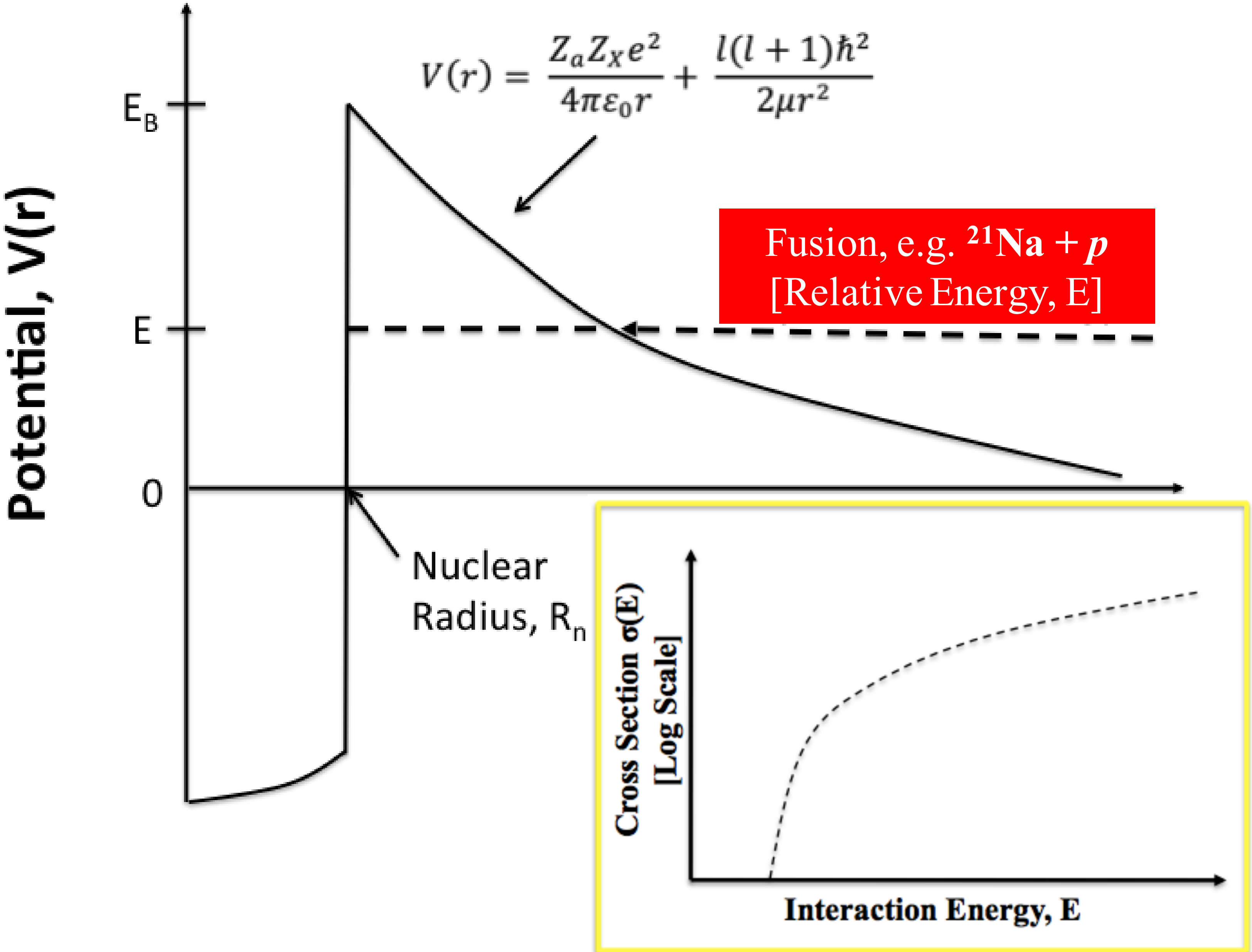
Nuclear Processes in Explosive Environments



$$V(r) = \frac{Z_a Z_X e^2}{4\pi\varepsilon_0 r} + \frac{l(l+1)\hbar^2}{2\mu r^2}$$

Fusion, e.g. $^{21}\mathbf{Na} + \boldsymbol{p}$
[Relative Energy, E]

Nuclear Processes in Explosive Environments



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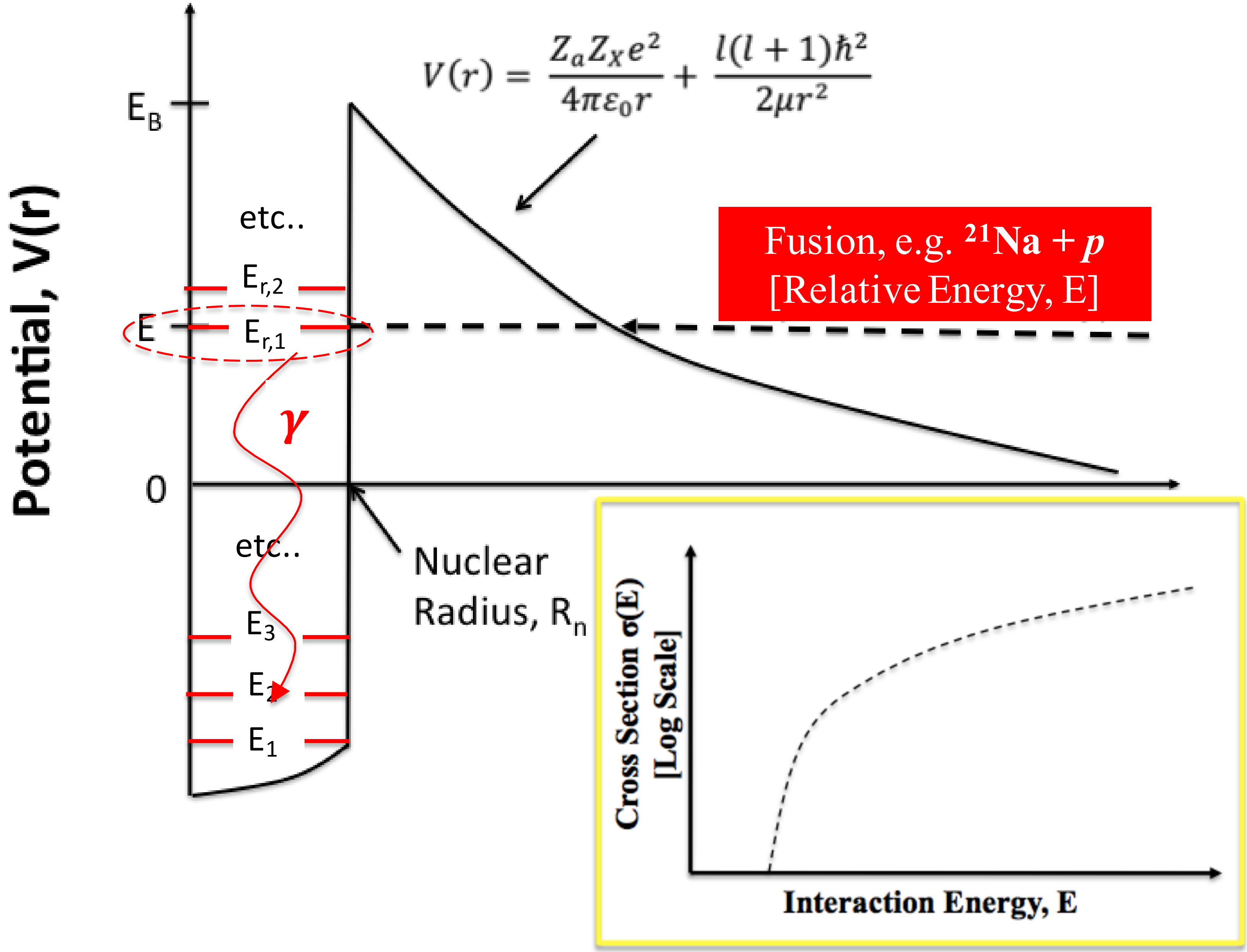
Nuclear Processes in Explosive Environments



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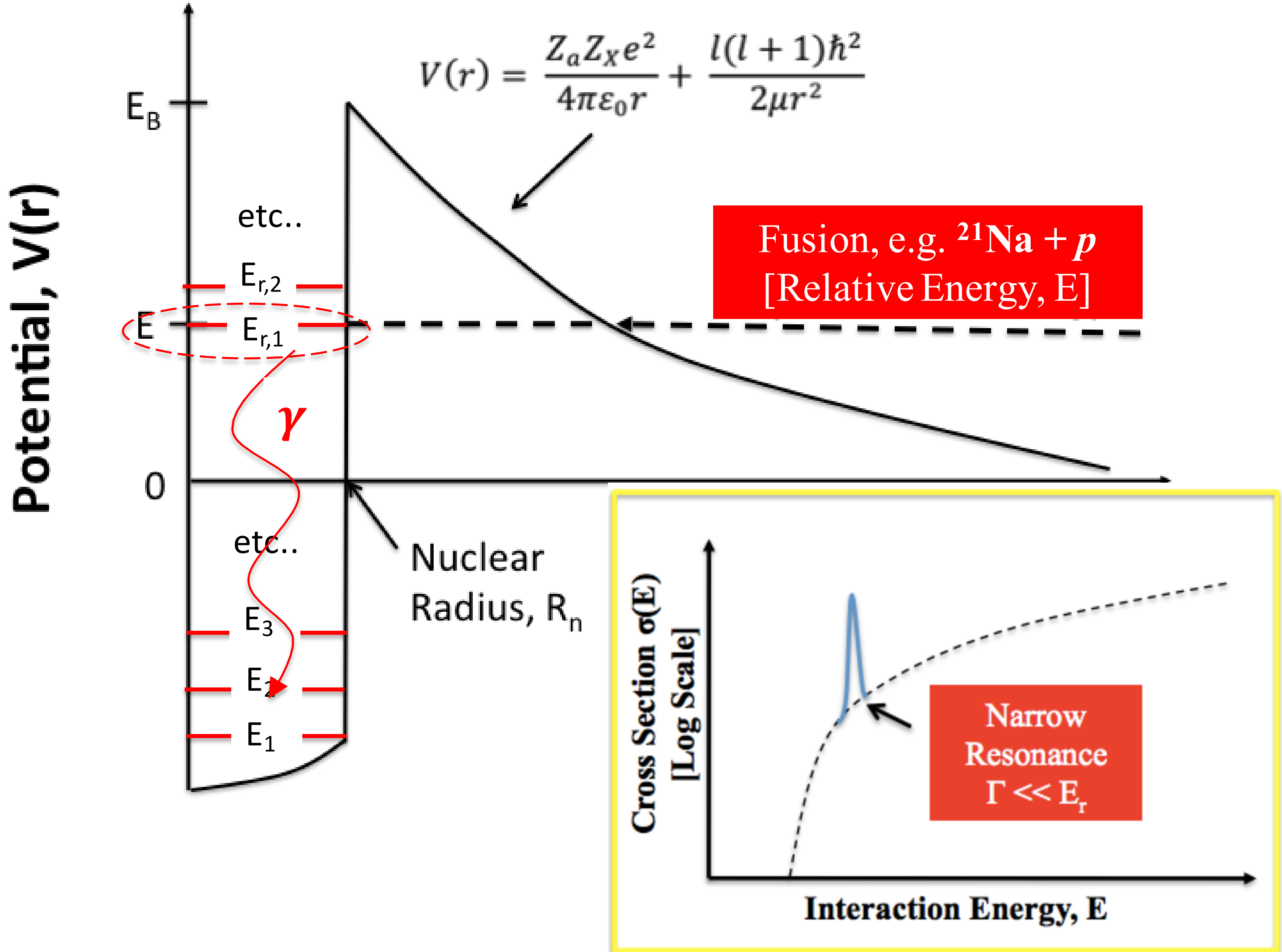
Nuclear Processes in Explosive Environments

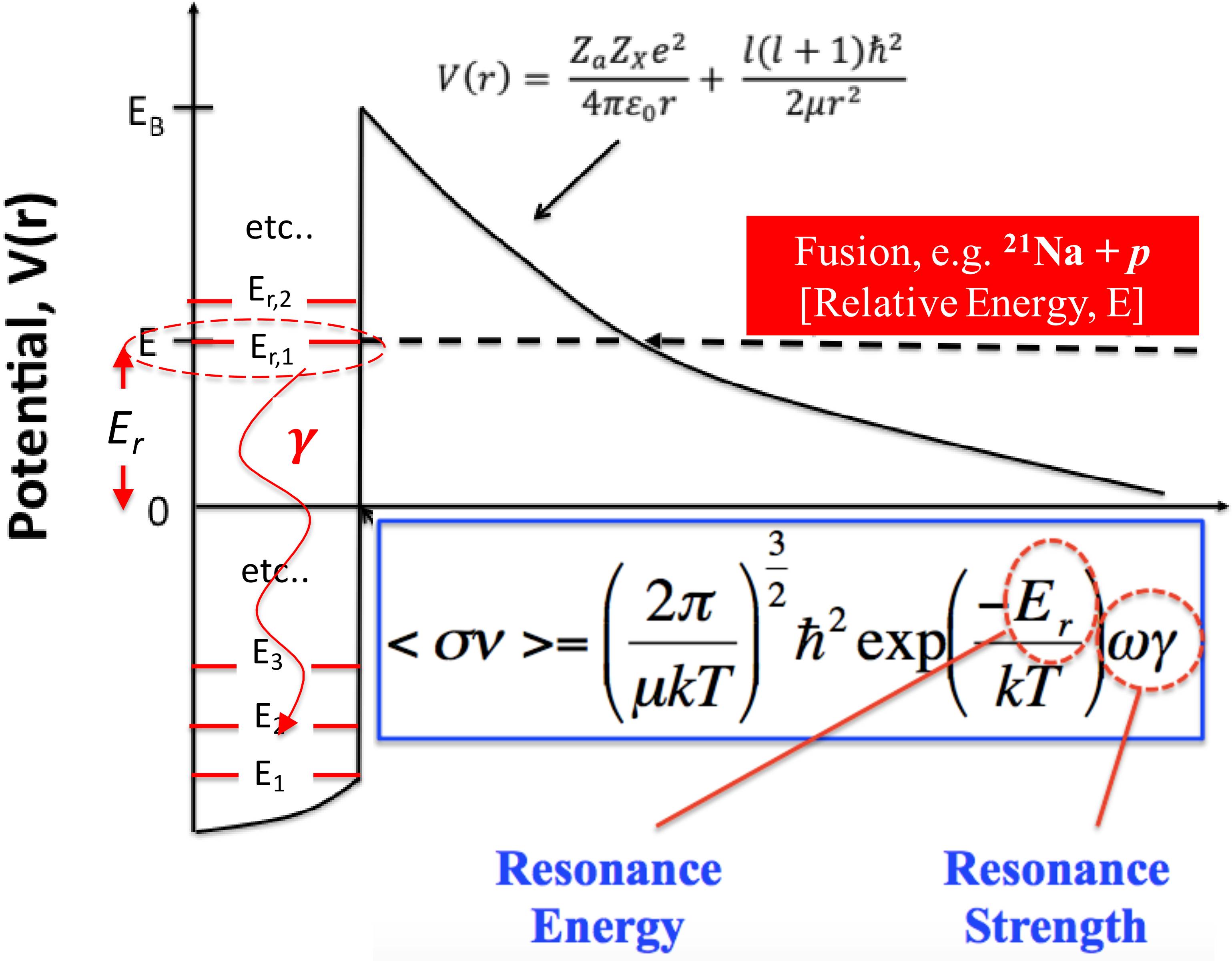


$$V(r) = \frac{Z_a Z_X e^2}{4\pi\varepsilon_0 r} + \frac{l(l+1)\hbar^2}{2\mu r^2}$$

Fusion, e.g. ^{21}Na + *p*
[Relative Energy, E]

Narrow Resonance
$\Gamma \ll E_r$

Nuclear Processes in Explosive Environments



$$V(r) = \frac{Z_a Z_X e^2}{4\pi\varepsilon_0 r} + \frac{l(l+1)\hbar^2}{2\mu r^2}$$

Fusion, e.g. $^{21}\mathbf{Na} + \boldsymbol{p}$
[Relative Energy, E]

$$<\sigma v> = \left(\frac{2\pi}{\mu kT}\right)^{\frac{3}{2}} \hbar^2 \exp\left(\frac{-E_r}{kT}\right) \omega\gamma$$

Resonance Energy

Resonance Strength

Influence of Partial Widths on Radiative Capture

We will now discuss the influence of the partial widths Γ_a and Γ_b on radiative capture reactions. In particular, we will consider cases in which only two channels are open, i.e. the particle channel Γ_a and the gamma-ray channel Γ_γ.

Suppose first that the charged-particle width is smaller than the gamma-ray partial width, a situation typical for low resonance energies. Since $\Gamma_a << \Gamma_\gamma$ we obtain from the definition of the resonance strength

$$\boxed{\omega\gamma = \omega\frac{\Gamma_a\Gamma_\gamma}{\Gamma_a + \Gamma_\gamma} \approx \omega\frac{\Gamma_a\Gamma_\gamma}{\Gamma_\gamma} = \omega\Gamma_a}$$

Thus, the resonance strength depends only on the charged-particle partial width.

While only the small energy region near E_r contributes to the reaction rate for narrow resonances, the concept of a Gamow peak is still useful in the case where the charged particle partial width plays a key role.

Influence of Partial Widths on Radiative Capture

Suppose now that the gamma-ray partial width is smaller than the particle width, $\Gamma_a >> \Gamma_\gamma$. This situation typically occurs for charged particles at higher resonance energies.

$$\boxed{\omega\gamma = \omega \frac{\Gamma_a \Gamma_\gamma}{\Gamma_a + \Gamma_\gamma} \approx \omega \frac{\Gamma_a \Gamma_\gamma}{\Gamma_a} = \omega \Gamma_\gamma}$$

In this case, the concept of a most important energy window, such as the Gamow peak, does not exist.

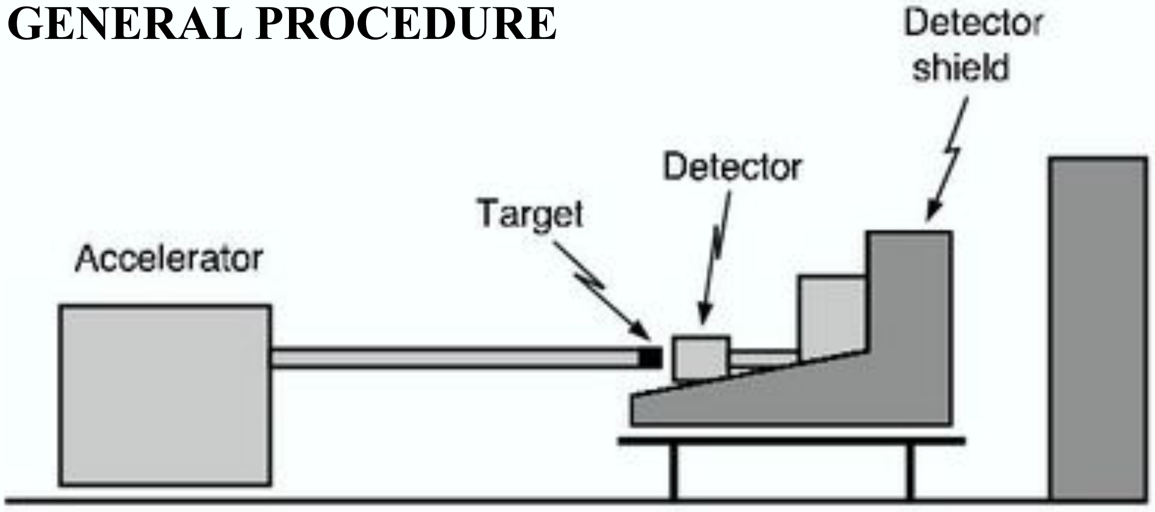
The smaller resonance energy, the larger the reaction rate contribution, as long as $\Gamma_a >> \Gamma_\gamma$. Consequently, it becomes very important to locate all of the low-energy resonances.

Nuclear Physics Experiments

Experimental procedures that are used in the field of nuclear astrophysics can be divided into two groups :

DIRECT MEASUREMENTS	A measurement of a cross section or a resonance strength in a given reaction of astrophysical interest
INDIRECT MEASUREMENTS	All other studies that are performed to improve the thermonuclear rates of this particular reaction, for example, elastic scattering, particle transfer, charge-exchange, and so on

GENERAL PROCEDURE

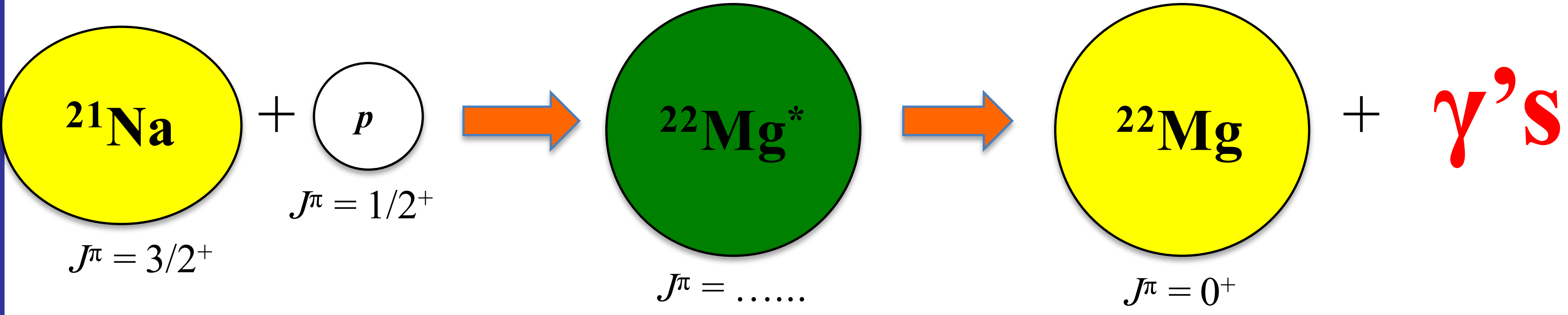


Most important reactions :

$$A(a,\gamma)B$$
$$A(a,b)B$$

Direct Experimental Measurements

Let us consider the experimental measurement of the ^{21}Na(p,γ)^{22}Mg radiative capture reaction that occurs in explosive stellar environments.



The rate is governed by the contributions of resonant capture to excited states above the proton-emission threshold energy ($S_p = 5504.3$ keV) in ^{22}Mg.

For each environment, the most important resonances are determined by the location of the Gamow window, as well as the relative l-transfer.

Excited states in ^{22}Mg with :

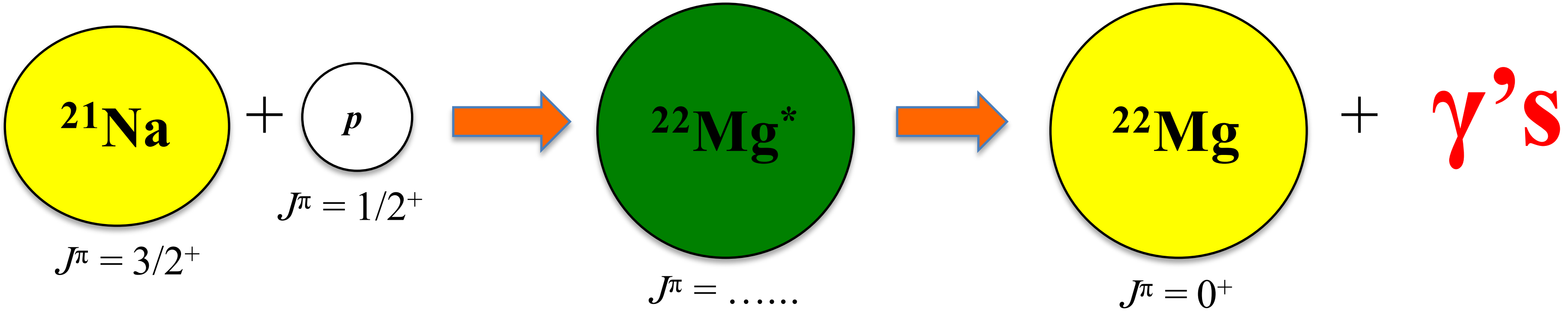
$J^{\pi}=1^{+}$ or 2^{+} correspond to $l = 0$ resonances

$J^{\pi}=0^{-}$, 1^{-}, 2^{-} or 3^{-} correspond to $l = 1$ resonances

$J^{\pi}=0^{+}$, 3^{+} or 4^{+} correspond to $l = 2$ resonances

Direct Experimental Measurement : DRAGON

Let us consider the experimental measurement of the ^{21}Na(p,γ)^{22}Mg radiative capture reaction that occurs in explosive stellar environments.



^{21}Na + ***p*** → **^{22}Mg*** → **^{22}Mg** + **γ's**

$J^{\pi} = 3/2^{+}$

$J^{\pi} = 1/2^{+}$

$J^{\pi} = \ldots\ldots$

$J^{\pi} = 0^{+}$

The rate is governed by the contributions of resonant capture to excited states above the proton-emission threshold energy (S_p = 5504.3 keV) in ^{22}Mg.

For each environment, the most important resonances are determined by the location of the Gamow window, as well as the relative l-transfer.

$$E_0 = 0.1220\left(Z_0^2 Z_1^2 \frac{M_0 M_1}{M_0 + M_1} T_9^2\right)^{1/3}$$

$$\Delta = 0.2368\left(Z_0^2 Z_1^2 \frac{M_0 M_1}{M_0 + M_1} T_9^5\right)^{1/6}$$

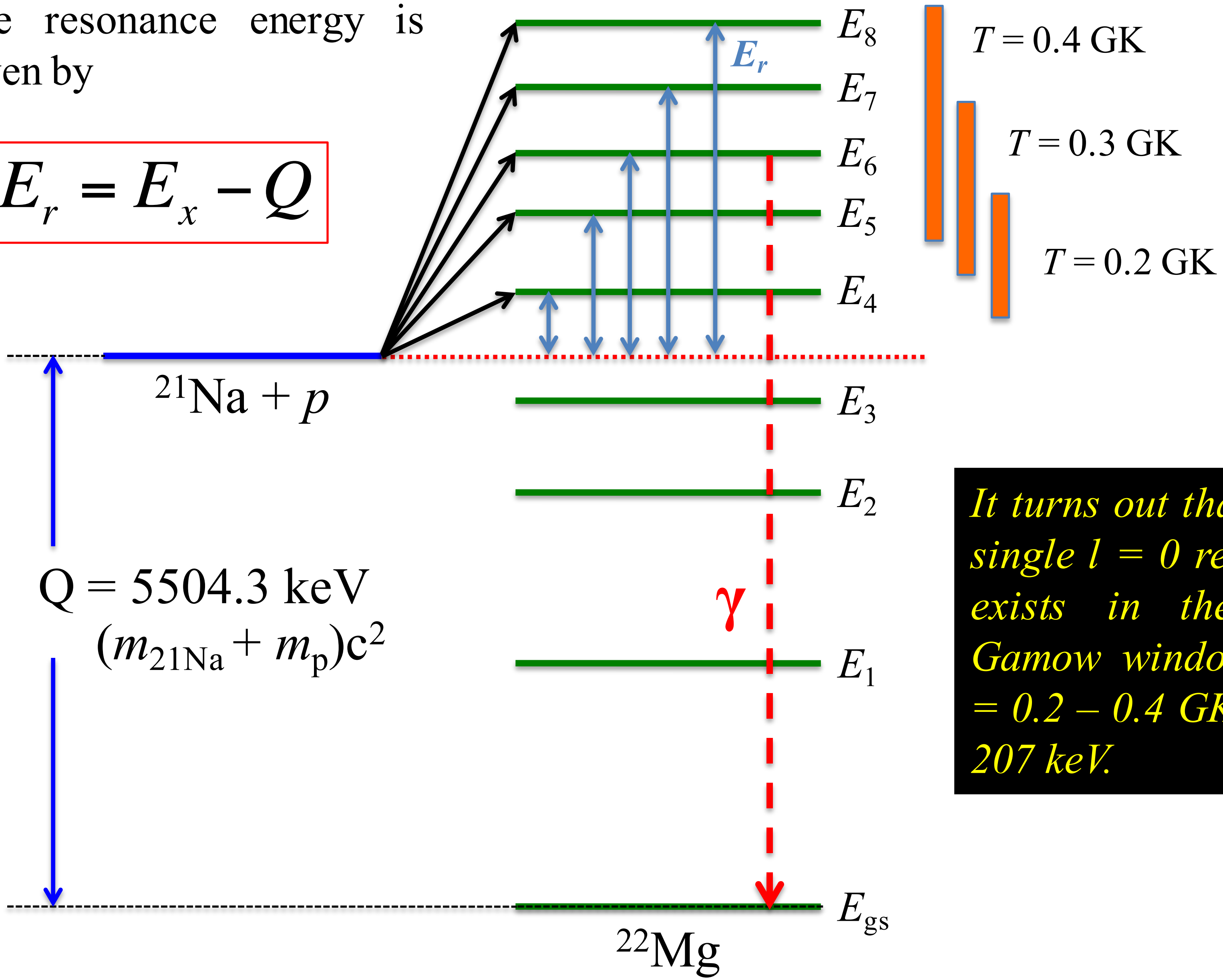
For classical novae
(T = 0.2 – 0.4 GK)

***E* ~ 140 – 440 keV**

Direct Experimental Measurements

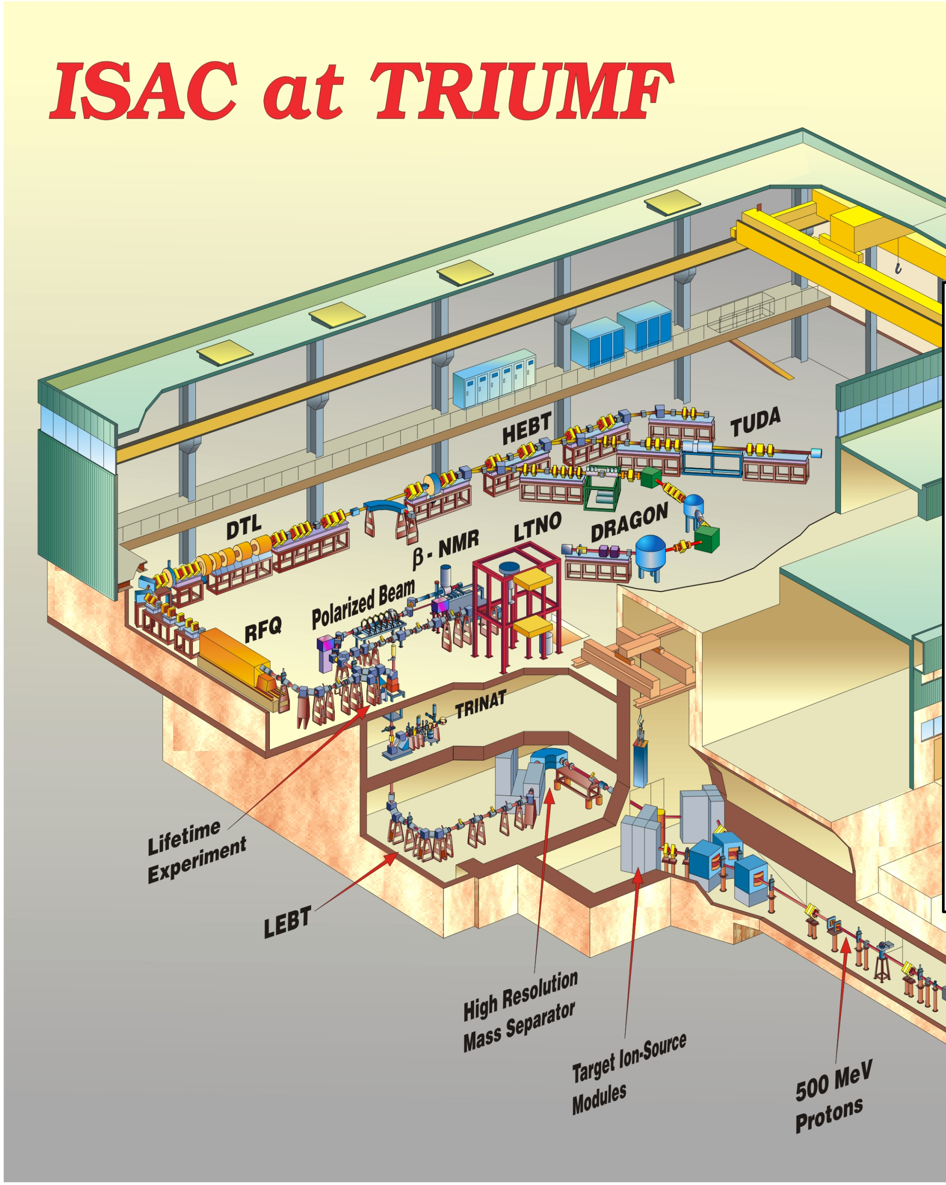
The resonance energy is given by

$$\boxed{E_r = E_x - Q}$$

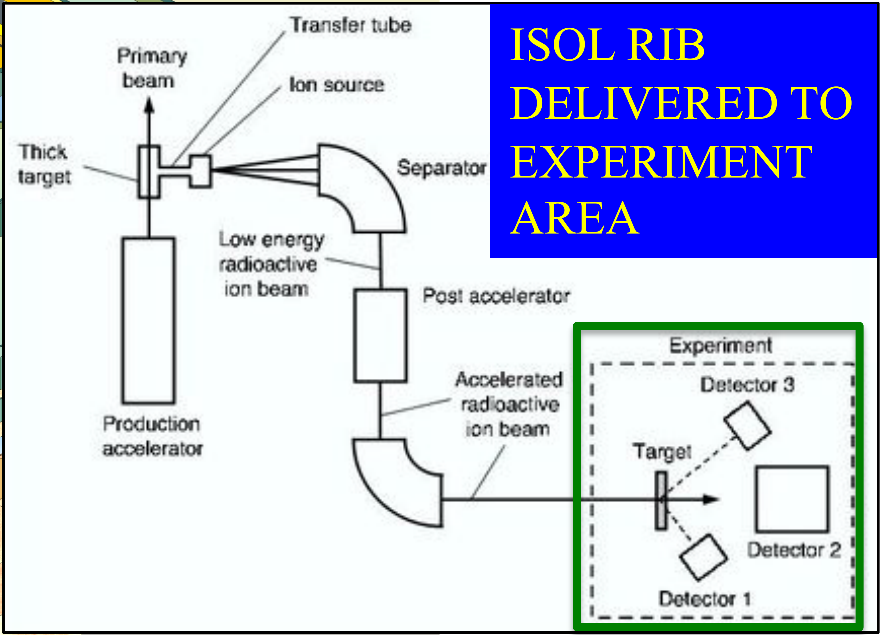


It turns out that only a single l = 0 resonance exists in the entire Gamow window for T = 0.2 – 0.4 GK at E_r = 207 keV.

Direct Experimental Measurement : DRAGON



ISOTOPE ON-LINE SEPARATOR (ISOL) TECHNIQUE

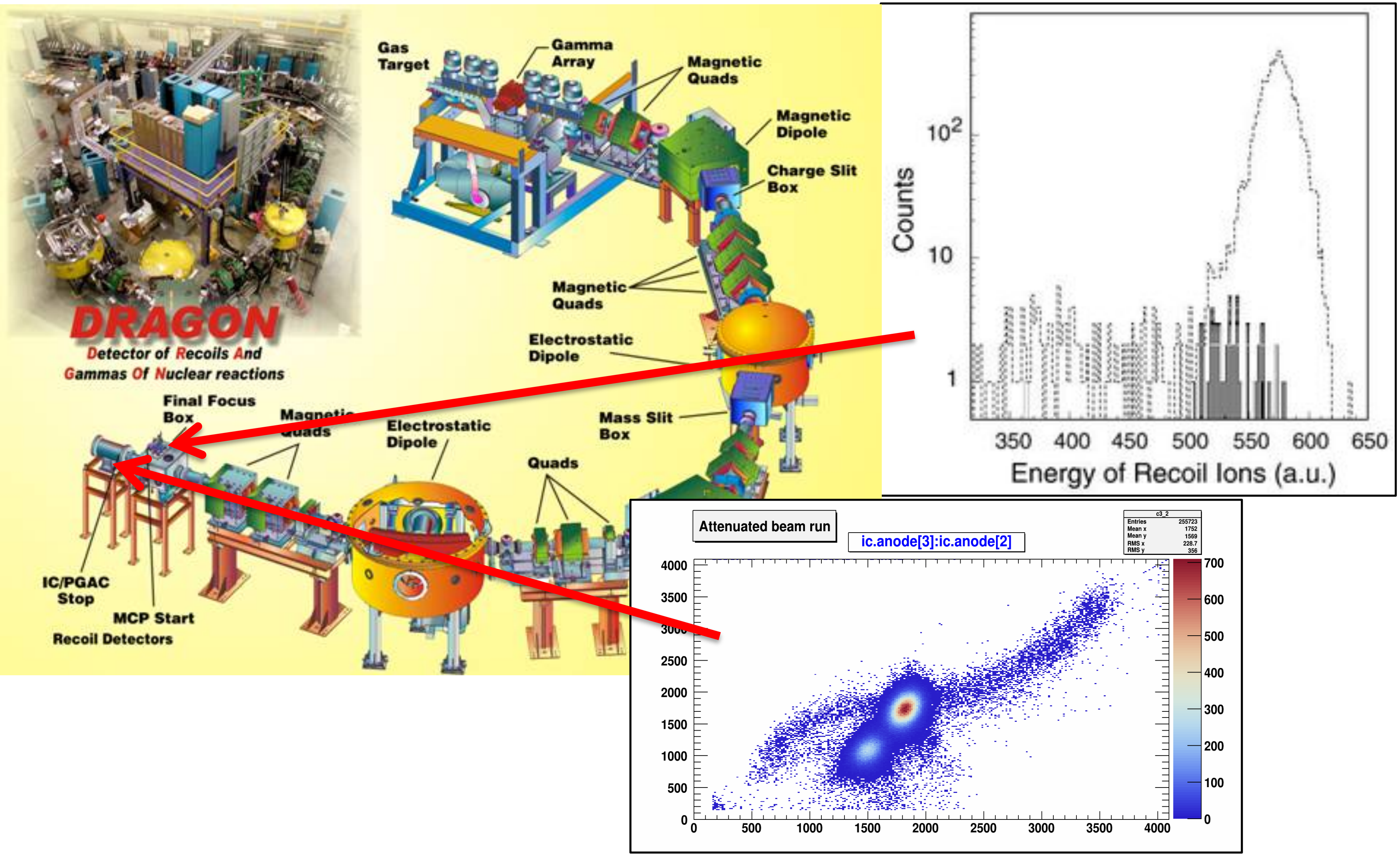


ISOL RIB DELIVERED TO EXPERIMENT AREA

Capable of delivering beams up to 1 x 10^{10} pps with energies $E_{\mathrm{beam}} = 0.15 - 1.5$ MeV/u.

DRAGON : Device for (p,γ) and (α,γ) measurement

A focal plane detection system (Si detector / MCP and Ion Chamber) is employed to identify heavy ions in coincidence with γ rays.



Indirect Measurements

Here, we will focus solely on resonant proton radiative capture reactions and low-energy resonances [i.e. (p,γ) and $E_\mathrm{r} \leq 500$ keV].

$$N_A\langle\sigma\upsilon\rangle = \frac{1.5399\times10^{11}}{\left(\mu T_9\right)^{3/2}}\sum_i(\omega\gamma)_i e^{-11.605E_r/T_9}$$

RESONANCE ENERGY

$$E_\mathrm{r} = E_\mathrm{x} - S_\mathrm{p}$$

RESONANCE STRENGTH

$$\omega\gamma = \left(\frac{2J_r+1}{(2j_0+1)(2j_1+1)}\right)\frac{\Gamma_a\Gamma_\gamma}{\Gamma_a+\Gamma_\gamma} \approx \omega\Gamma_p$$

$$\Gamma_p = 2\cdot\frac{\hbar^2}{\mu R^2}\cdot P_l\cdot C^2S\cdot\theta_p^2$$

Indirect Measurements

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NEED Spins, Excitation Energies and Particle Partial Widths

NCE ENERGY

$$\boldsymbol{E_\mathrm{r} = E_\mathrm{x} - S_\mathrm{p}}$$

RESONANCE STRENGTH

$$\omega\gamma = \left(\frac{2J_r+1}{(2j_0+1)(2j_1+1)}\right)\frac{\Gamma_a\Gamma_\gamma}{\Gamma_a+\Gamma_\gamma} \approx \omega\Gamma_p$$

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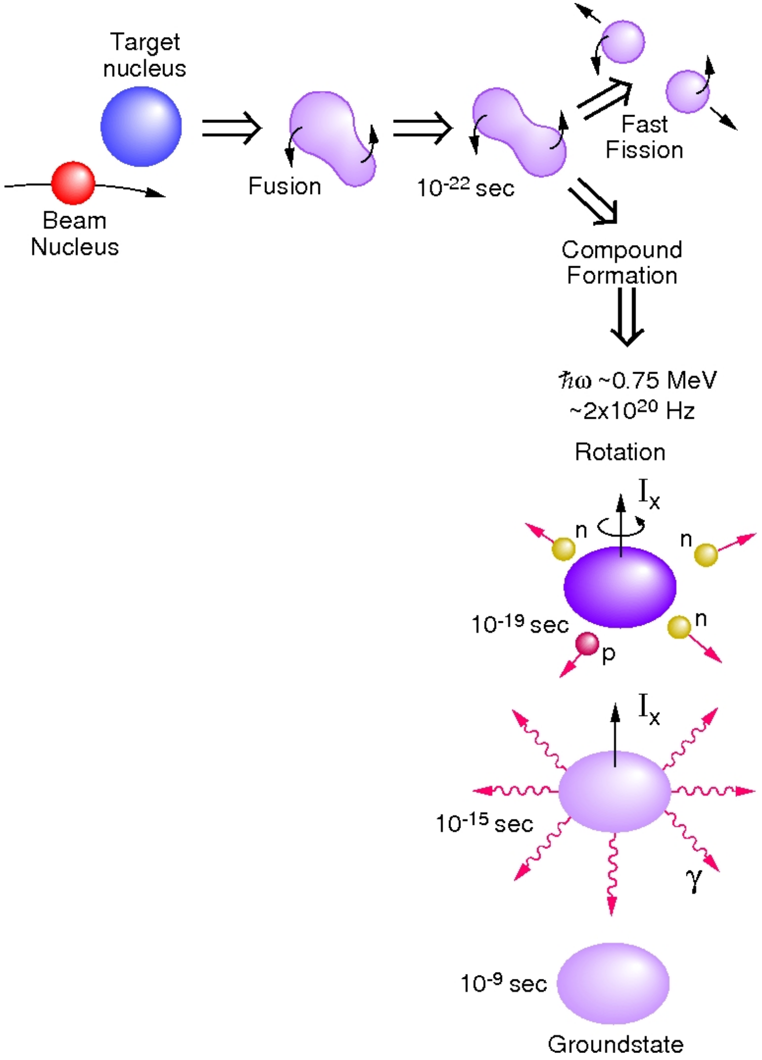
Indirect Measurements : Gamma-ray Spectroscopy

Modern γ-ray spectroscopy techniques provide the means to obtain precise resonance energies and spin-parity assignments.



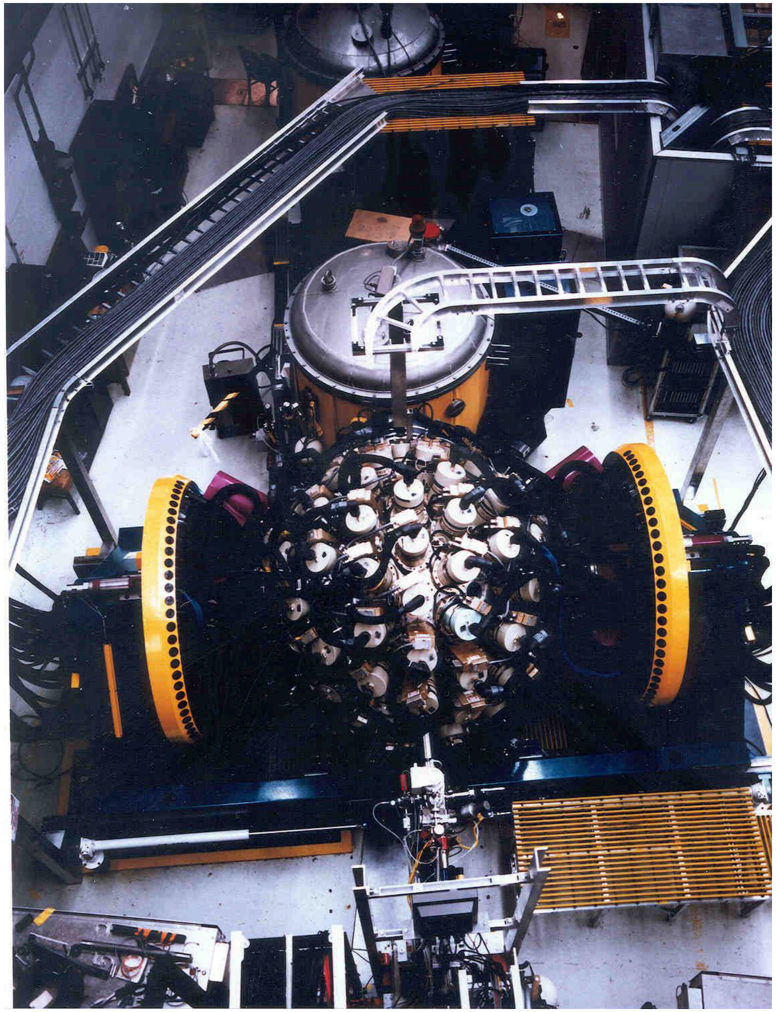
Let us consider the ^{21}Na(p,γ)^{22}Mg reaction again.

In this case, a stable ^{12}C beam is used to bombard a stable ^{12}C target. The radioactive nucleus ^{22}Mg ($t_{1/2}$ ~ 3.9 s) is produced via the evaporation of TWO neutrons from the excited compound nucleus ^{24}Mg*.

This is usually written as ^{12}C(^{12}C,2n)^{22}Mg.

Indirect Measurements : Gamma-ray Spectroscopy

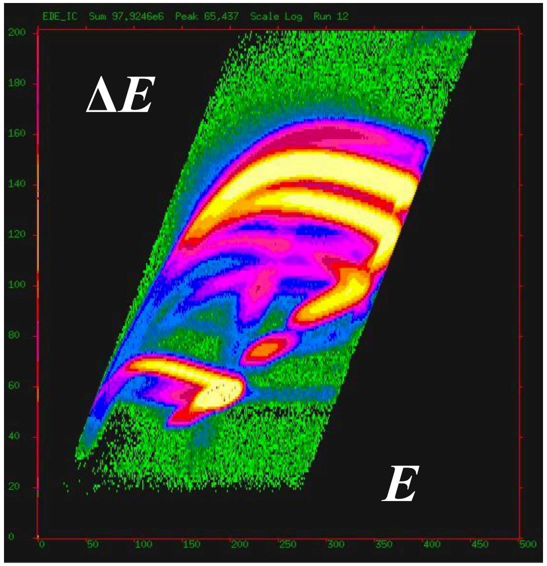
Modern γ-ray spectroscopy techniques provide the means to obtain precise resonance energies and spin-parity assignments.



Prompt γ rays are detected with a 4π γ-ray array, such as Gammasphere (consists of ~100 Germanium detectors).

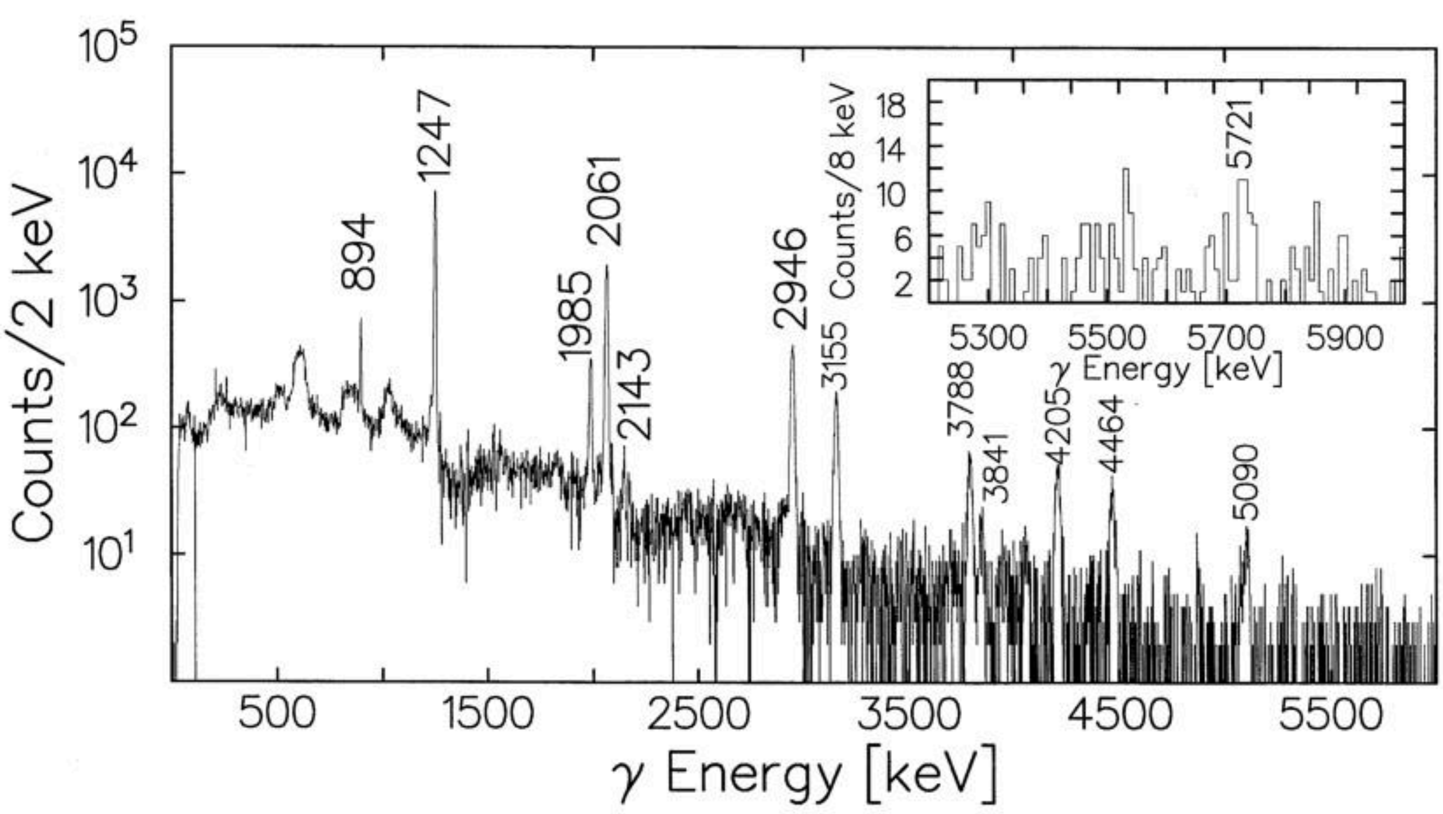
Recoils of a certain mass (e.g. A = 22) are transmitted to the focal plane by a recoil mass spectrometer, such as the Fragment Mass Analyzer.

Finally, recoils are separated by atomic number Z at the focal plane by an ionization chamber.



Indirect Measurements : Gamma-ray Spectroscopy

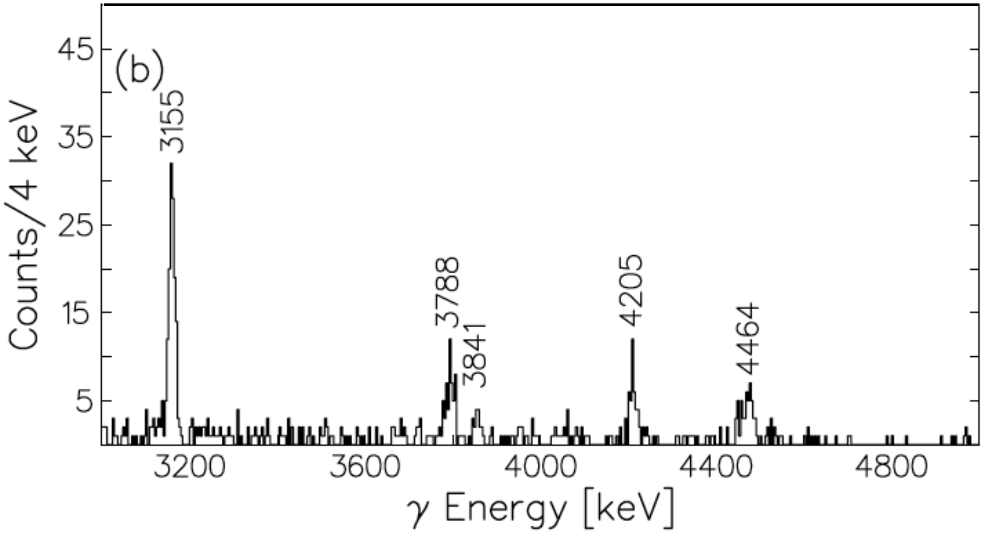
The resulting γ rays obtained for ^{22}Mg obtained at Argonne National Laboratory are shown below.



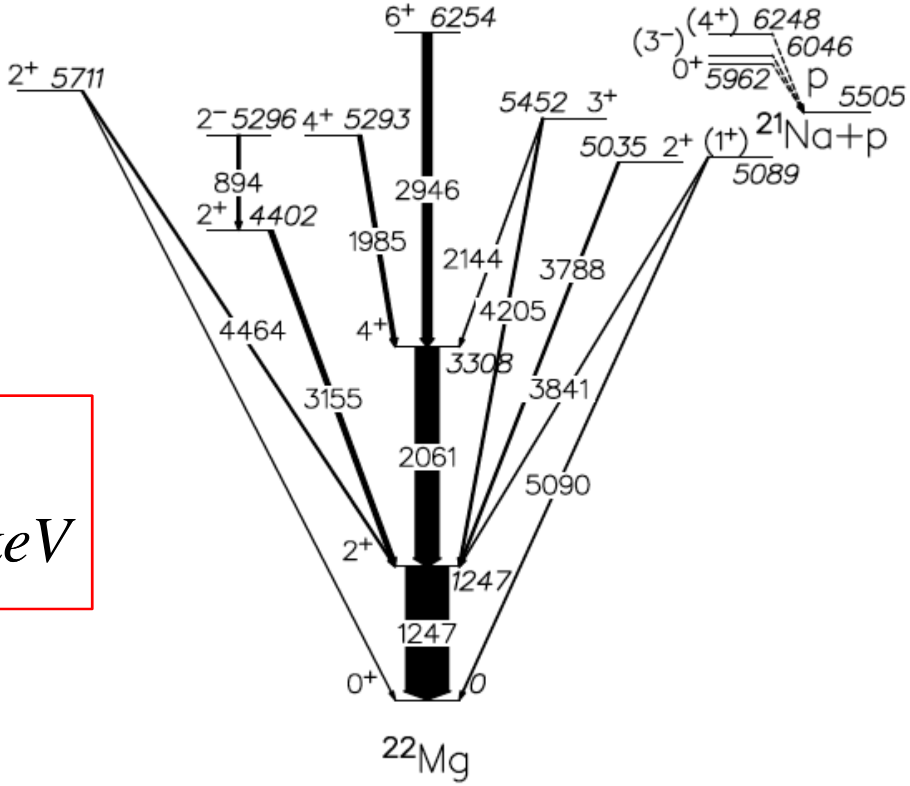
Precise excitation energies are given by the energies of γ rays. However, it is essential to account for the recoil of the compound nucleus.

$$E_{recoil} = \frac{E_\gamma^2}{2Mc^2}$$

Indirect Measurements : Gamma-ray Spectroscopy



By performing coincidence measurements, it is possible to create a detailed level scheme of the nucleus.



The resonance energies are then obtained from the relation

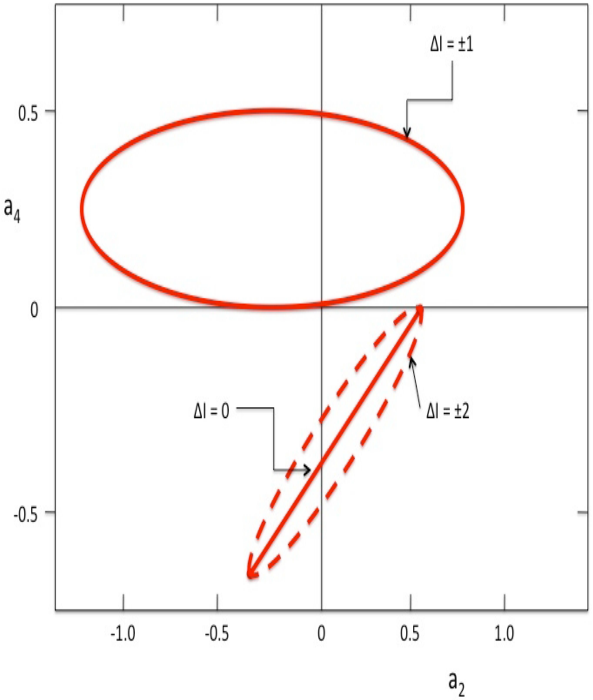
$$E_r = E_x - S_p$$

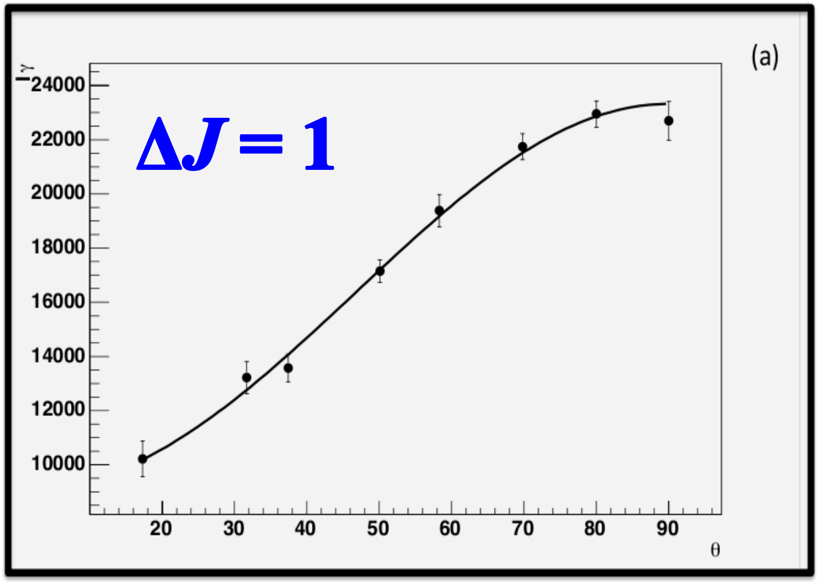
$$E_r = E_x - Q_{^{21}Na+p} = E_x - 5504.3keV$$

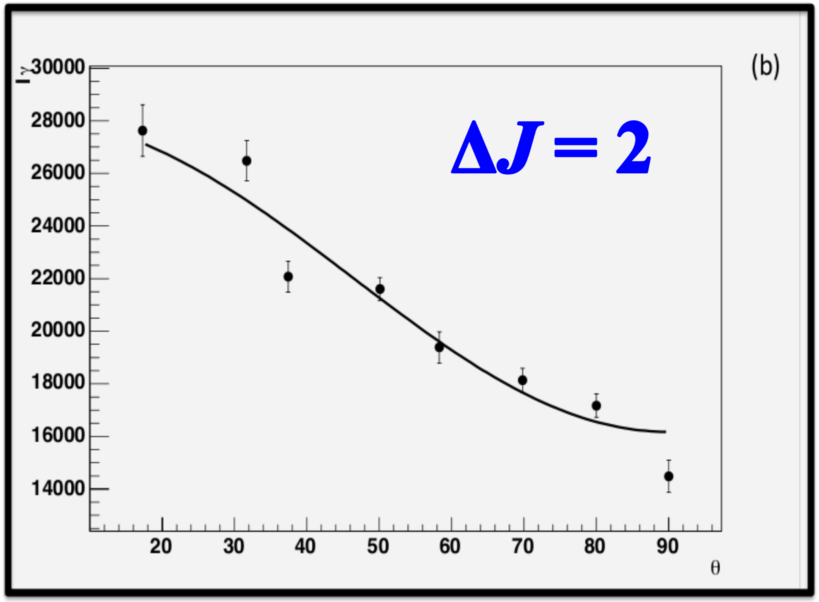
Indirect Measurements : Gamma-ray Spectroscopy

The spins of the resonant states may be obtained by performing an angular distribution analysis of the γ rays (in other words, measuring the intensity of γ rays as a function of angle).

$$\boxed{W(\theta) = A_0[1 + a_2 P_2 \cos\theta + a_4 P_4 \cos\theta]}$$



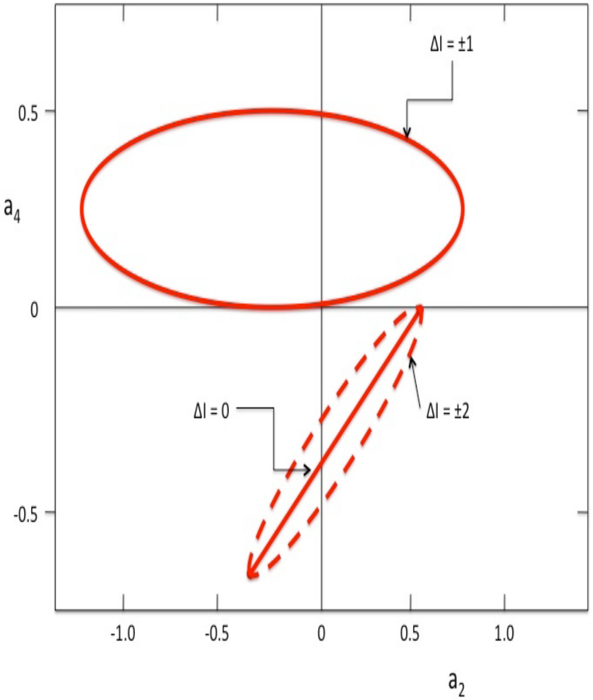


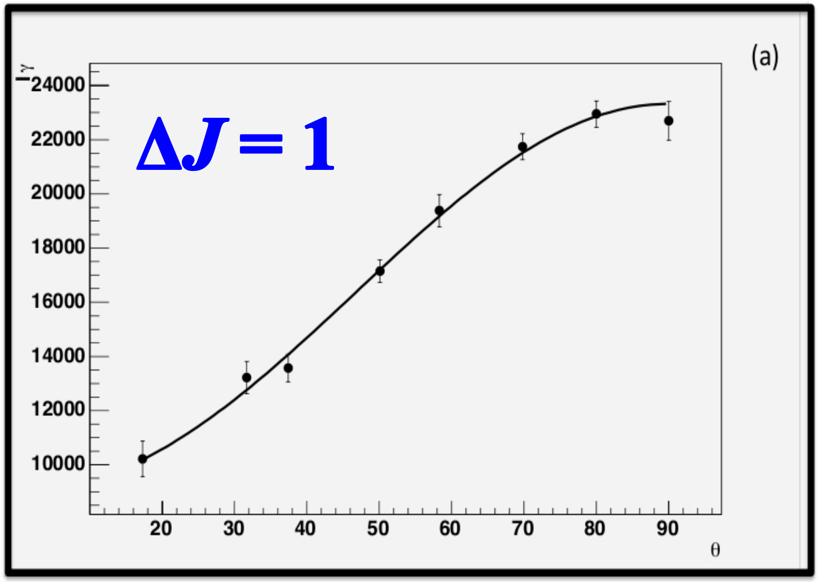


Indirect Measurements : Gamma-ray Spectroscopy

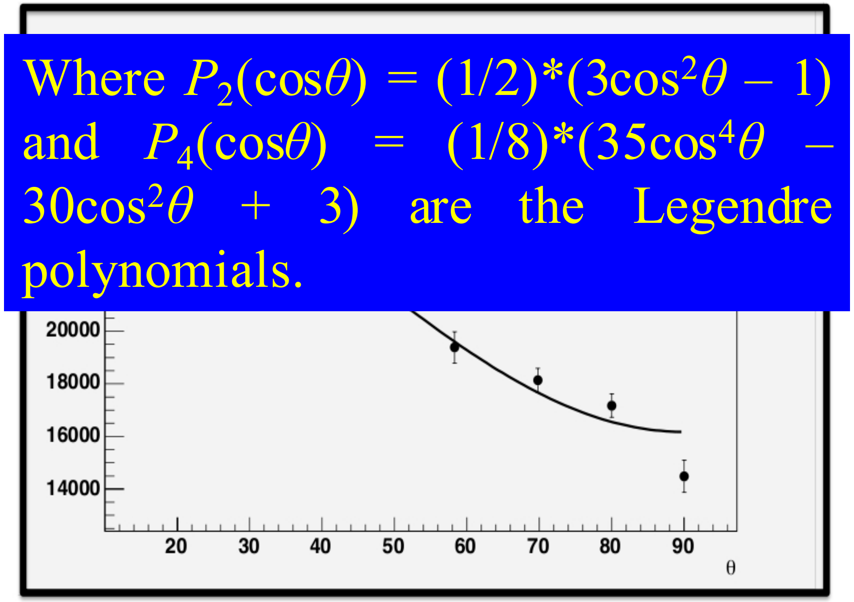
The spins of the resonant states may be obtained by performing an angular distribution analysis of the γ rays (in other words, measuring the intensity of γ rays as a function of angle).

$$W(\theta) = A_0[1 + a_2 P_2 \cos\theta + a_4 P_4 \cos\theta]$$



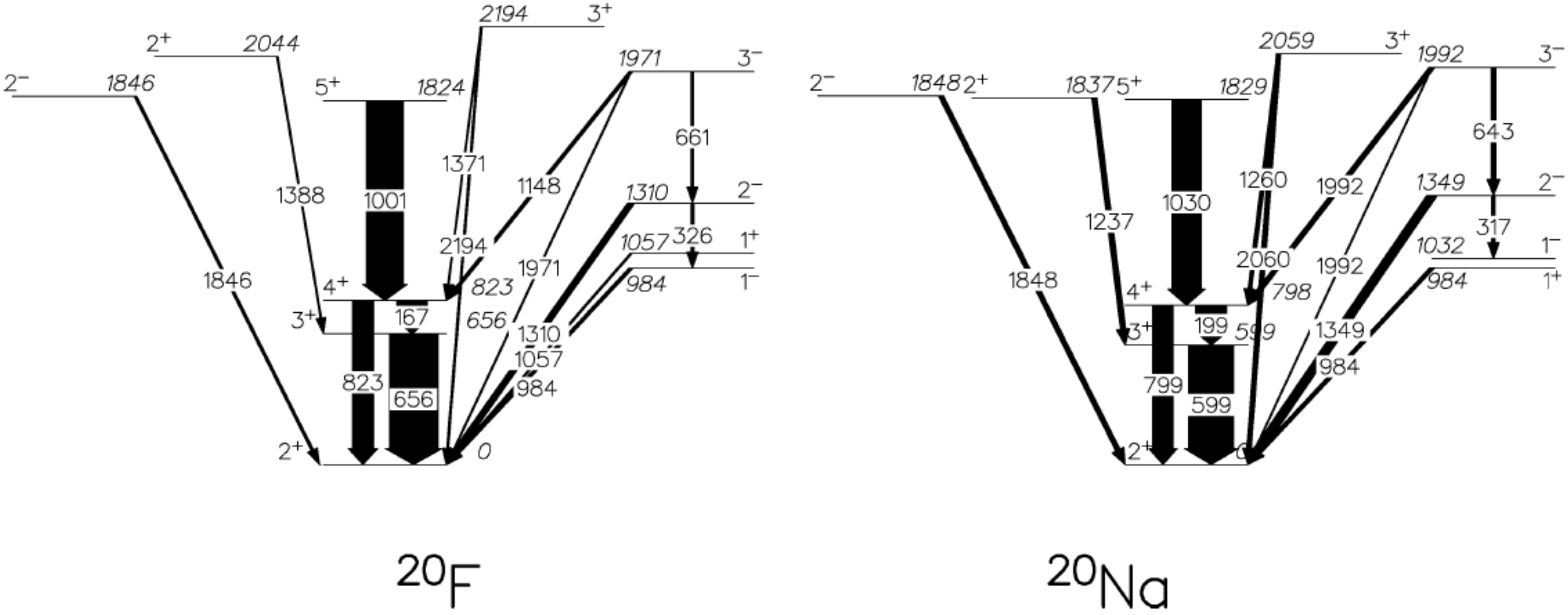


Where $P_2(\cos\theta) = (1/2)*(3\cos^2\theta - 1)$ and $P_4(\cos\theta) = (1/8)*(35\cos^4\theta - 30\cos^2\theta + 3)$ are the Legendre polynomials.



Indirect Measurements : Gamma-ray Spectroscopy

The parities are obtained from the concept that the structure of mirror nuclei (nuclei with the same number of protons and neutrons, in which the Z and N numbers are swapped) are nearly identical.



By identifying mirror analogues, it is possible to adopt parities assigned to the more well-studied stable mirror partner. The example above shows the nuclear structures of the mirror nuclei $^{20}F_9$ and $^{20}Na_{11}$.

Indirect Measurements : Gamma-ray Spectroscopy

With γ-ray spectroscopy, we are able to obtain :

1. Precise resonance energies
2. Spins of resonant states
3. Parities of resonant states – these together with the spins can be used to determine the relative l – transfer between the incident and final systems [e.g. ^{21}Na + p and ^{22}Mg].

ABLE TO ESTIMATE THE RESONANT CONTRIBUTIONS TO STELLAR REACTION RATES

$$\boxed{N_A\langle\sigma\upsilon\rangle = \frac{1.5399\times10^{11}}{(\mu T_9)^{3/2}}\sum_i(\omega\gamma)_i e^{-11.605E_r/T_9}}$$

Indirect Measurements : Transfer Reactions

While γ-ray spectroscopy is able to obtain many of the quantities required to accurately determine stellar reaction rates in explosive astrophysical environments, a critical parameter is missing – THE SPECTROSCOPIC FACTOR.

$$\boxed{\Gamma_p = 2 \cdot \frac{\hbar^2}{\mu R^2} \cdot P_l \cdot C^2 S \cdot \theta_p^2}$$

If we intend to investigate a (p,γ) reaction, we need to use a surrogate TRANSFER reaction in order to extract the proton spectroscopic factor.

Let us consider the astrophysical $^{26}Al(p,\gamma)^{27}Si$ reaction **:**

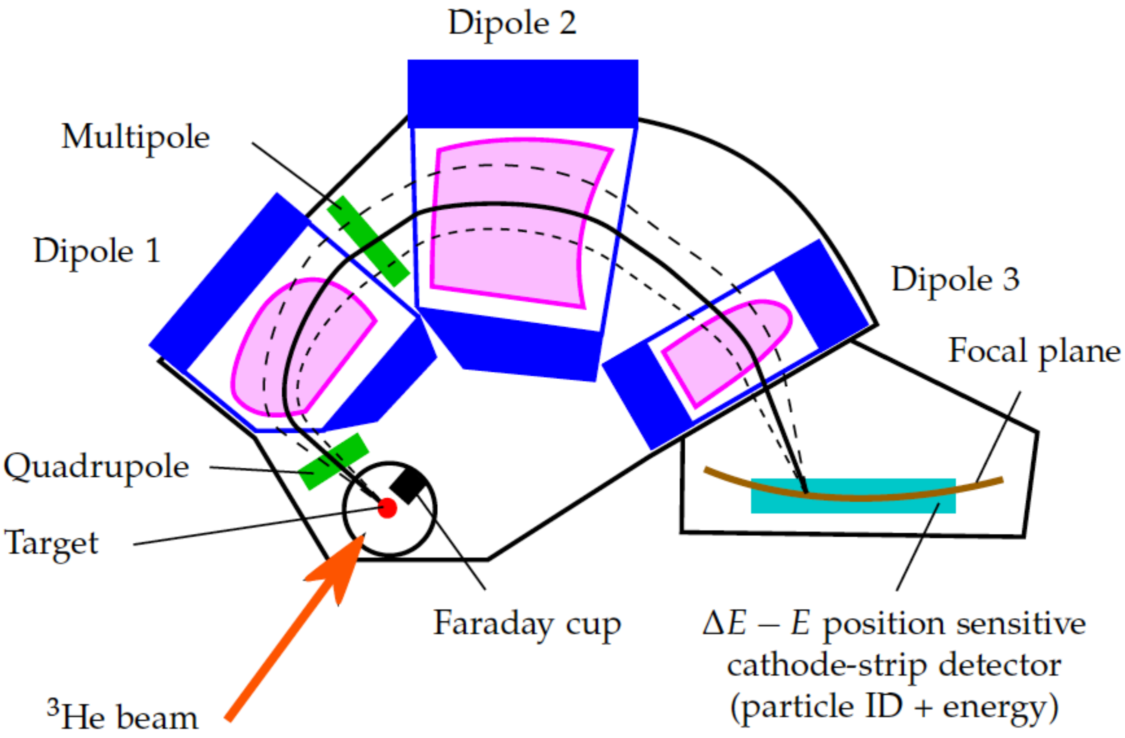
The relevant transfer reaction is $^{26}\mathrm{Al}(^3\mathrm{He},d)^{27}\mathrm{Si}$

These reactions need to be performed in normal kinematics (i.e. use a ^{3}He beam). Therefore the target nuclide needs to be stable or have a long half-life. For the example above, ^{26}Al is radioactive but $t_{1/2} = 7.2 \times 10^5$ yr.

Normal Kinematics : (^{3}He,*d*) Reactions

Transfer reactions are very sensitive to the relative proton *l*-transfer between the incident and exit systems. In particular, the cross sections for low *l*-transfers (i.e. $l = 1$, 2 and 3), the most important for nuclear astrophysics, are maximum at small angles in the COM system.

For normal kinematics experiments – $\theta_{lab} \sim \theta_{com}$



A ^{3}He beam is used to bombard a target and the reaction products are transmitted through a magnetic spectrograph. The reaction products are then separated at the focal plane using a suitable detector (proportional counter, scintillator, silicon strip detector.

Normal Kinematics : (^{3}He,*d*) Reactions

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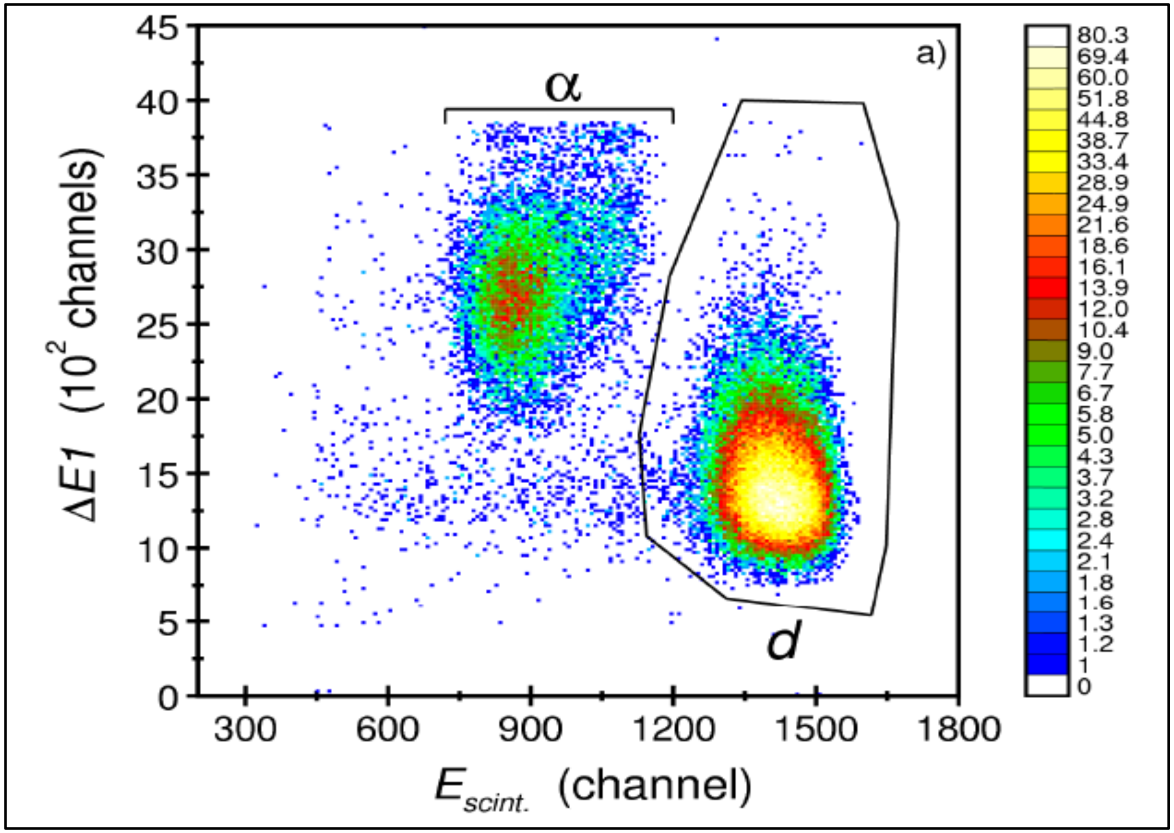

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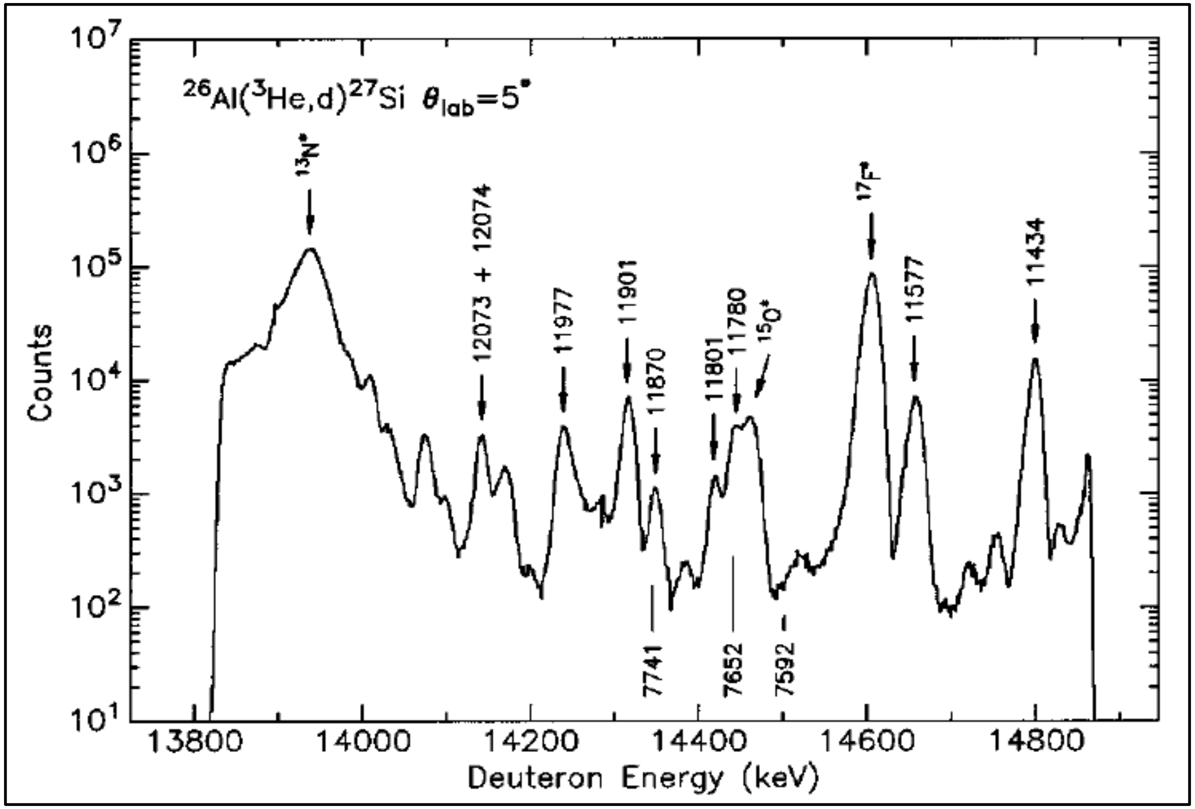

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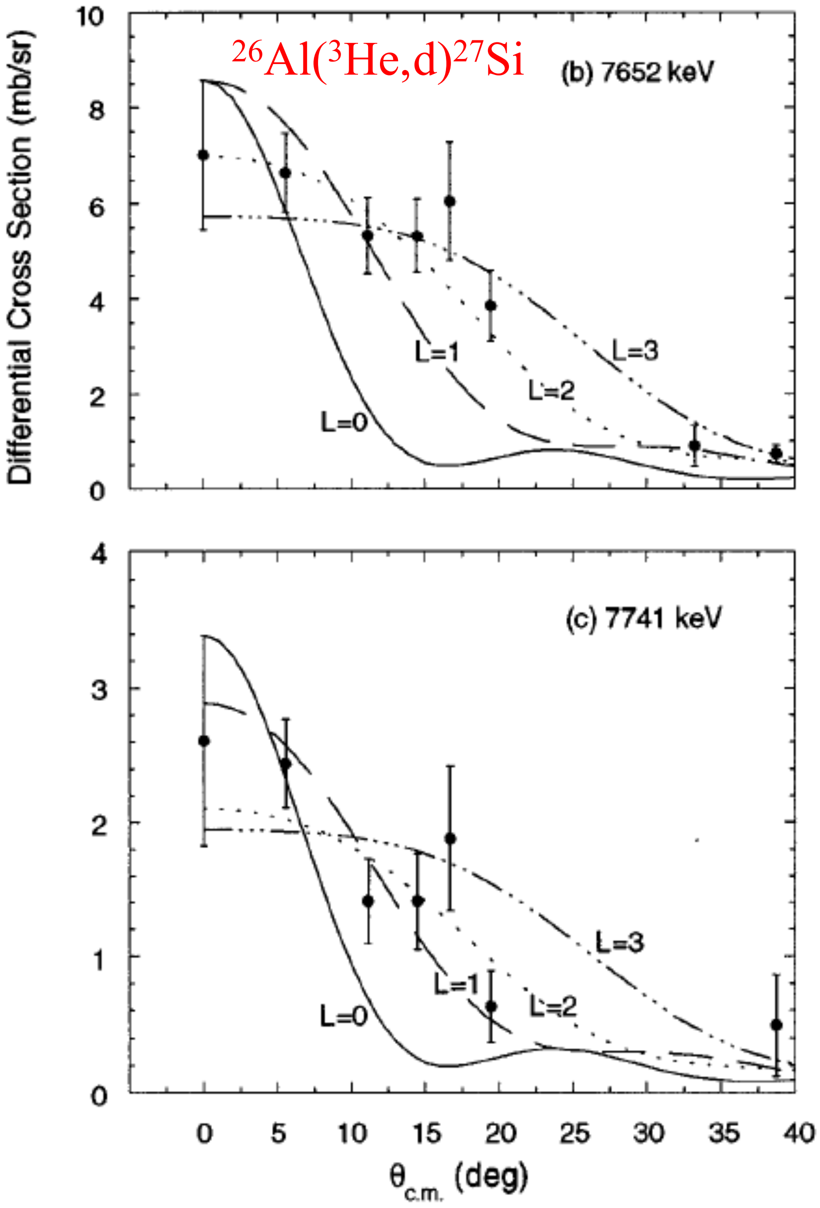
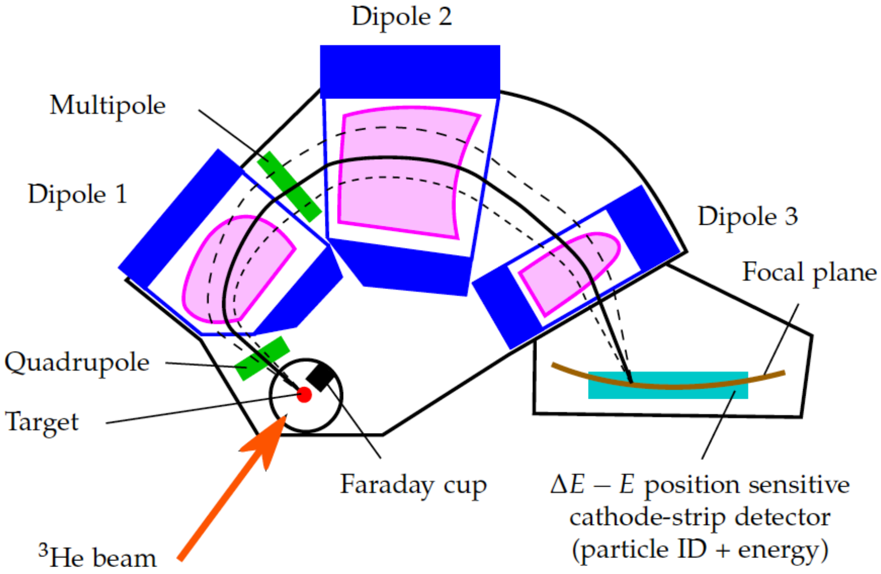
Normal Kinematics : (^{3}He,*d*) Reactions

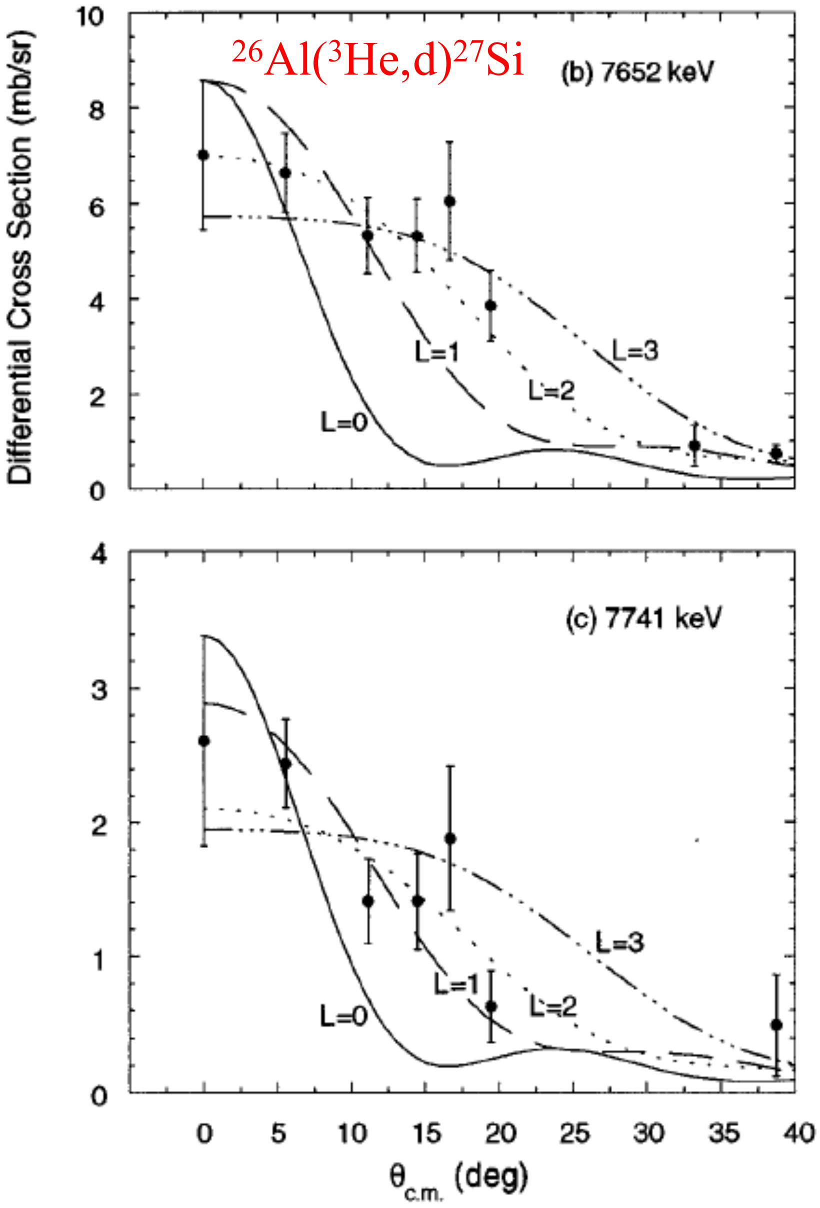




The magnetic spectrograph can be moved to different angles and as such, the differential cross section can be determined as a function of centre-of-mass angle.

$$\boxed{\frac{d\sigma}{d\Omega} = \frac{N}{N_{BEAM} \cdot N_{TARGET} \cdot \eta \cdot d\Omega}}$$

Normal Kinematics : (^{3}He,*d*) Reactions



1. It is clear that the differential cross section is related to the relative *l* – transfer and consequently, transfer reactions may be used to determine spin-parity assignments.

2. The dotted points in the plots represent experimental data, whereas the curves are theoretical predictions for the shapes of the distributions. A comparison between these two values may be used to determine the SPECTROSCOPIC FACTOR.

$$\boxed{\frac{d\sigma}{d\Omega}(\exp) \propto C^2 S \frac{d\sigma}{d\Omega}(theory)}$$

$$\boxed{\Gamma_p = 2 \cdot \frac{\hbar^2}{\mu R^2} \cdot P_l \cdot C^2 S \cdot \theta_p^2}$$

State-of-the-Art and Future Experiments for Explosive Nuclear Astrophysics

Explosive Nuclear Astrophysics

Recap

- **In Lecture 1 we discussed**

  - Some explosive astrophysical scenarios
  - Looked at how to calculate reaction rates
  - Looked at the indirect techniques of gamma-ray spectroscopy and transfer reactions

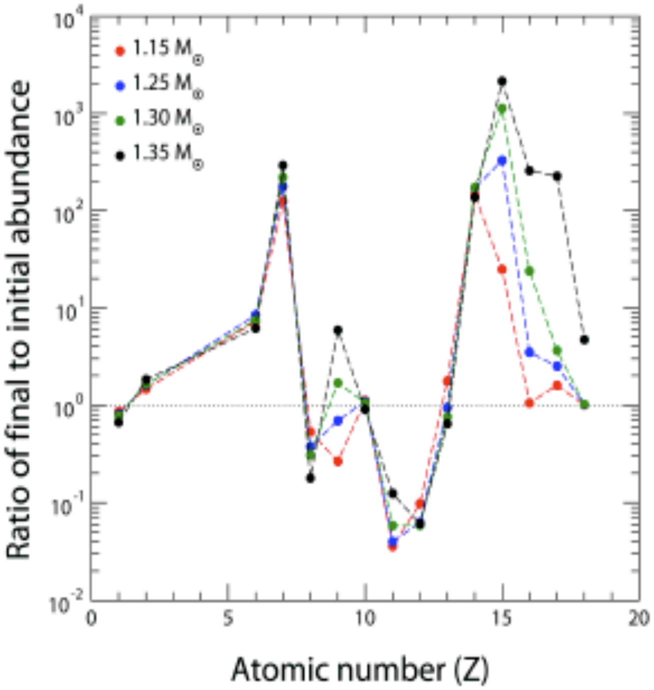
- **Today (lecture 2) we will look at**

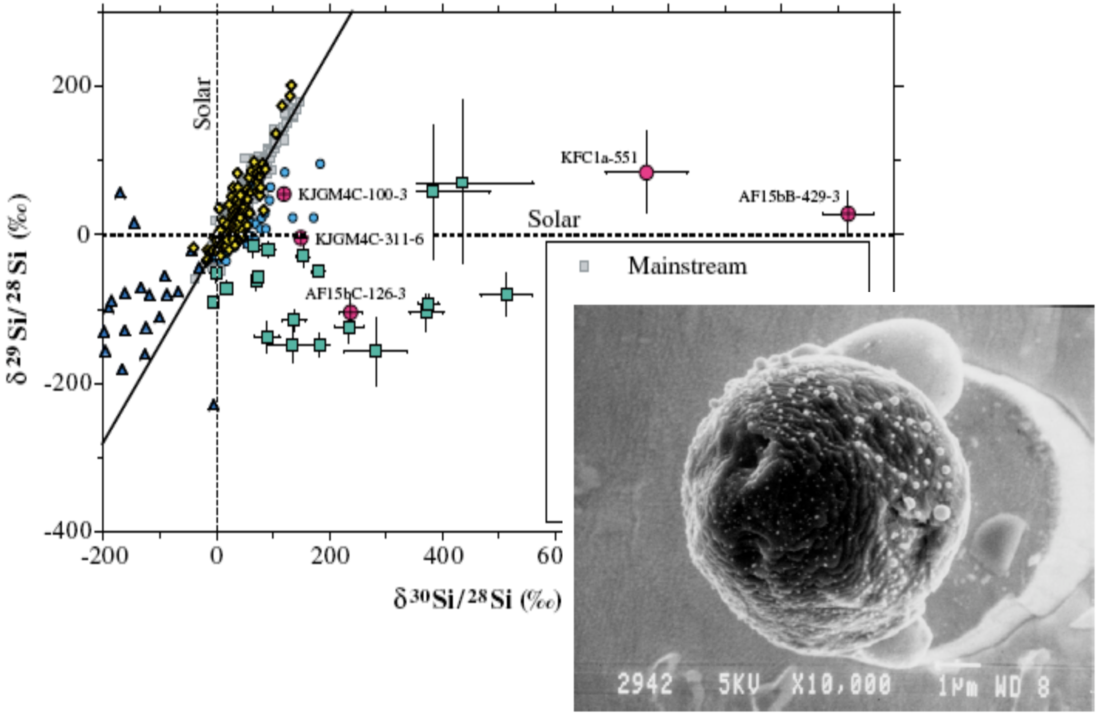
  - Some selected (biased!) highlights from recent years
  - Future work at new RIB facilities
  - Future work we could do here

Astronomical Observations of ONe Novae

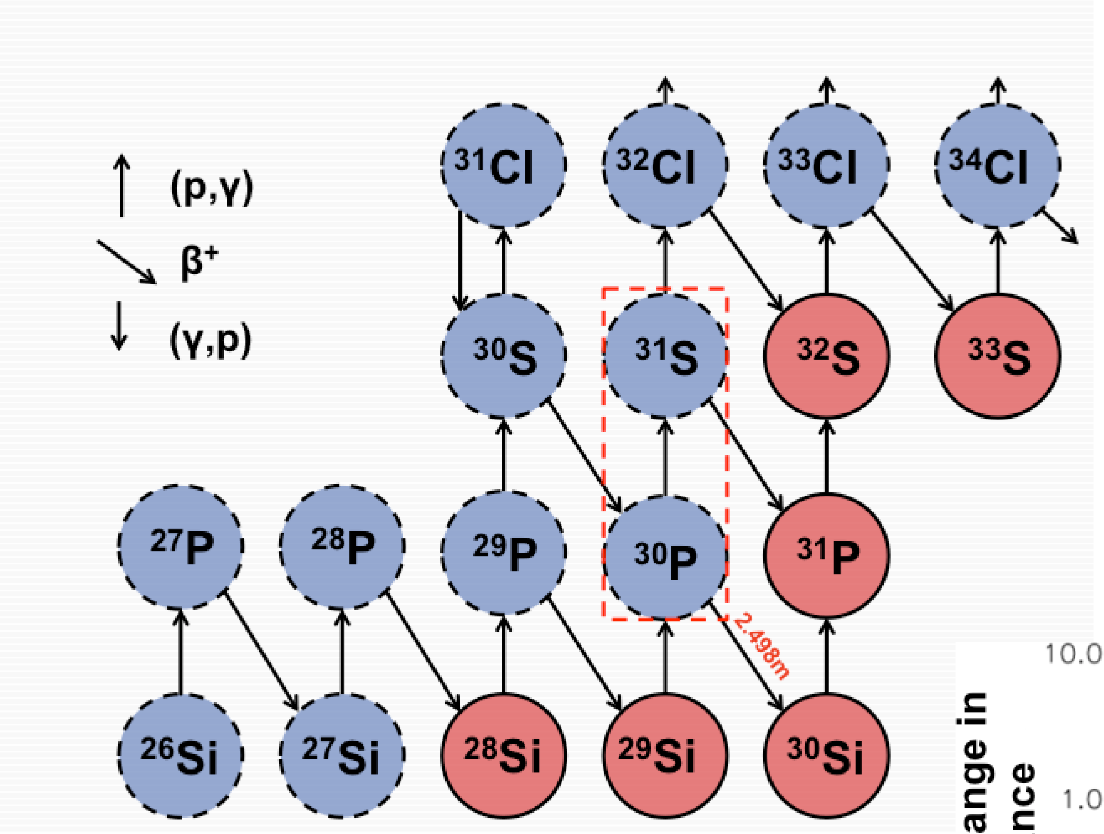
Table 1
Summary of Observed Abundances (in Mass Fractions) for Neon Novae from UV, optical, and IR Spectroscopy

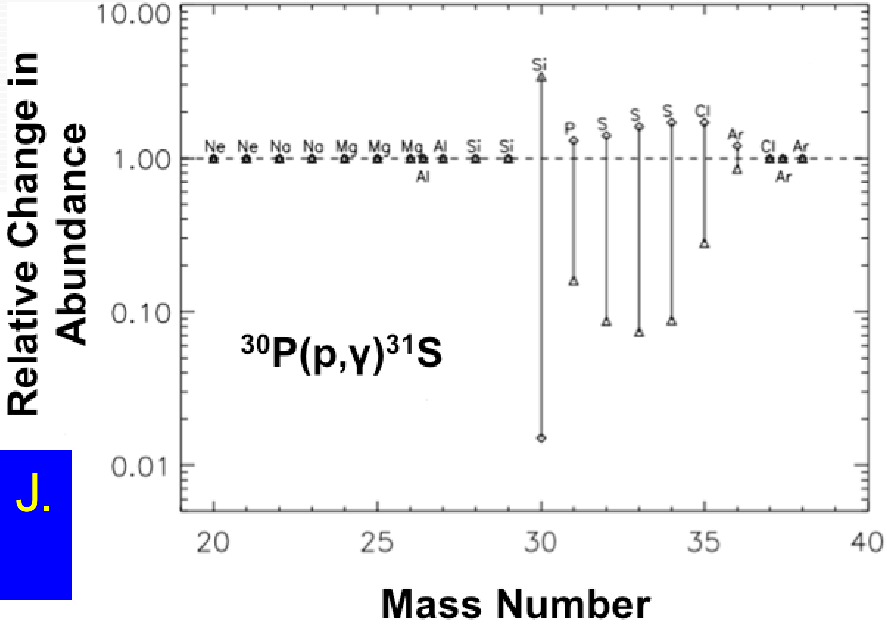
	LMC 1990#1[1]	V4160 Sgr[2]	V838 Her[2]	V382 Vel[3]	QU Vul[4]	V693 CrA[5]	V1974 Cyg[6]	V1065 Cen[7]	Solar[8]
X_{He}/X_H	4.8(8)E-01	7.1(4)E-01	5.6(4)E-01	4.0(4)E-01	4.6(3)E-01	5.4(22)E-01	4.8(8)E-01	5.4(10)E-01	3.85E-01
X_C/X_H	3.7(15)E-02	1.43(7)E-02	2.28(23)E-02	2.6(13)E-03	9.5(59)E-04	1.06(44)E-02	3.1(9)E-03	···	3.31E-03
X_N/X_H	1.48(42)E-01	1.27(8)E-01	3.29(47)E-02	2.28(54)E-02	1.61(10)E-02	1.84(67)E-01	6.0(15)E-02	1.40(33)E-01	1.14E-03
X_O/X_H	2.4(10)E-01	1.35(9)E-01	1.42(38)E-02	4.13(38)E-02	3.2(14)E-02	1.63(66)E-01	1.55(85)E-01	4.7(15)E-01	9.65E-03
X_{Ne}/X_H	1.6(10)E-01	1.38(5)E-01	1.22(5)E-01	4.0(7)E-02	5.1(4)E-02	6.7(34)E-01	9.7(40)E-02	5.34(98)E-01	2.54E-03
X_{Mg}/X_H	1.37(71)E-02	≈8.4E-03	1.2(7)E-03	2.45(14)E-03	1.02(49)E-02	9(7)E-03	4.3(28)E-03	4.4(13)E-02	9.55E-04
X_{Al}/X_H	2.3(11)E-02	···	1.8(13)E-03	1.63(16)E-03	4.1(11)E-03	5.0(46)E-03	>7.8E-05	···	8.74E-05
X_{Si}/X_H	4.8(39)E-02	1.09(6)E-02	7(2)E-03	5(3)E-04	2.4(18)E-03	2.4(18)E-02	···	···	1.08E-03
X_S/X_H	···	···	1.48(15)E-02	···	···	···	···	2.3(13)E-02	5.17E-04
X_{Ar}/X_H	···	···	···	···	4.0(3)E-05	···	···	4.6(17)E-03	1.29E-04
X_{Fe}/X_H	···	2.4(8)E-03	2.35(63)E-03	···	9.53(54)E-04	···	8.8(72)E-03	1.16(40)E-02	1.81E-03
X_H[9]	4.7(9)E-01	4.65(37)E-01	5.63(36)E-01	6.6(4)E-01	6.3(3)E-01	3.8(14)E-01	5.5(8)E-01	3.6(10)E-01	7.11E-01





Nova Nucleosynthesis





$^{30}P(p,\gamma)^{31}S$

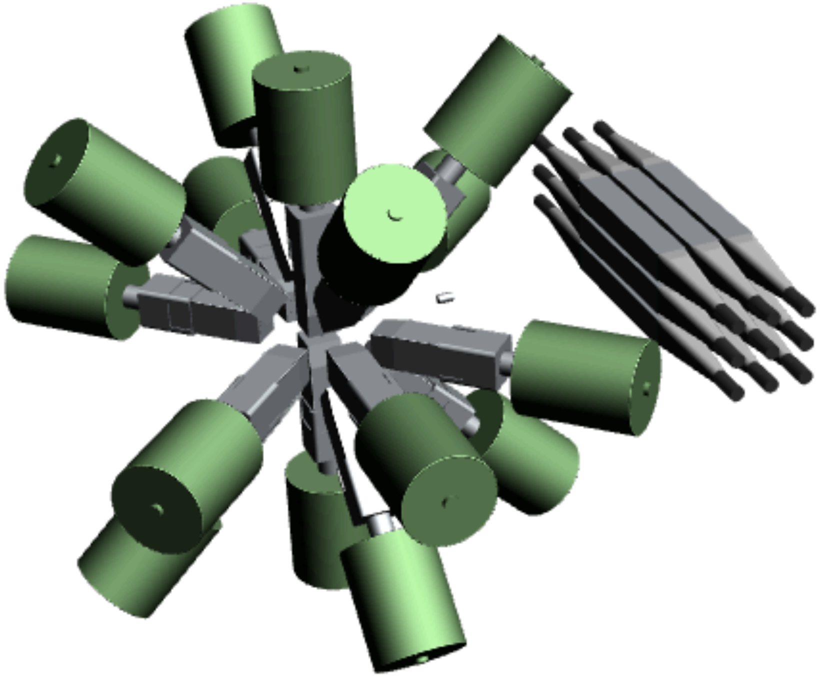
C. Iliadis *et al.*, Astrophys. J. Suppl. Ser. 142, 105 (2002).

Submitted LoI for Astrophysical Measurements with GAMKA at iThemba Laboratory

- **Programme of measurements of key astrophysical nuclei via (^{3}He,*n*) reactions. Including**
  ^{29}Si(^{3}He,n)^{31}**S**
  ^{58}Ni(^{3}He,n)^{60}**Zn**
  ^{40}Ca(^{3}He,n)^{42}**Ti**
  ^{32}S(^{3}He,n)^{34}**Ar**

- **Take advantage of the excellent angular coverage of GAMKA and channel selectivity from the neutron wall**

- **Possibility of determining parities with polarization measurements**

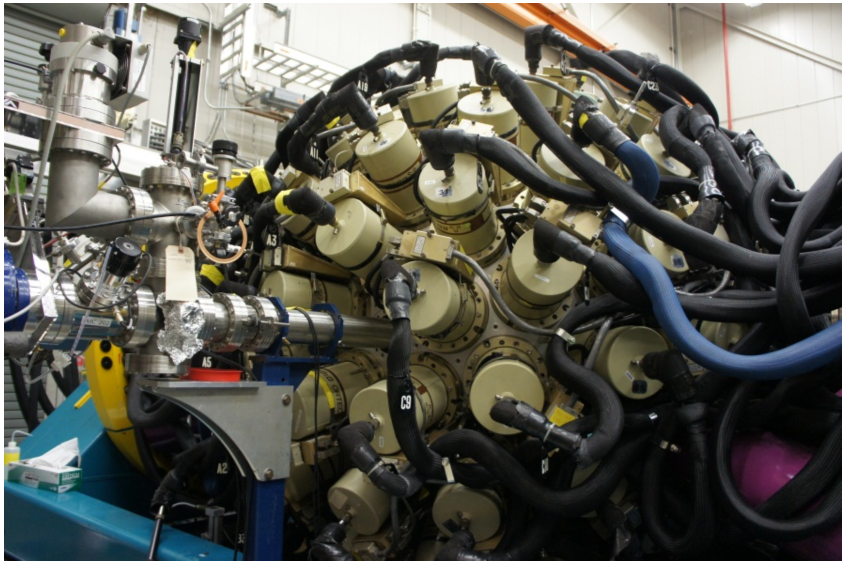


The future GAMKA array in conjunction with the double neutron wall WAFANA WAFANA.

LoI submitted – Surrey, York, iThemba, UWC, Stellenbosch, Brighton

The Power of (^{3}He,*n*) for populating low-spin states

- **Key low-spin states** in ^{26}Si populated in a **^{24}Mg(^{3}He,*n*)** reaction. These were **not observed** in a previous ^{12}C(^{16}O,2*n*) study [D. Seweryniak *et al*., Phys. Rev. C **75** 062801(R) (2007)].
- **Gamma-rays detected with Gammasphere but no additional channel selection.**



The Gammasphere detector array at Argonne National Laboratory

D. T. Doherty *et al*., Phys. Rev. C **92** 035808 (2015)

Inverse Kinematics

In many instances, normal kinematic measurements are not desirable due to the large number of contaminants in radioactive targets and in fact, are often not possible due to the short-lived nature of the nuclei of interest. As such, it is often necessary to perform measurements in inverse kinematics (i.e. heavy beam, light target).

We need to consider what target and reaction is appropriate in this case. Let us again consider investigating the $^{26}Al(p,\gamma)^{27}Si$ *reaction :*

1. ^{3}He is a tricky target option to investigate the ^{26}Al(^{3}He,d)^{27}Si reaction.

2. The ^{26}Al(d,n)^{27}Si transfer reaction is also a surrogate for (p,γ).

3. Deuterium is a viable target option – CD_2 (poly-deuterated ethylene).

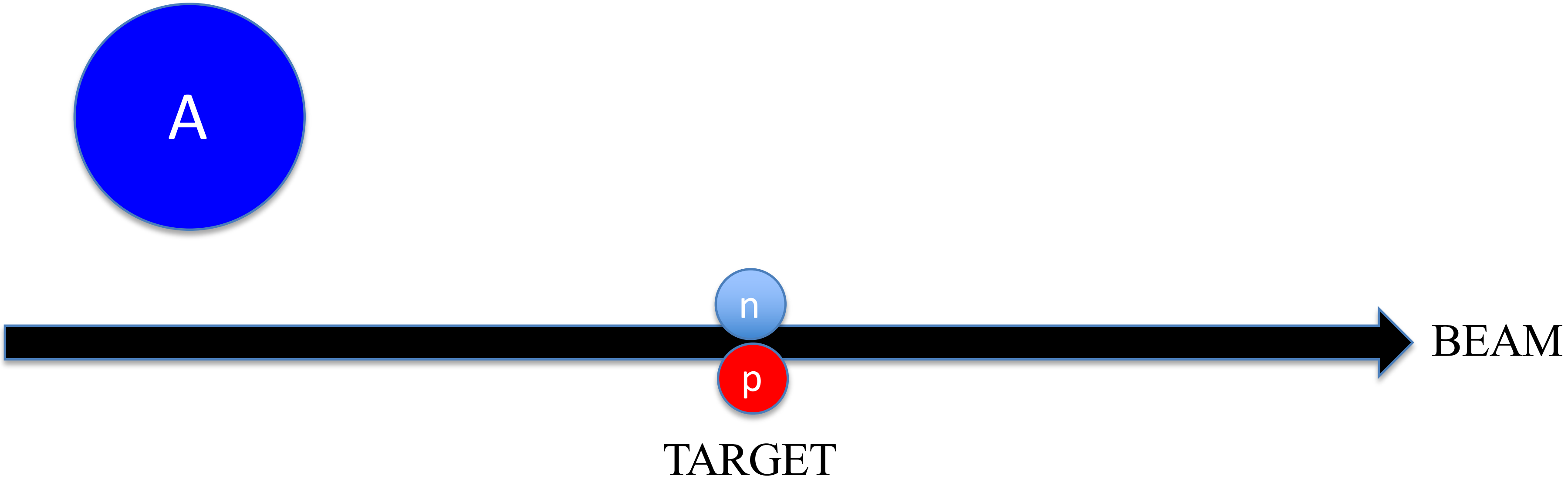
4. However, the detection of neutrons is extremely difficult.

A possible solution to the problem is to use the concept of mirror nuclei as described earlier (where the structures are nearly identical) and measure the neutron spectroscopic factors of the analogue systems in ^{27}Al via the ^{26}Al(d,p)^{27}Al transfer reaction.

Inverse Kinematics : (*d,p*) Reactions

Inverse kinematic (d,p) reactions are fundamentally different to normal kinematic (^{3}He,d) reactions. If we consider a general reaction A(d,p)B :

BEFORE



Inverse Kinematics : (*d,p*) Reactions

Inverse kinematic (d,p) reactions are fundamentally different to normal kinematic (^{3}He,d) reactions. If we consider a general reaction A(d,p)B :

AFTER

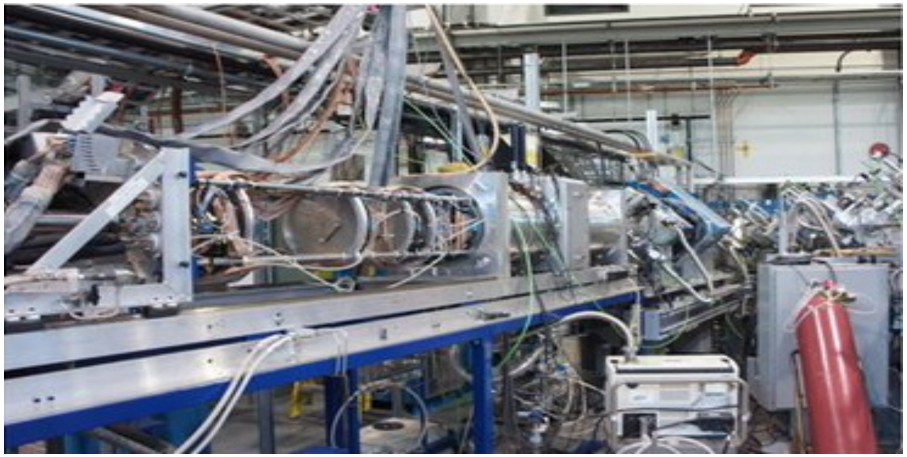
Protons are emitted at backward laboratory angles

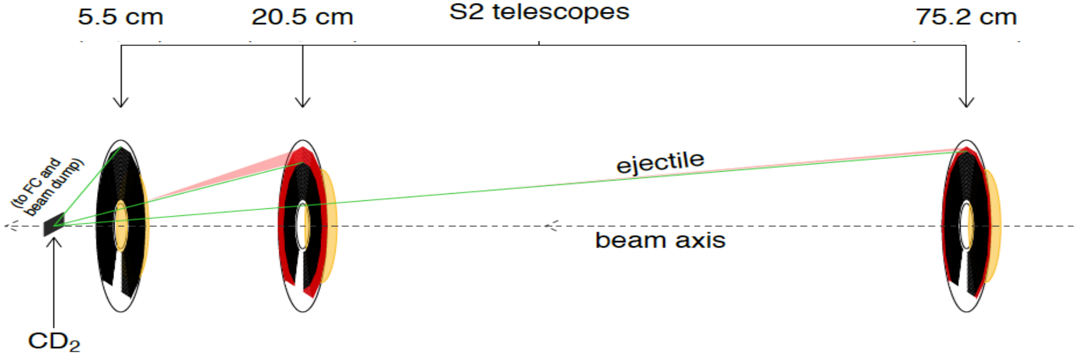
Inverse Kinematics : (*d,p*) Reactions

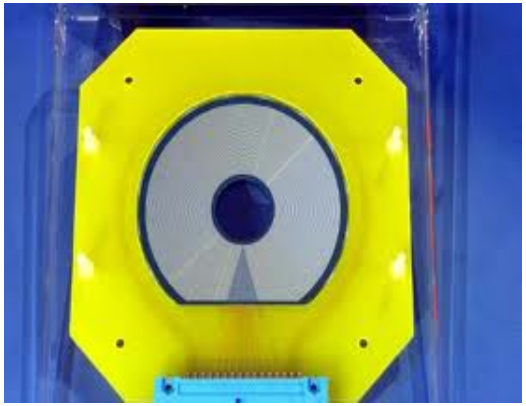
We still want to cover the region of importance for nuclear astrophysics (i.e. centre-of-mass angles 0° – 30°). As such, the first thing we will need to do is convert from the centre-of-mass angles to laboratory angles, in order to determine where we need to perform the measurement.

$$\boxed{\tan(\theta_{lab}) = \frac{\sin(\theta_{cm})}{\cos\left(\theta_{cm}\right) + \frac{m_p}{m_B}} \rightarrow \theta_{\exp} = 180 - \theta_{lab}}$$

Consequently, protons need to be detected at laboratory angles from ~ 180 – 150°.

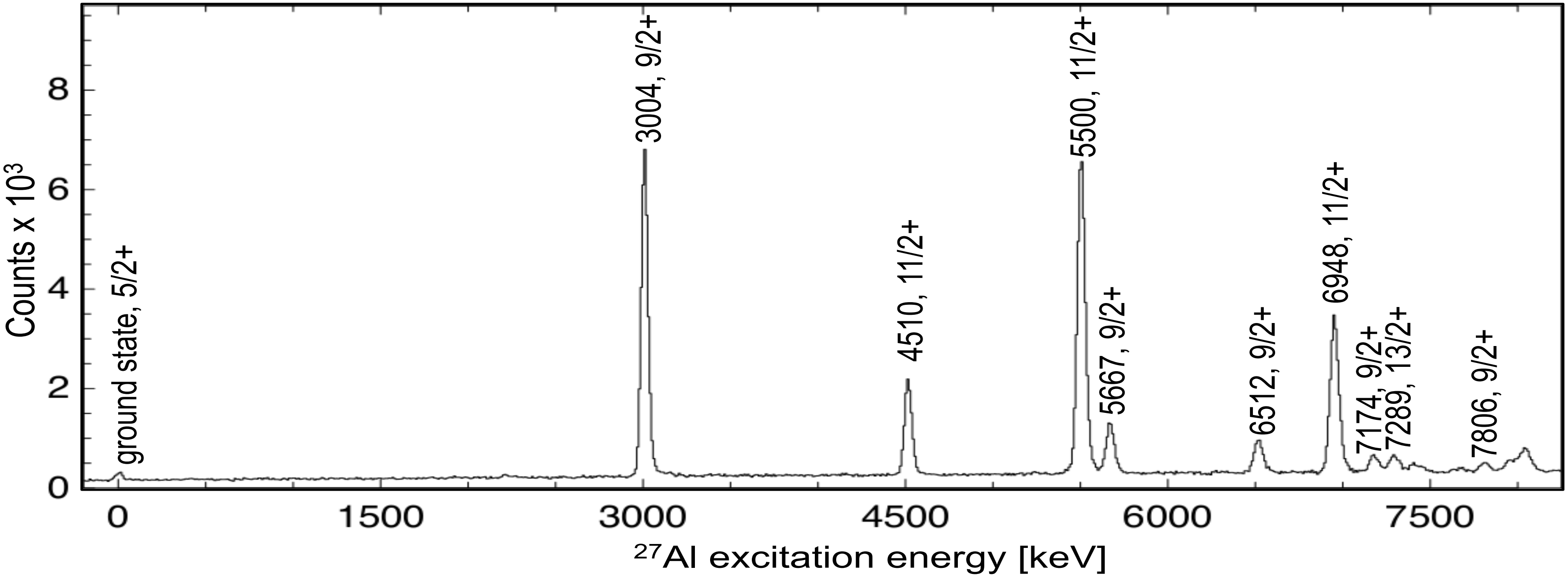


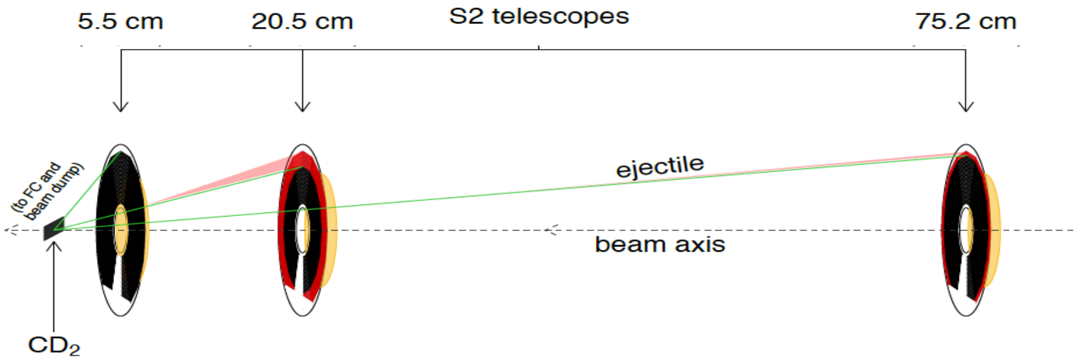


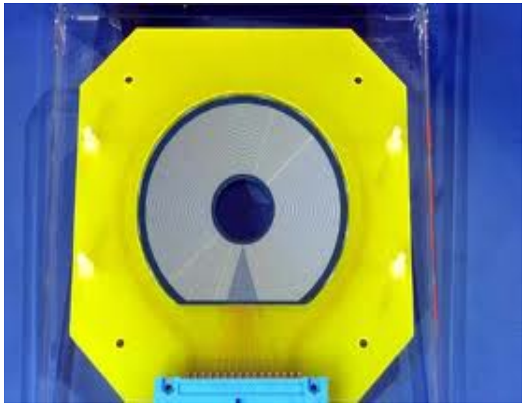


Inverse Kinematics : (*d,p*) Reactions

Annular silicon strip detectors are placed at backward laboratory angles and used to detect resulting protons.



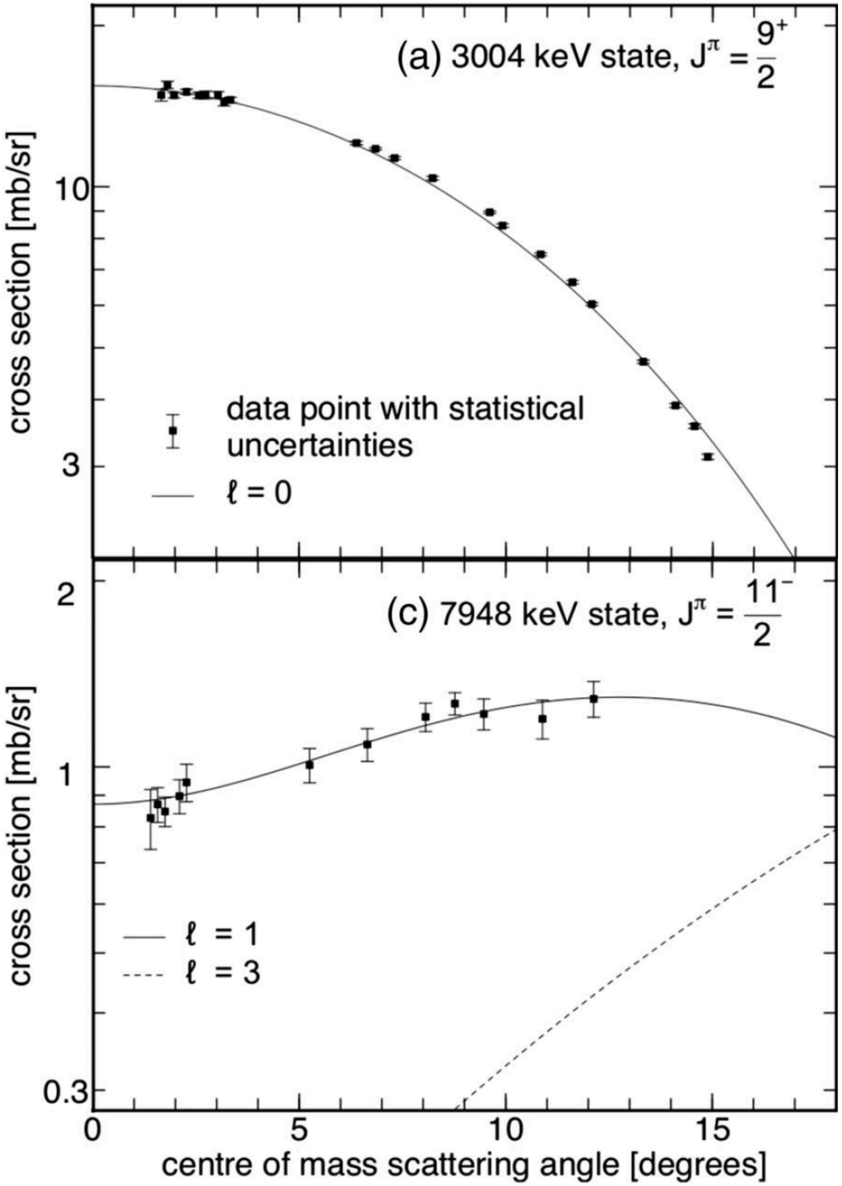




Inverse Kinematics : (*d*,*p*) Reactions

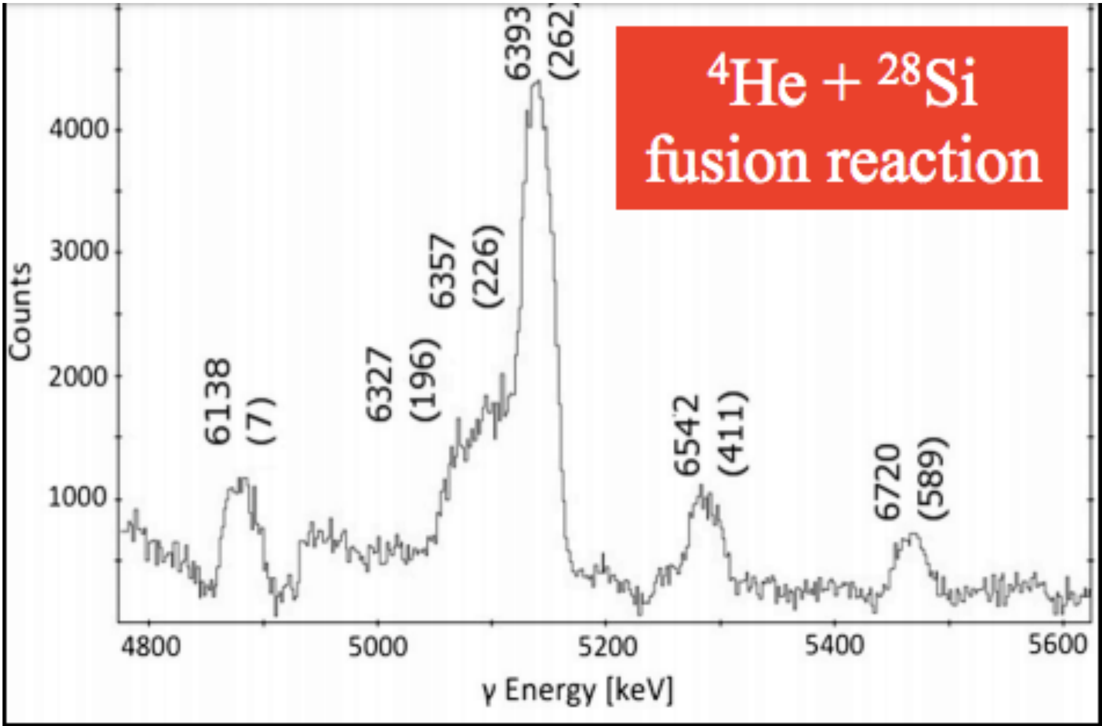
$$\frac{d\sigma}{d\Omega} = \frac{N_{\text{det}}}{N_{BEAM} \cdot N_{TARGET} \cdot \eta \cdot d\Omega}$$

$$\frac{d\sigma}{d\Omega}(\exp) \propto C^2 S \frac{d\sigma}{d\Omega}(theory)$$

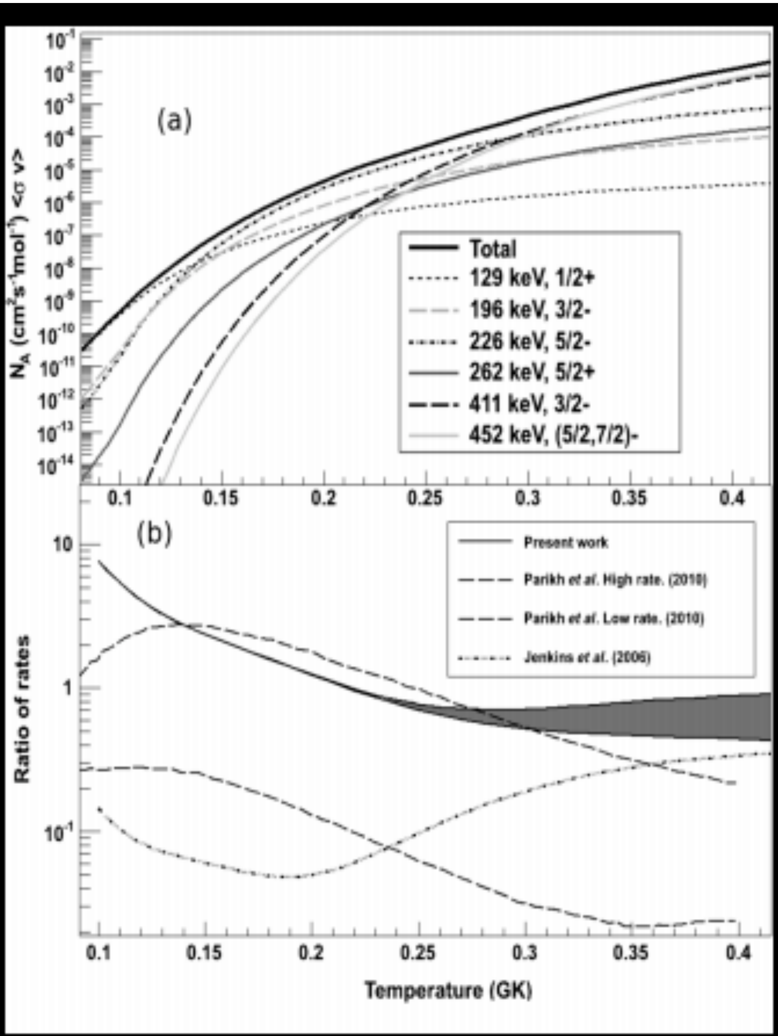


V. Margerin *et al.*, Phys. Rev. Lett. **115** 062701 (2015) … and …
S. Pain *et al.*, Phys. Rev. Lett. **114** 212501 (2015)

Identifying Key Resonant States for the ^{30}P(p,γ)^{31}S reaction



^{4}He + ^{28}Si fusion reaction



- Obtained precise E_r and J^π for all resonances $E_r \leq 505$ keV
- Key remaining uncertainty in RESONANCE STRENGTHS

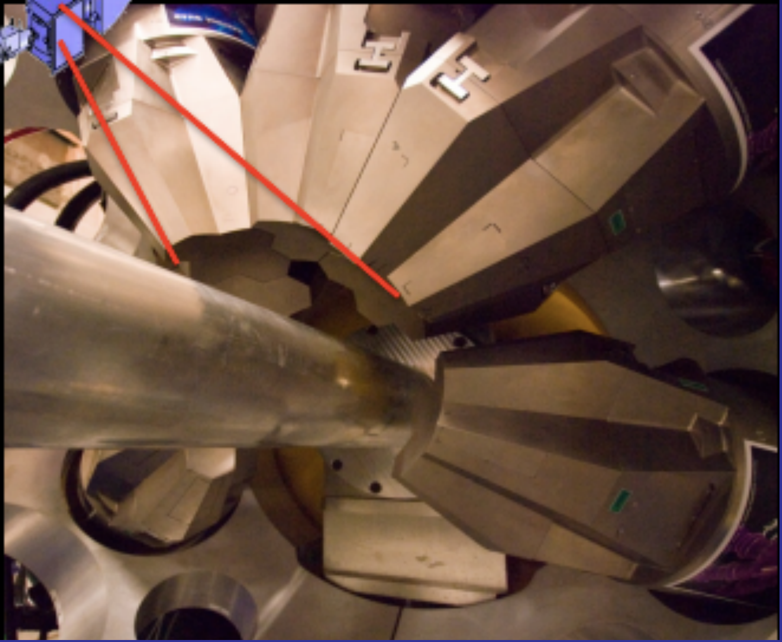
D.T. Doherty, G. Lotay *et al.*, Phys. Rev. Lett. 108, 262502 (2012).

First Attempt at Determining the Resonance Strengths : Fragmentation beams at NSCL

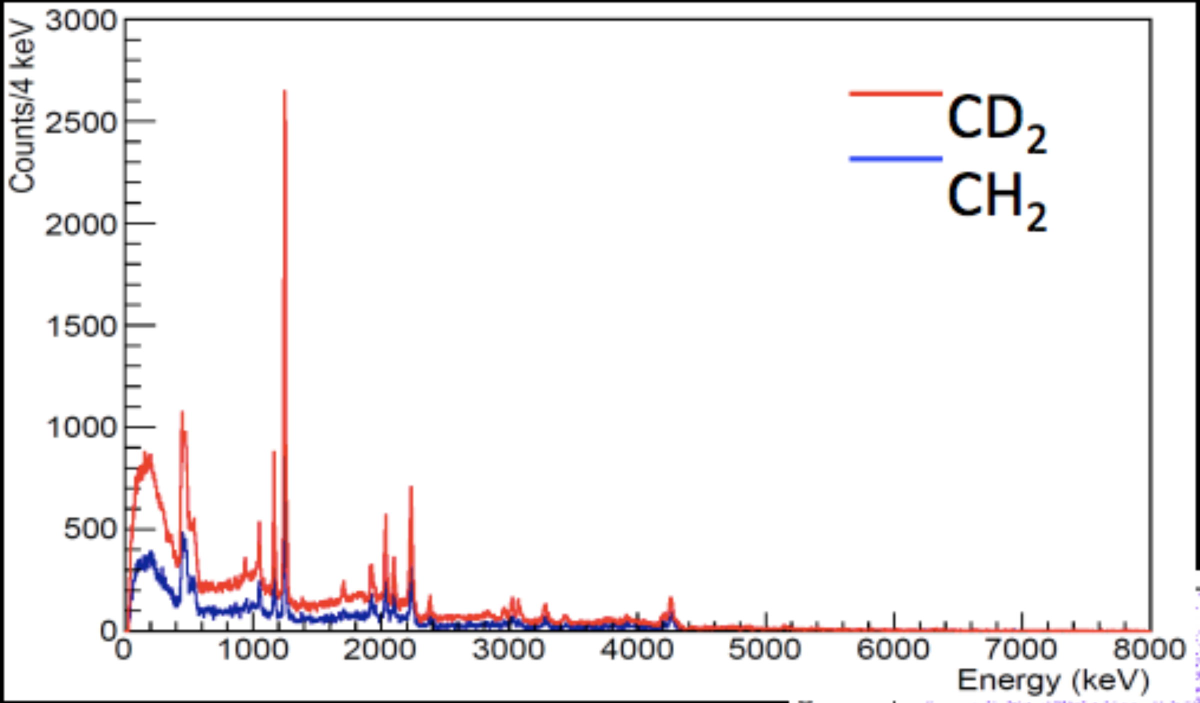
- 75pnA beam of ^{36}Ar on ^{9}Be target to produce ~10^6 pps ^{30}P (30 MeV/u)
- Bombarded ~ 0.2 mg/cm^2 thick CD_2
- GRETINA used in coincidence with S800 to gate on ^{31}S γ rays

Reaction product identification by S800 spectrograph

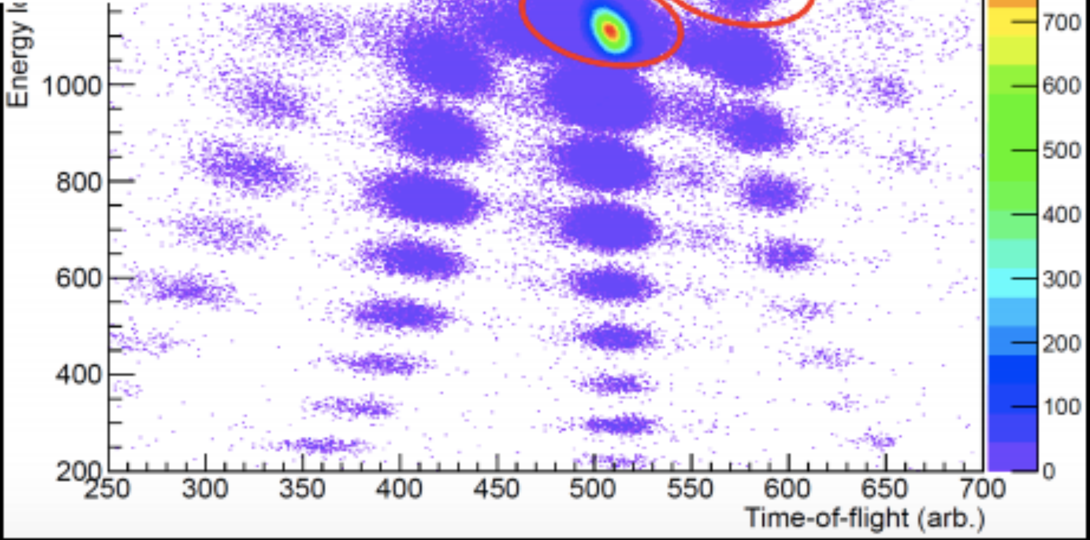
A1900 fragment separator



First Attempt at Determining the Resonance Strengths : Fragmentation beams at NSCL



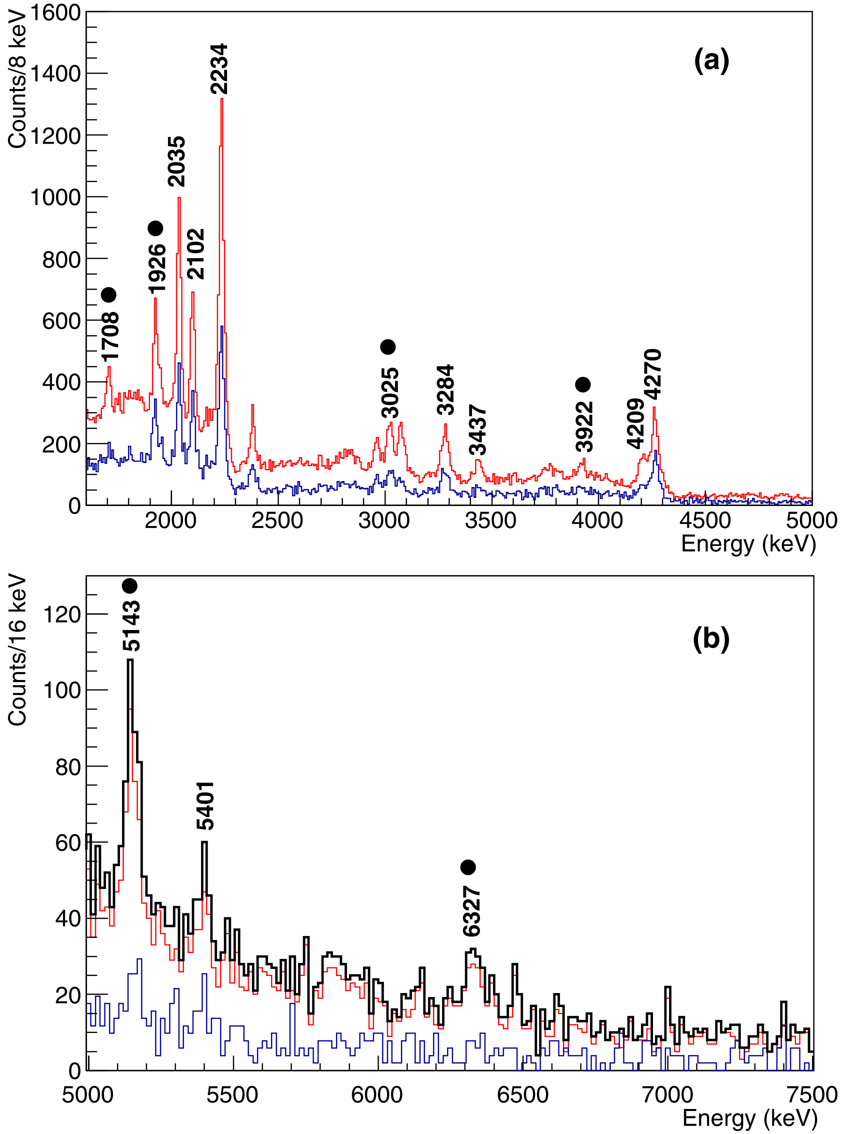
- Gate on known γ rays from key ^{31}S resonant states



- Obtain angle-integrated cross section from recoils in S800

First Resonance Strength Information

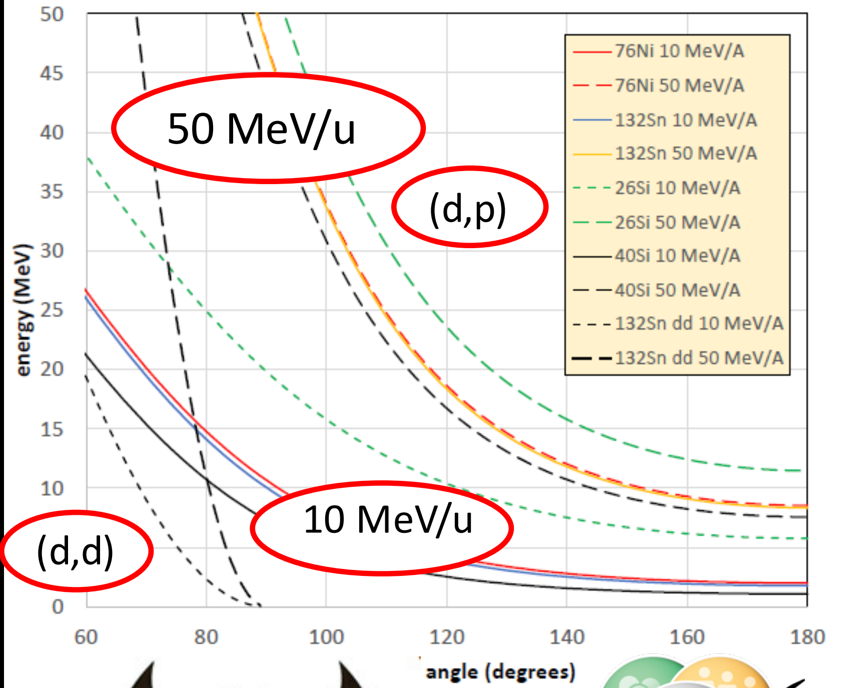
- Challenging measurement but with some interesting results
- To progress one needs to move from an integrated cross-section to a differential one
- Detect light-ion close to the target position



A. Kankainen *et al*., Phys. Lett. B **769** 549 (2017)

DRACULA – Surrey/UK Proposed Light-Particle Array for (d,p) and (^{6}Li,d) (t,p) etc., at FRIB

G LOTAY, D T DOHERTY & W N CATFORD (Surrey UK)



DRACULA

FRIB

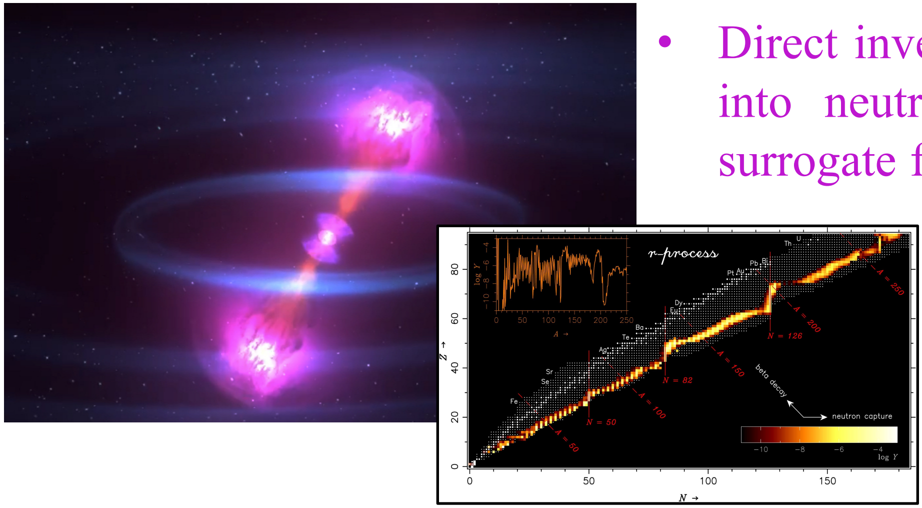
DIRECT
REACTION
ARRAY
for the
CORE
UNDERSTANDING
of
LIGHT NUCLEI
and
ASTROPHYSICS

BUILDING ON OUR PREVIOUS SILICON
SUCCESSES AND COLLABORATION

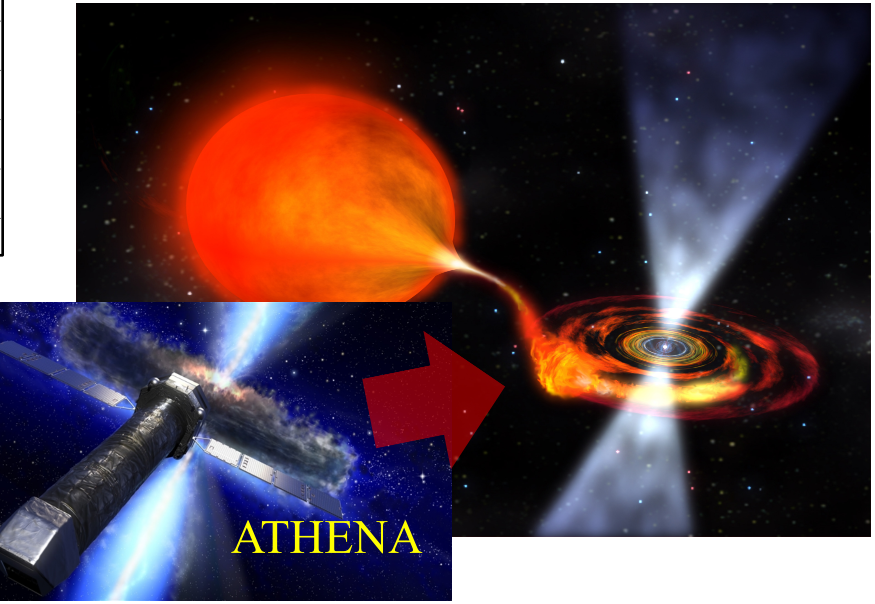
TIARA

sharc

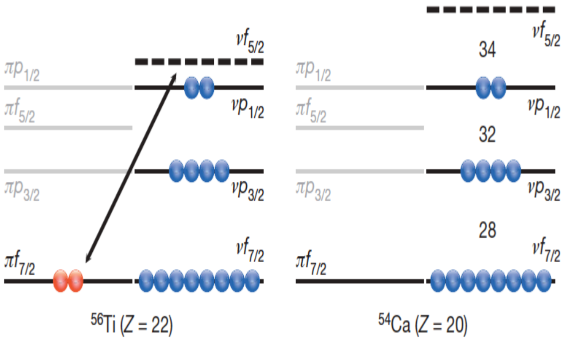
- existing arrays such as GODDESS at RIA3 are ideal for reaccelerated FRIB beams
- the **OPPORTUNITY** is for a dedicated array to exploit slower fast beams
- designed to mount in front of the S800
- designed to fit inside GRETA/GRETINA
- while 10 MeV/A is ideal for assigning ℓ_{transfer}, 50 MeV/A still **works fine** for transfer
- there will be no untagged beam contaminant
- there will be no chemistry or breeding issues
- we can use **any of the beams** from FRIB
- we will need **higher stopping power**
- we will need low noise, especially to extend to (^{9}Be,^{8}Be$\rightarrow\alpha\alpha$) etc.
- we have costed **digital electronics** with 300 MHz sampling to allow Si-PSD with nTD silicon
- the electronics/DAQ would be designed to also be suitable to connect to GODDESS
- we foresee important extensions to study (t,p) and (p,t) with GRETA and in-flight beams
- Discussions and collaboration with SDP, AG, BMS

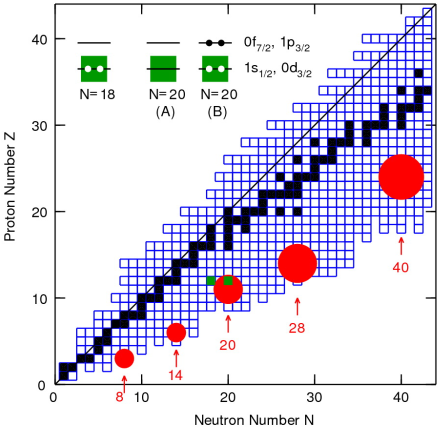


- Direct investigation of *r* process reactions and insight into neutron star mergers [e.g. ^{76}Ni(d,p)^{77}Ni as a surrogate for (n,γ) reactions around ^{78}Ni]



- Study of proton-rich nuclei involved in the *rp* process and their influence on X-ray bursts – targets of the ESA's ATHENA satellite [e.g. resonance strengths in the ^{56}Ni(α,p) reaction via ^{56}Ni(^{6}Li,d)]

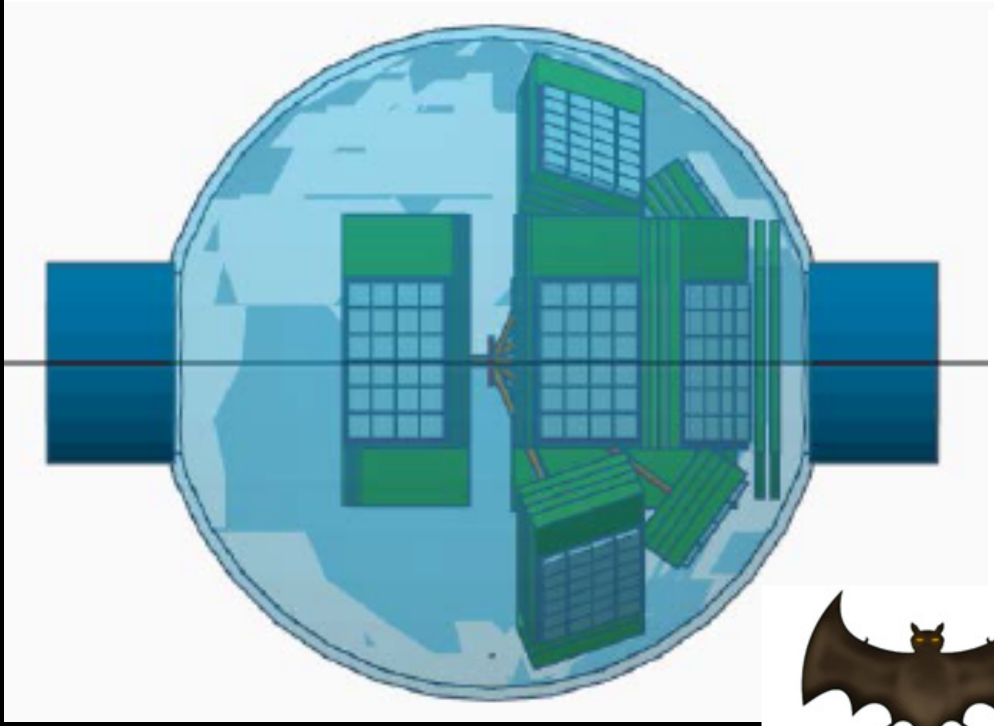




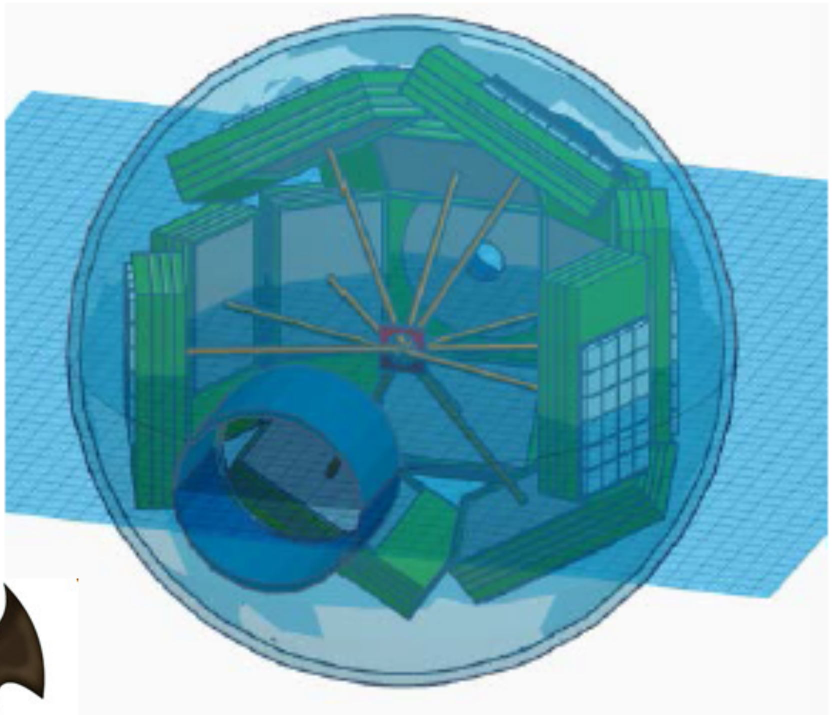
- Study of the evolution of magic numbers away from stability via single nucleon transfer reactions [e.g. ^{54}Ca(d,p)] and the 2nd island of inversion [e.g. ^{64}Cr(d,p)]

DRACULA – Surrey/UK Proposed Light-Particle Array for (d,p) and (^{6}Li,d) (t,p) etc., at FRIB

VIEW FROM BEAM-LEFT SIDE

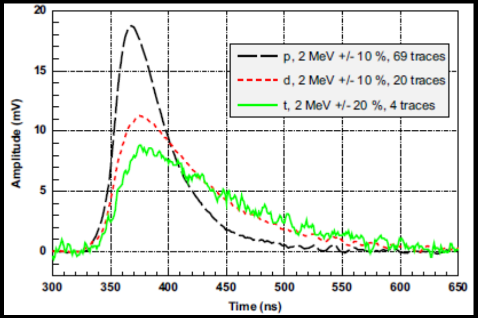


VIEW TOWARDS BEAM-ENTRY PORT



DRACULA

VOLTAGE TRACES FOR 2 MeV SIGNALS FOR p, d, t ; 50ns/div
[Data: Orsay NIM A732, 87 (2013)]



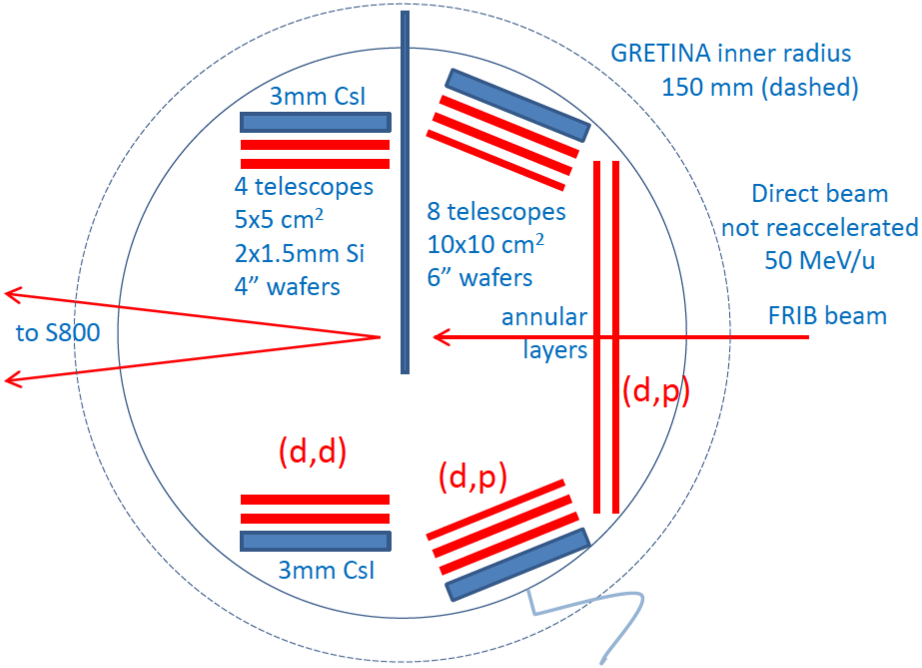
PRESENT STATUS of PROJECT: OUTLINE PROPOSAL ACCEPTED BY STFC, July 18.
Full submission requested for 2019 start date.

<u>PRELIMINARY DESIGN</u> FOR COSTINGS (£3.7m/4years incl. manpower)

Telescopes of 4” Si DSSD 1mm + 2 x SiPAD 1.5mm + CsI/SiPM 3mm
Initial instrumentation for (d,p) at up to 50 MeV/u & elastic normalization
Feedthroughs to air for each channel, fast ASIC preamps in air
New custom digital electronics/DAQ; liaison with FRIB for compatibility
1500 channels, 250 or 500 MHz sampling, 14-bit; PSD with nTD Si possible

The UKRI (STFC’s parent) HAS ALSO REQUESTED a bid for an EXTENDED PROJECT that will include A FULL S800 UPGRADE.

DRACULA at iThemba(?)



GRETINA inner radius
150 mm (dashed)

3mm CsI

4 telescopes
5x5 cm²
2x1.5mm Si
4” wafers

8 telescopes
10x10 cm²
6” wafers

Direct beam
not reaccelerated
50 MeV/u

FRIB beam

to S800

annular
layers

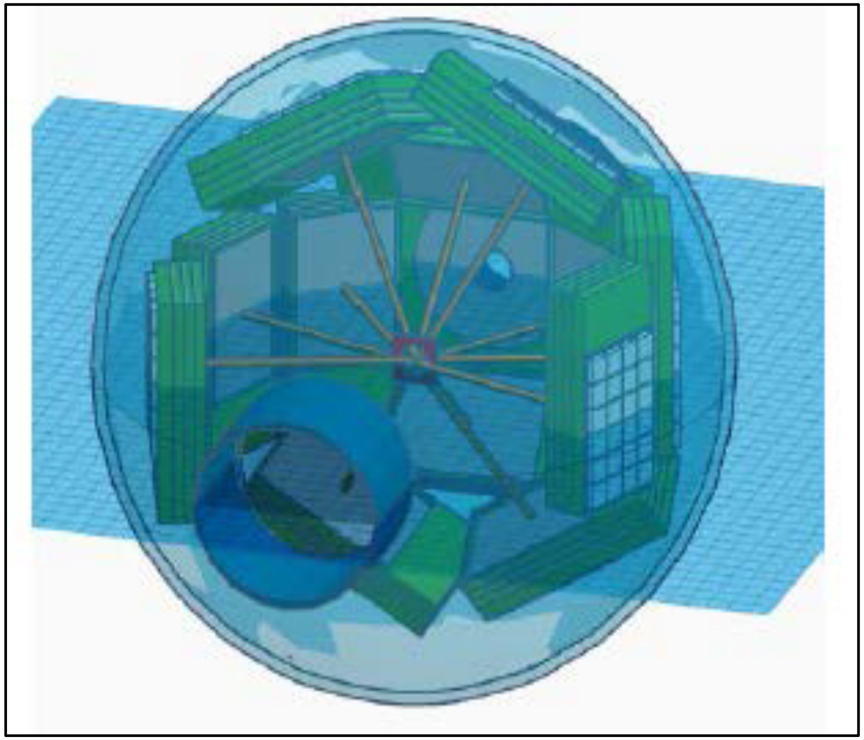
(d,p)

(d,d)

(d,p)

3mm CsI

Cables take signals out of vacuum for digitisation



- It would be invaluable to commission DRACULA with stable beams (and still do some great physics!).
- Few places in the world with the combination of high-energy beams, a world-leading gamma-ray array (GAMKA) and a spectrometer for identifying reaction products
- Number of astrophysically important (p,t) and (p,d) reactions to be done