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Studies of Nuclear Structure and Nuclear Astrophysics

- Research Activity of I. Wiedenhöver and Graduate Students
  - Big-Bang Nucleosynthesis
  - Type-Ia SN-ejecta and X-Ray-Burst Timescales / Nucleosynthesis
  - Super-radiance and Continuum Interactions
  - Collectivity in exotic N=28 nuclei

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Topic 1: Big-Bang Nucleosynthesis
(Section 4.1)

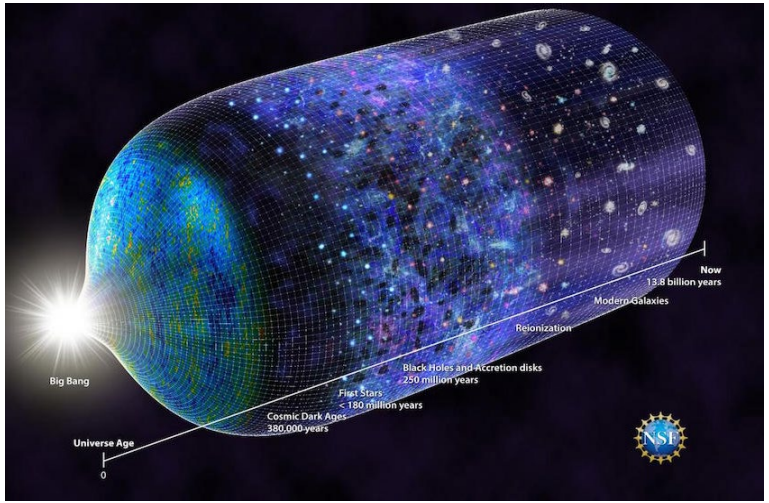
- Measurement of d+^{7}Be reactions affecting destruction of ^{7}Li during Big-Bang nucleosynthesis (BBN)
  - Experiments at FSU with SE-SPS and Sabre
  - Experiments at TRIUMF with ANASEN

How to investigate the Big One

1) WMAP, Planck: Cosmic Microwave Background analysis gives “Baryon density”
(CMB originates 300000 years after B.B.)

2) Optical spectroscopy on ultra-metal-poor Halo stars gives elemental incl. Lithium-abundance
(originates 3-8 minutes after B.B)

3) Future: Direct detection of primordial neutrinos
(seconds after B.B.)



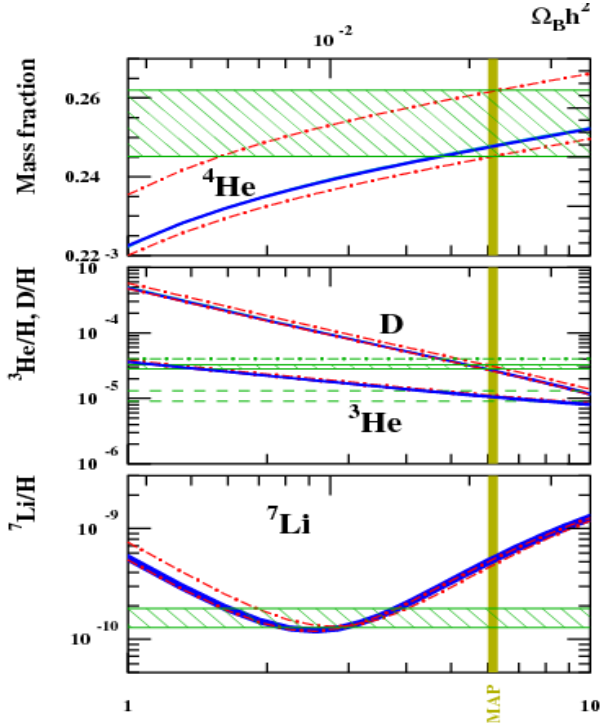
Proposed method: $t + \nu \rightarrow^3 He + e^-$

- Exceedingly difficult; $E_\nu = 2 \cdot 10^{-4}$ eV
- 10 events / year / 100g of Tritium
- Upper limits expected from Katrin
- Proposed project for detection: Ptolemy
  (Princeton / Argonne / Savannah River / INFN)

Precise Nuclear Physics information is needed to investigate the consistency between these messengers and Cosmology;

Primordial Nucleosynthesis, the "Primordial Lithium Problem"

Mass-fractions of light elements as function of Hadron density η



$(6.079 \pm 0.09) \times 10^{10}$

A. Coc et al. PRD 87,123630 (2013)R.

Observed values:

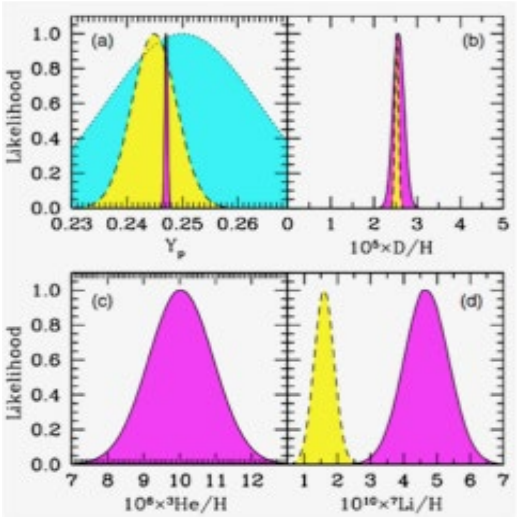
^{4}He/H = (0.244–0.258)×10^0

D/H = $(2.82^{+0.20}_{-0.19})\times10^{-5}$

^{3}He/H = $(0.9 - 1.3) \times 10^{-5}$

^{7}Li/H = $1.58^{+0.35}_{-0.2} \times 10^{-10}$

Sbordone et.al., A&A 522, A26 2010



Yellow: observation

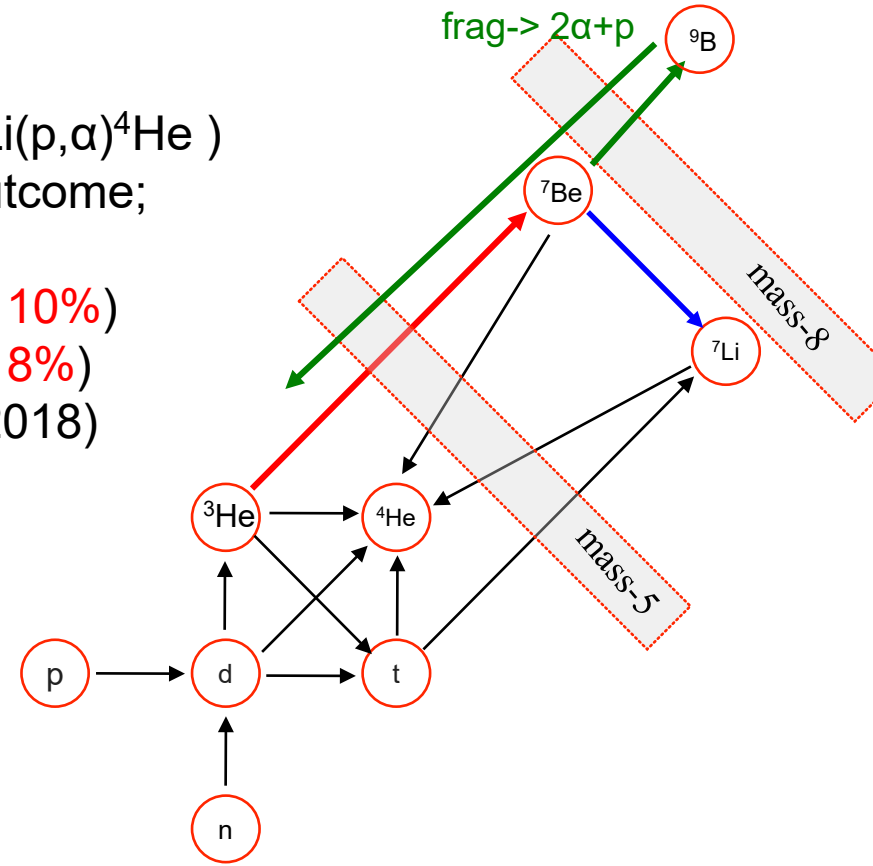
Magneta: BBN calculation, with "nuclear" uncertainties.

R. Cyburt et al.: RMP 88, 15004 (2016)

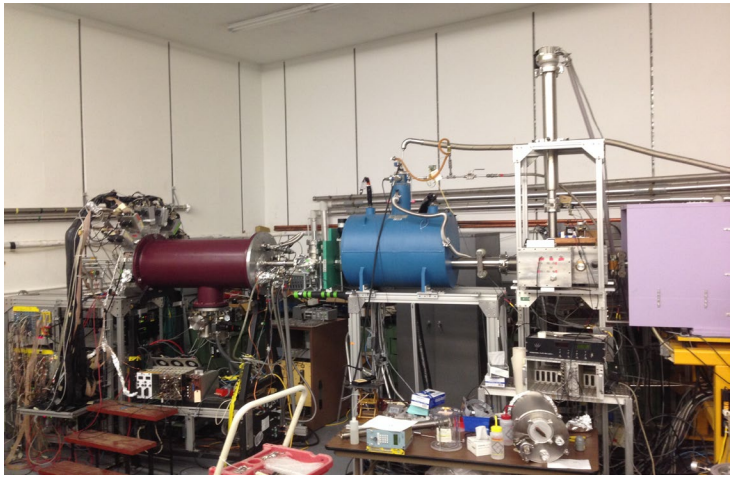
Nuclear Processes Affecting Primordial ^{7}Li

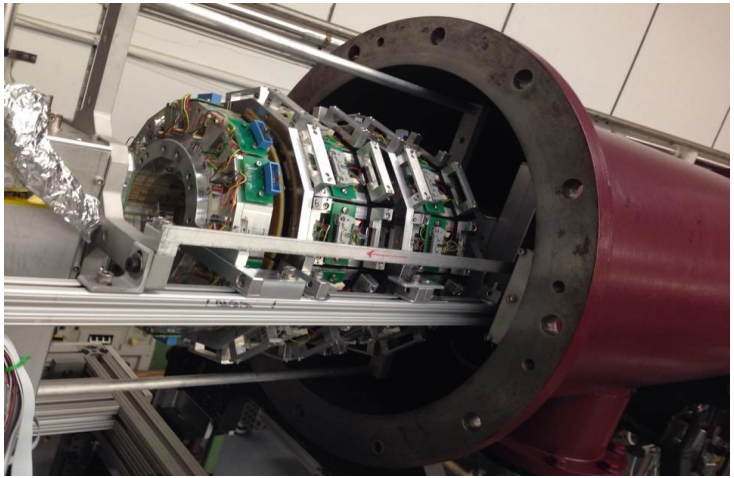
Primordial ^{7}Li produced in ^{7}Be → ^{7}Li EC decay “after it’s over” ($T_{1/2}$ = 53.2 d)
(^{7}Li is destroyed quickly at high Temp.; ^{7}Li(p,α)^{4}He)
In order of importance for the ^{7}Be (^{7}Li) outcome;

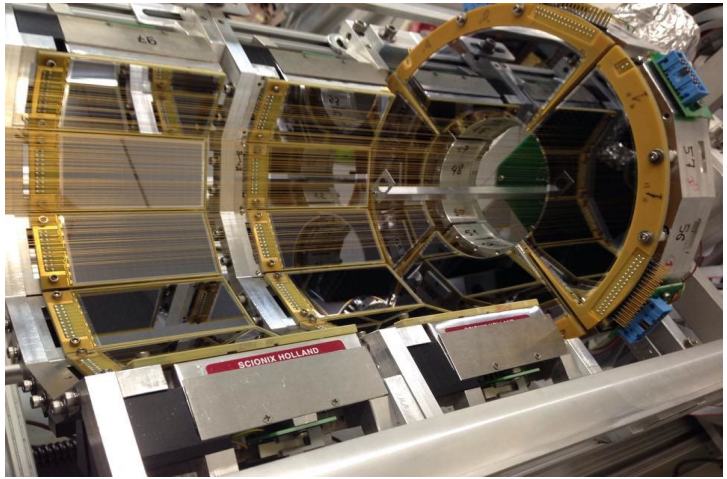
1) Production ^{3}He(α,γ)^{7}Be (rate known to 10%)
2) Destruction ^{7}Be(n,p)^{7}Li (now known to 8%)
   n-tof collaboration, PRL 121, 042701 (2018)
3) Destruction: ^{7}Be(d,α)^{5}Li(p)^{4}He
   Little was known before,
   after FSU exp. Rijal et al. [148]:
   known within factor 0.5..3,
   leads to ^{7}Li reduction by 1-8% .



Anasen at FSU



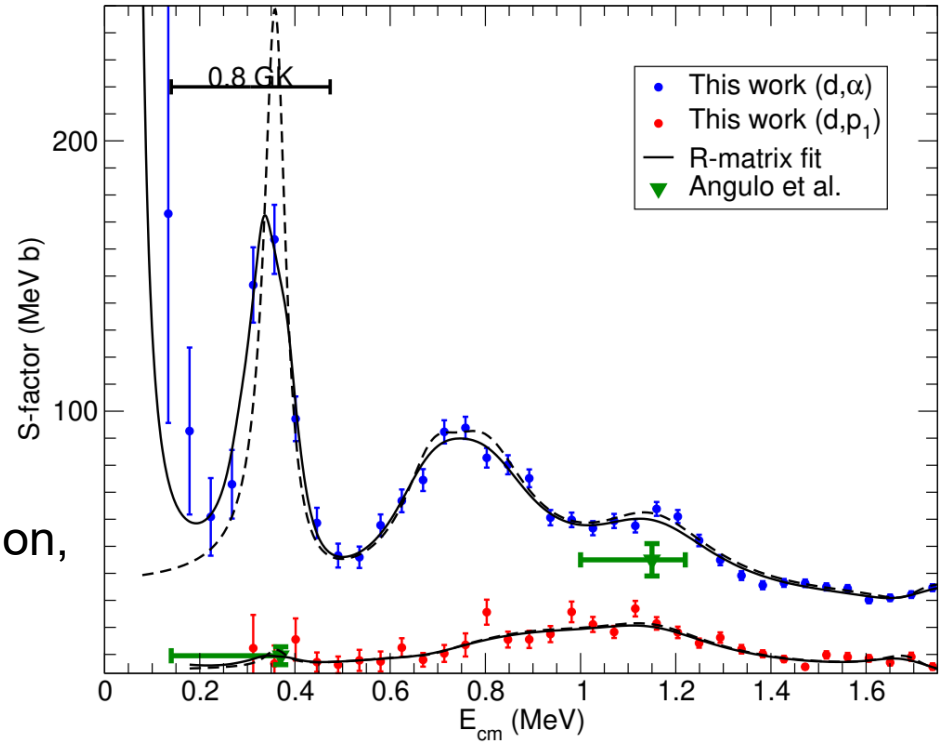




ANASEN: d+^{7}Be Cross Section

Rijal et al. PRL 122, 182701 (2019)

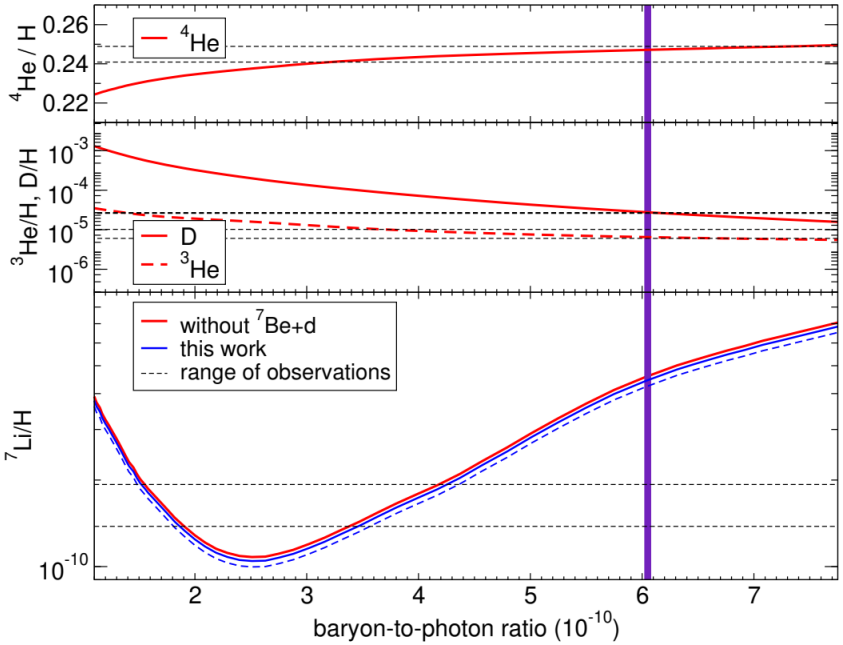
- Cross section is dominated by (d,α) channel, very little (d,p)
- Observed resonance at E_{cm} =0.36(5) MeV
- Data analyzed with R-matrix fit, including detector resolution, and without (dashed)
- Cross section below 0.2 MeV uncertain because of limited resolution, acceptance for (d,p)
- Two data-points of Angulo et al. consistent with (d,p) channel at low energies



BBN outcome including the new ^{7}Be+d rate

Rijal et al. PRL 122, 182701 (2019), Erratum 123, 239902 (2019)

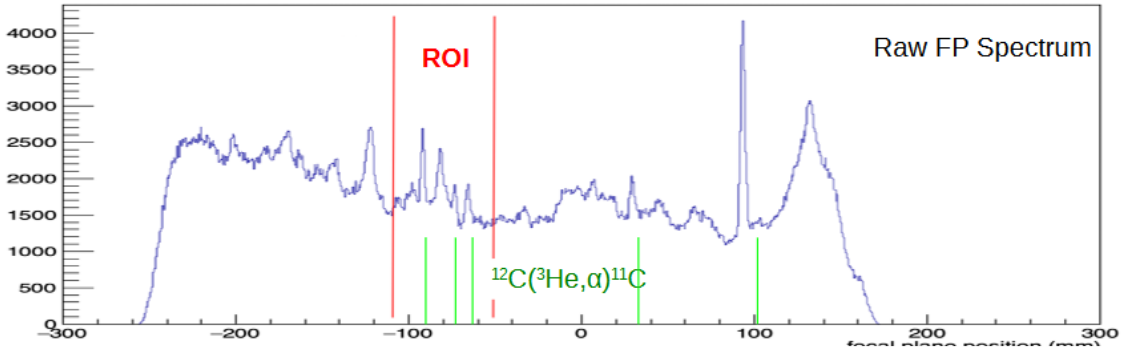
- Using SBBN, H_0 = 67.9 km/s/Mpc found by Planck (Ade et al. 2016)
- Using updated Reaclib-network (Cyburt et al. 2010)
- Without d+^{7}Be reaction, $Li^{7}/H = 4.67 \cdot 10^{-10}$
- With d+7Be reaction $Li^{7}/H = 4.24..4.61 \cdot 10^{-10}$
- The reaction results in <= 8% reduction of BBN Li production
- The data from our experiment does not solve the primoridal Lithium problem.
- Large uncertainties remain, stemming from resonance parameters.

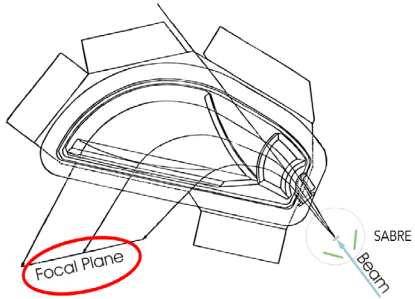


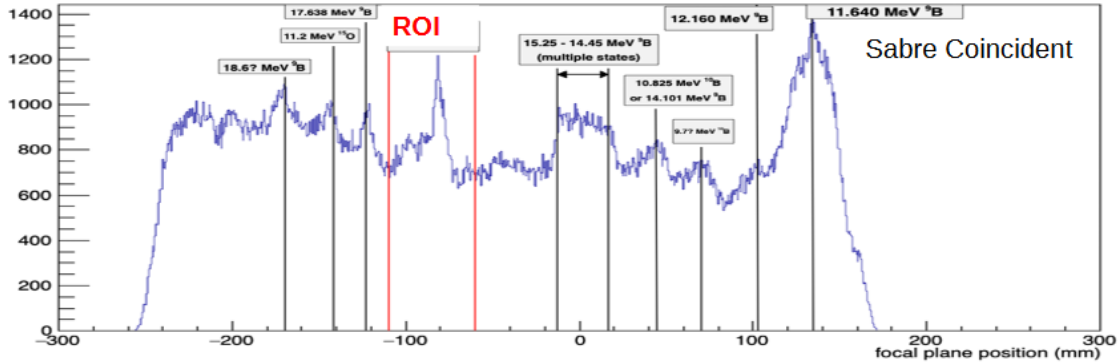
Experiment at SE-SPS + Sabre: $^{10}B(^{3}He,\alpha)^{9}B$

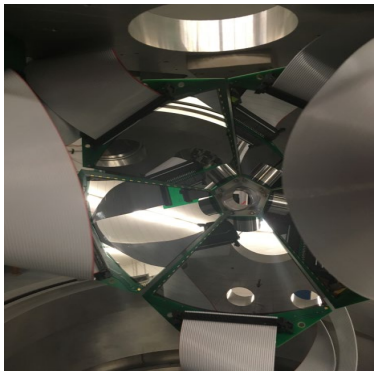
(Ph.D. Thesis Gordon McCann)

- Measure $^{10}B(^{3}He,\alpha)^{9}B$ to populate d+^{7}Be 16.8 MeV (5/2+) resonance, determine energy with spectrograph, coinc. with decay α / d / p



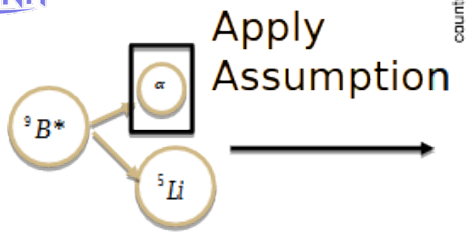


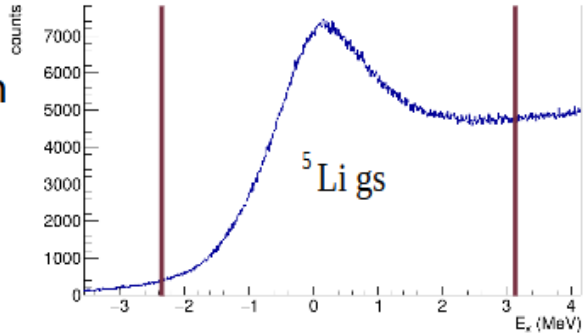


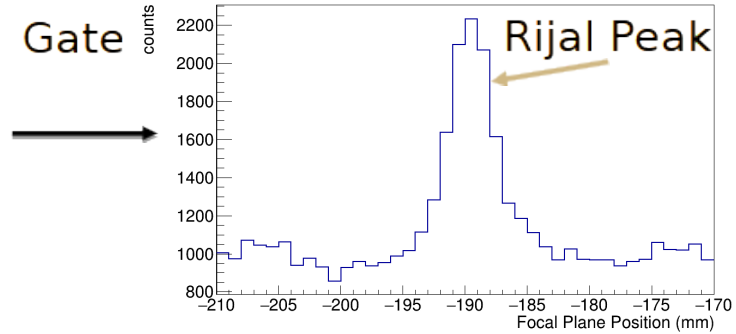


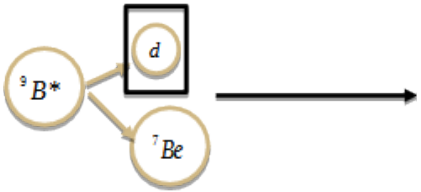
Decay-Channel Identification 1

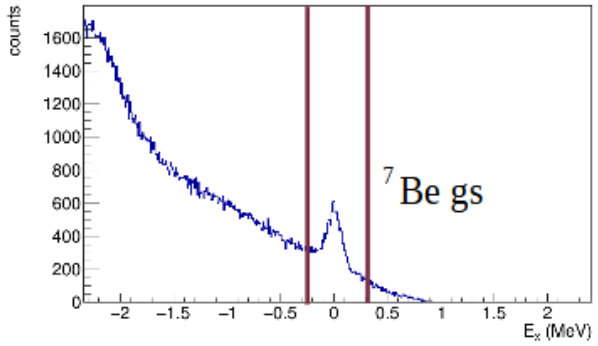
- Reconstruct Q-values for α- and d- decays, SE-SPS & Sabre kinematics:

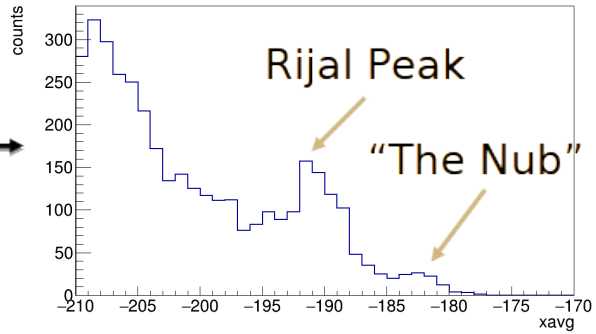








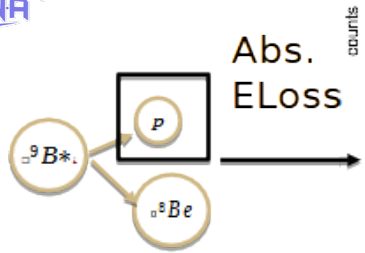




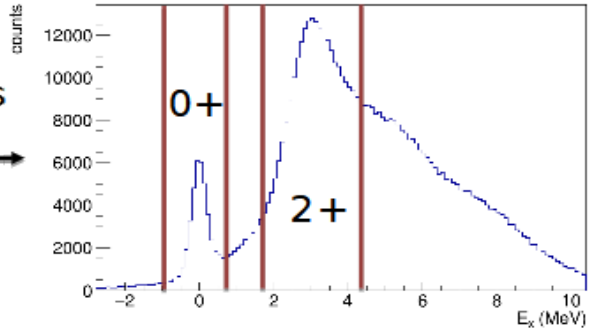
Who ordered that ? A "Nub" appears in the ^{7}Be + d channel, at E_R=0.161 MeV

Decay-Channel Identification 2

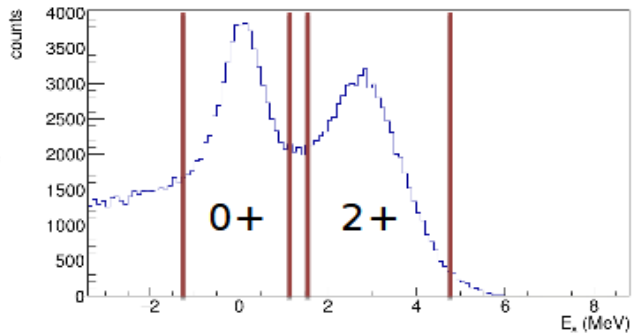
Reconstruct Q-values for p- decays + (Absorber/Punch-through) correction



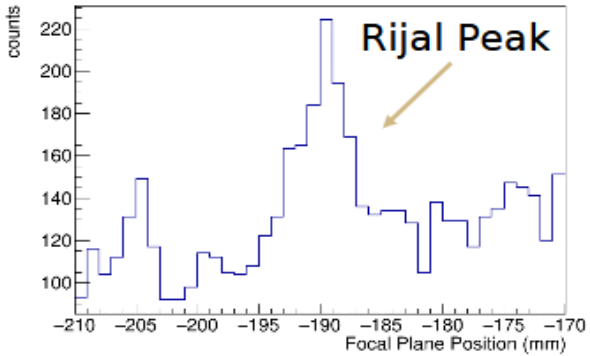
Abs. ELoss



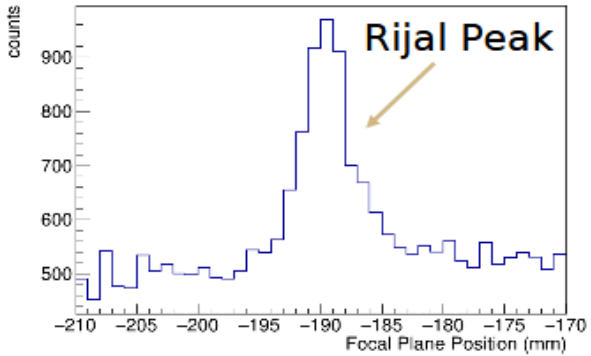
Abs. & Punch Thru



Gated on 0+ gs



Gated on 2+ 1st ex



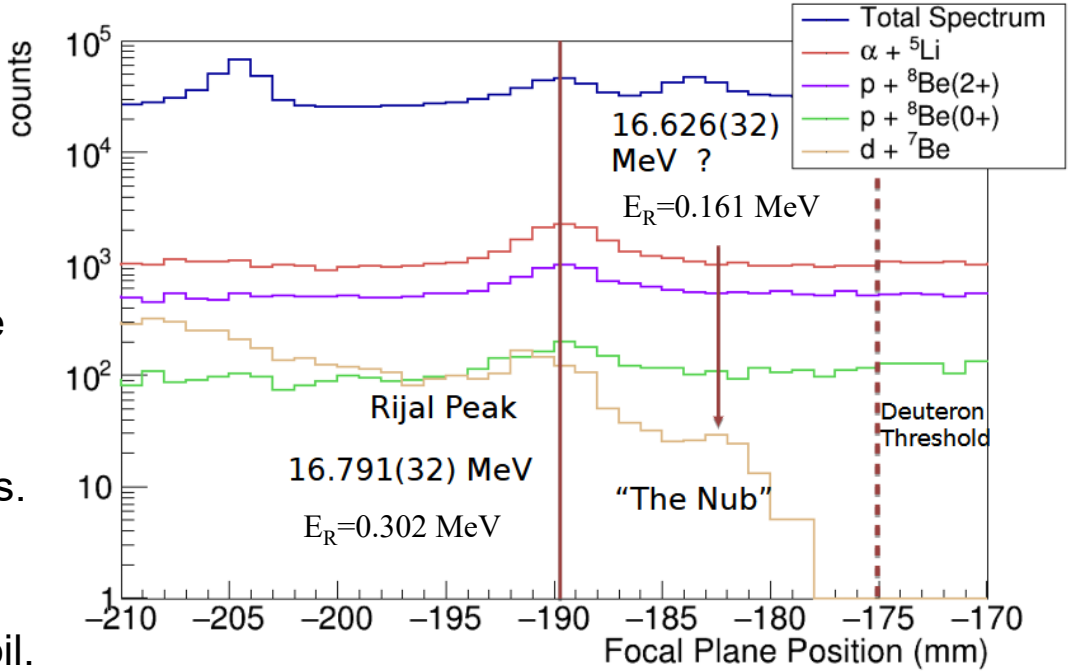
Resonance Parameters “Rijal” Peak

	E_x(MeV)	E_r(keV)	Γ(keV)	Γ_α(keV)	Γ_d(keV)	Γ_{p0}(keV)	Γ_{p2}(keV)
Exp. 1	16.805 (20)	317(20)	55(9)	33(6)	4(1)	—	—
Exp. 2	16.791 (32)	303(32)	58(9)	38(6)	4(1)	2(1)	12(2)
Rijal[1]	16.848 (50)	360(50)	54.3	50	3.3	—	1
Scholl[2]	16.800 (10)	312(10)	80(5)	—	—	—	—

1. Rijal, N. et al. Measurement of d + Be 7 Cross Sections for Big-Bang Nucleosynthesis. Physical Review Letters 122, (2019).
2. Scholl, C. *et al.* High-resolution study of the 9Be(3He,t)9B reaction up to the 9B triton threshold. *Phys. Rev. C* **84**, 014308 (2011)

The State of the State(s)

- The parameters of the "Rijal" peak have been determined with high precision and confidence.
- The "Nub" offers a conundrum:
- At E_R=0.161 MeV, it would have a major impact on ^{7}Be+d reactions.
- It is not resolved in p,α channels.
- It could also be a background signal from ^{16}O(^{3}He,α)^{15}O, in coincidence with the ^{15}O recoil.



- We have scrutinized the data but can not exclude this possibility.

This Proposal, Y1: Repeat the experiment with SE-SPS + Sabre at different kinematics and with better PID (Thesis Adam Ring)

Triumf Experiment S1849: Excitation Function of d+^{7}Be

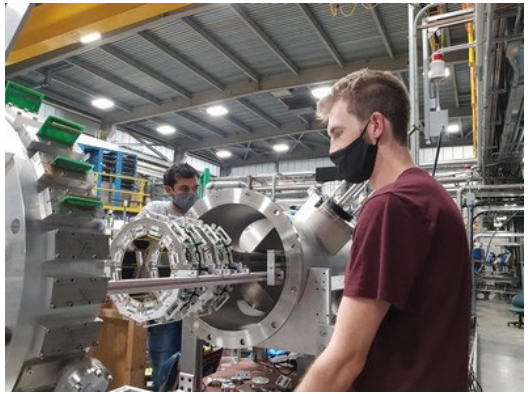
Excitation function with thin, solid CD_2 target inside ANASEN, config. with 3.2π coverage, Si only.

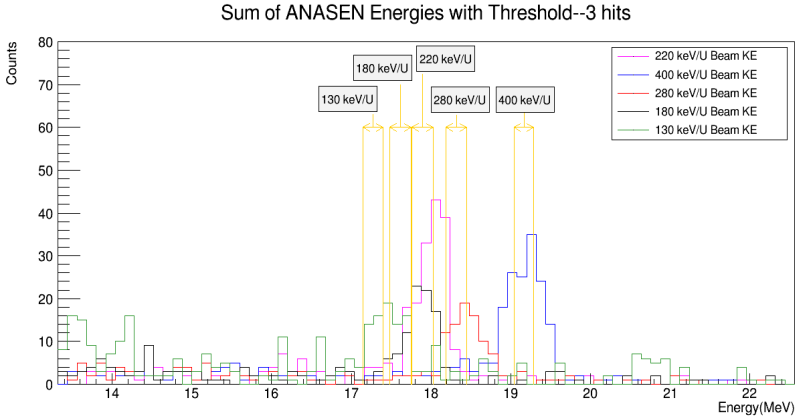
@TRIUMF: Installed Oct 2021, Exp. in November 2021

Detected triple coincidence p+α+α,

BUT:

- Beam delivered a factor 10 below request, for half of the time, at 5 energies.
- Accelerator tuning is crucial: Beam energy shows systematic deviation, not covering the 161 keV resonance
- DAQ problems (diagnosed after run) killed the experiment for good.





This Proposal, Y2-3:

Repeat experiment IF the 161 keV resonance is REAL (Thesis Adam Ring)

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Topic 2: Nucleosynthesis in Stellar Explosions

- Context (Sect 2.2): Nuclear reactions affecting
  - outer layers of TIa SN, CCSN, (α,p) process (XRB, Novae)
- Results on ^{25}Al(p,γ), ^{18}Ne(α,p)
- Proposed ANASEN experiments

Ejecta of Type-Ia Supernovae (P.Hoeflich, FSU)

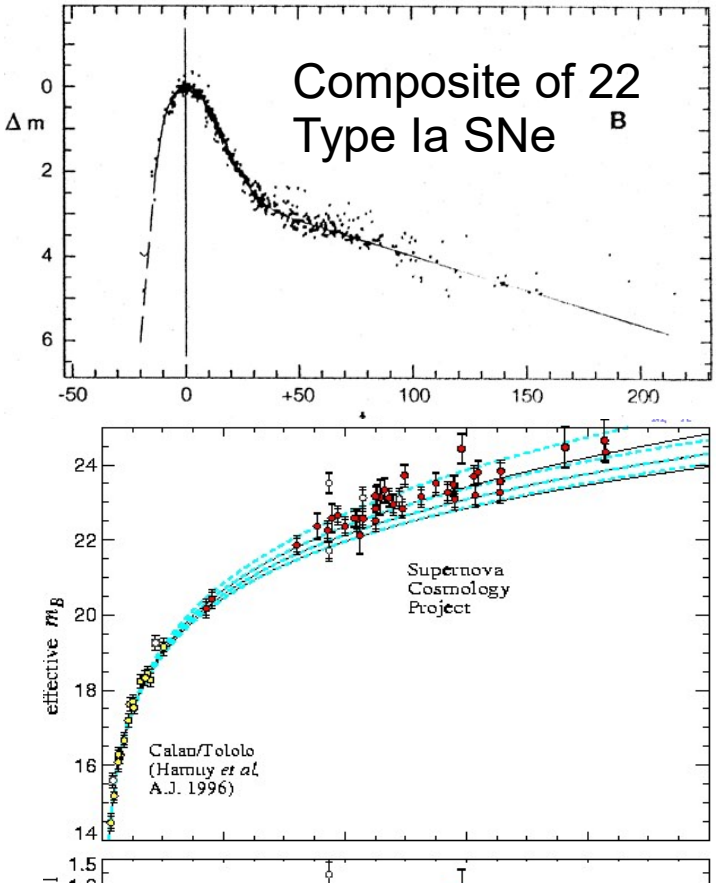
Type-Ia Supernovae (SNe) are standard(izable) candles, used to quantify accelerating expansion of universe.

P. Hoeflich et al.: Investigate the role of the progenitor star on the light curve.

Details matter: Helium / Hydrogen-rich accretion, ignition mechanism

Binary system:
Accretion of material to a White Dwarf, approaches Chandrasekhar limit, conflagration – detonation transition

Or: White Dwarf – White Dwarf merger (Double-Degenerate)

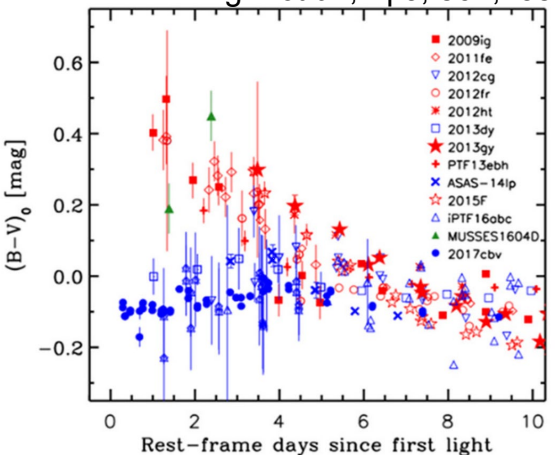


Ejecta of Type-Ia Supernovae (with P.Hoeflich, FSU)

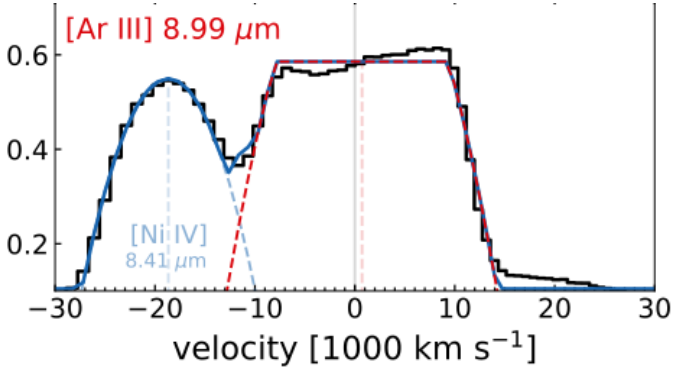
- Early-light observations show the outer layers of the progenitor star, NS products of accreted material, Early light is much more diverse than the later “standard candle” light.
- Right: Observations show two classes of early SNe Ia lightcurves; (“red” vs. “blue”)
- Exciting detailed observations from SN Ia now possible with James-Webb telescope: Right: MIR Ar-III lineshape asymmetric, “shell” of ^{36}Ar ejected at ~13.5 km/s.

Precise Observations create challenge for theory and Nuclear physics !

Stritzinger *et al.*, ApJ, 864,L35



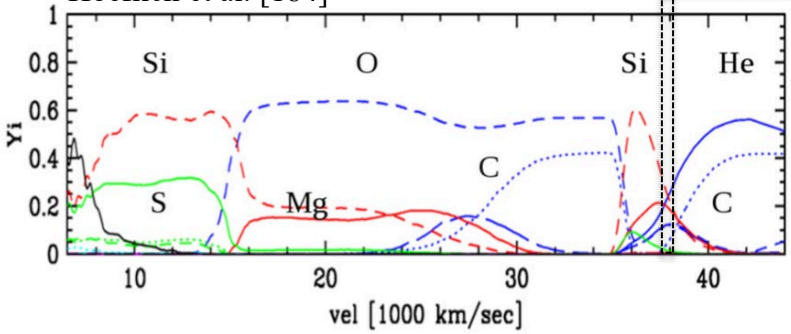
[185] Kwok et al. ApJL 944, L3 (2023)



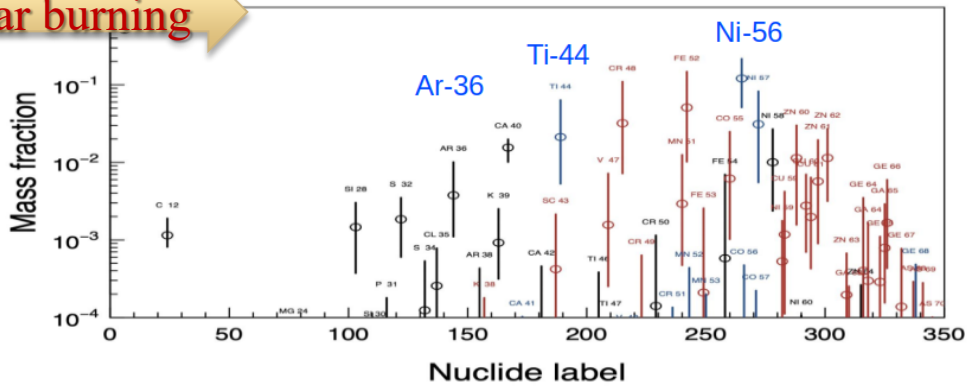
Nuclear Sensitivity Study on TIa SN

- Collaboration between P. Hoeflich (FSU), C. Iliadis (UNC) and I.W.
- Test sensitivity of chemical composition in outer layers of Tia SN on nuclear reaction rates, especially in the outer Helium-layers.
- Reaction rates varied independently within uncertainty, using Starlib [186]
- Reaction Rates matter, equilibrium not reached.
- Large uncertainties in key isotopes, e.g. Ar-36, Ti-44
- Key reactions to be studied in this proposal:
  ^{44}Ti(α,p) (see SAC) ^{39}K(p,α), to be measured with ANASEN (GS, Y3)

Layers of progenitor star, Helium accretion
Hoeflich et al. [184]



Nuclear burning



The ^{18}Ne(α,p)^{21}Na reaction

High-impact reaction in (α,p) process nucleosynthesis.
Parikh et al. [188] and Cyburt et al. [203]

Difficult Experiment:

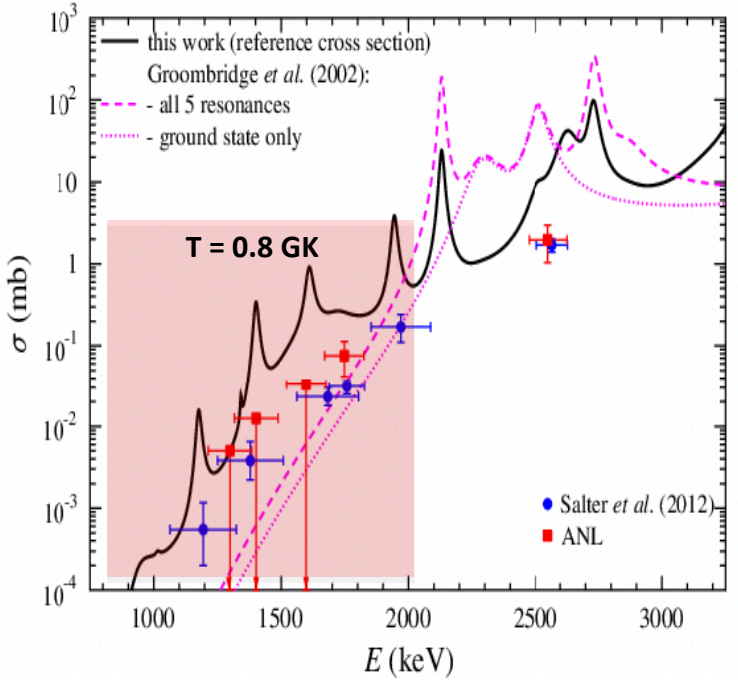
- Short-lived ^{18}Ne nucleus, limited intensity
- He-gas targets
- Relevant cross sections very low,
  5 mbarn – 1μbarn

Previous studies:

- 1999,2002 Groombridge *et al.*:
  ^{18}Ne(α,p)^{21}Na
- 2012 Salter *et al.*:
  ^{21}Na(p,α)^{18}Ne

Disagreement between "*forward*" *(α,p)* and "*time-reverse*" *(p,α)*

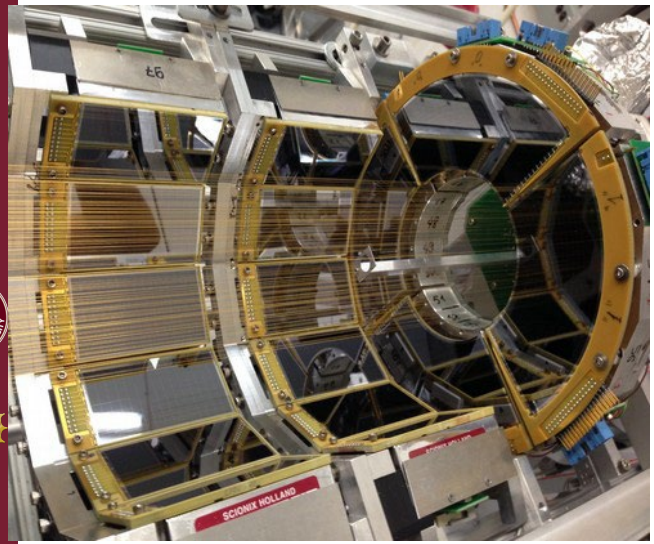
^{21}Na: excited-state population matters even at lowest reaction energies

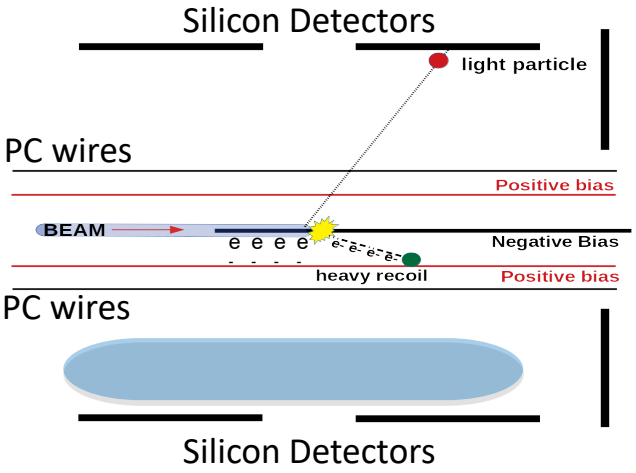


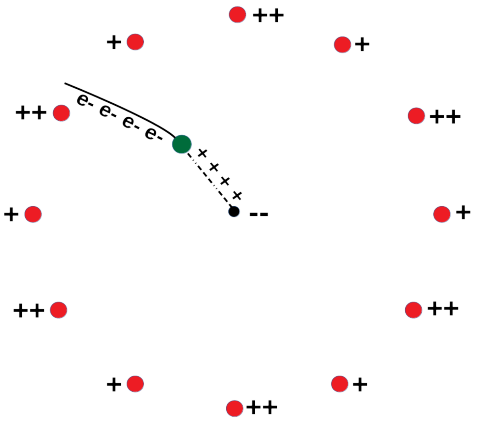
P. Mohr, A. Matic, Phys.Rev.C 87, 035801 (2013)

ANASEN: A High-Rate Active-Target Detector

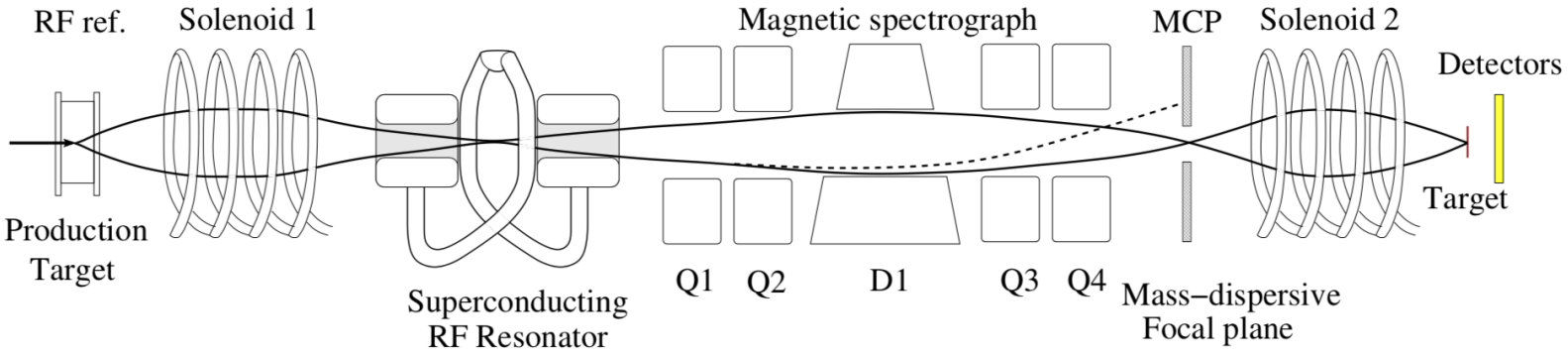
- ANASEN was developed through a collaborative MRI between LSU and FSU 2011-2014 E.Koshchiy *et al.*, NIM, A 870 (2017) 1–11
- It has a high-rate beam capability, with 10^5+ pps
- Ph.D. project Maria Anastasiou; Added high-rate ion chamber with differential readout = “Pseudo-Frisch Grid” for HI coincidence detection



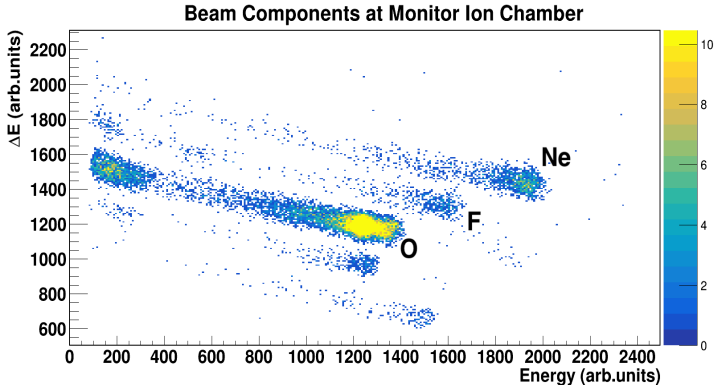




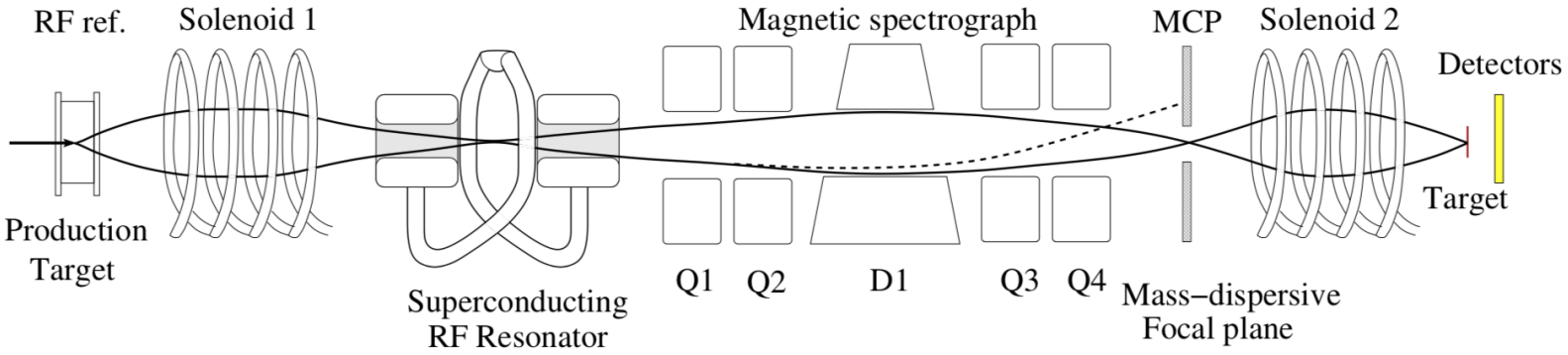
The ^{18}Ne Beam



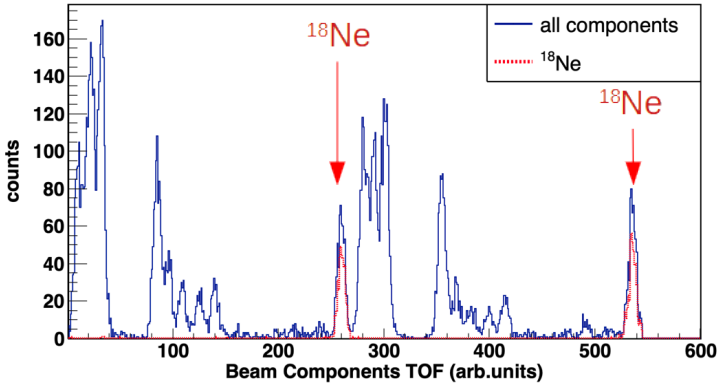
- ^{18}Ne beam, in-flight production ^{16}O(^{3}He,n)^{18}Ne
- Use RF-resonator to ”cool” ^{18}Ne products
- ^{18}Ne at 80 MeV, 2·10^{3}pps, 15% purity
- MCP vs RF offline-selection to 98% purity
- ANASEN active-gas target



The ^{18}Ne Beam



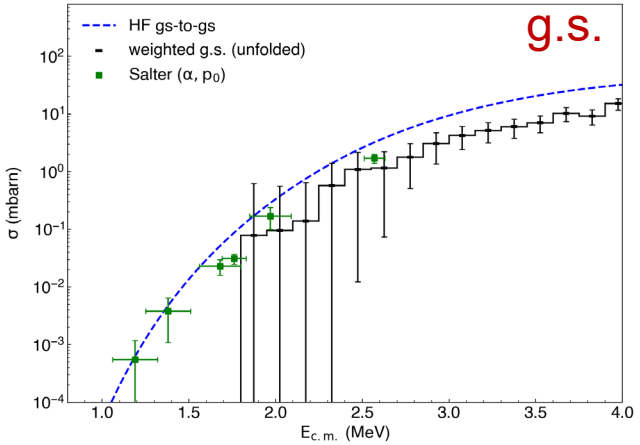
- ^{18}Ne beam, in-flight production ^{16}O(^{3}He,n)^{18}Ne
- Use RF-resonator to ”cool” ^{18}Ne products
- ^{18}Ne at 80 MeV, 2·10^{3}pps, 15% purity
- MCP vs RF offline-selection to 98% purity
- ANASEN active-gas target

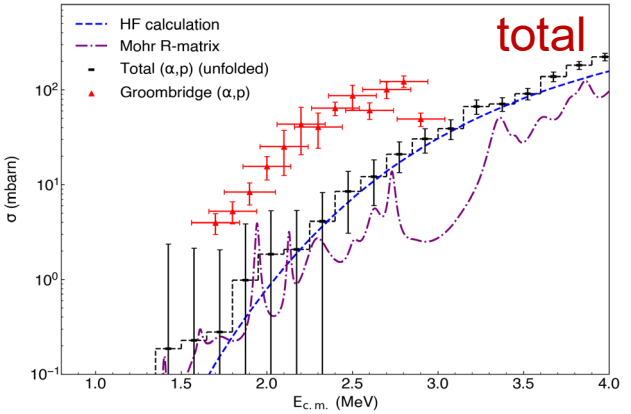


Results: $^{18}Ne(\alpha,p)^{21}Na$ with ANASEN

Anastasiou et al.: PRC 105,055806 (2021)

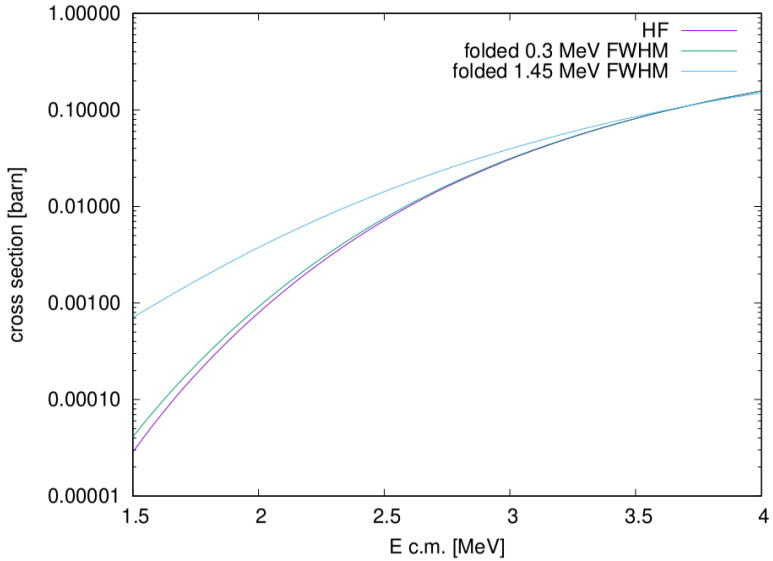
- g.s. and 0.33 MeV:
  The (α,p_0) cross section for ^{21}Na g.s. population is consistent with data from (p,α) by Salter *et al.*
- total cross-section:
  - Groombridge *et al.* systematically too high by a factor 10
  - Cross section at low energies close to Hauser-Feshbach calc.
  - R-Matrix analysis (Mohr et al.) systematically too low
- Our experiment reaches sensitivity σ~4 mbarn, touches Gamow-window for X-ray bursts





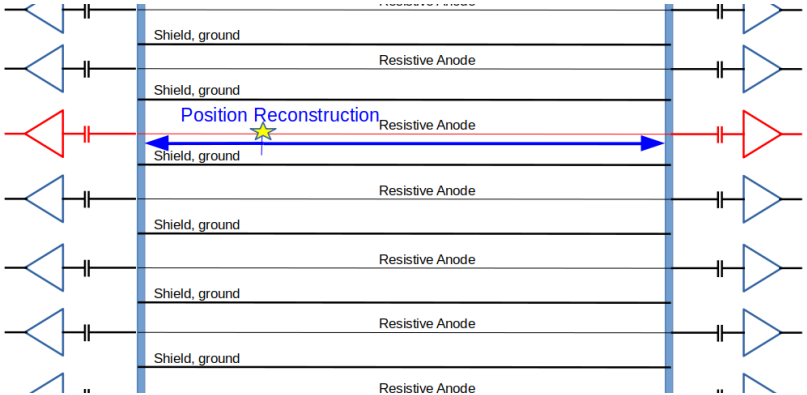
What's needed to "nail" (α,p) reactions ?

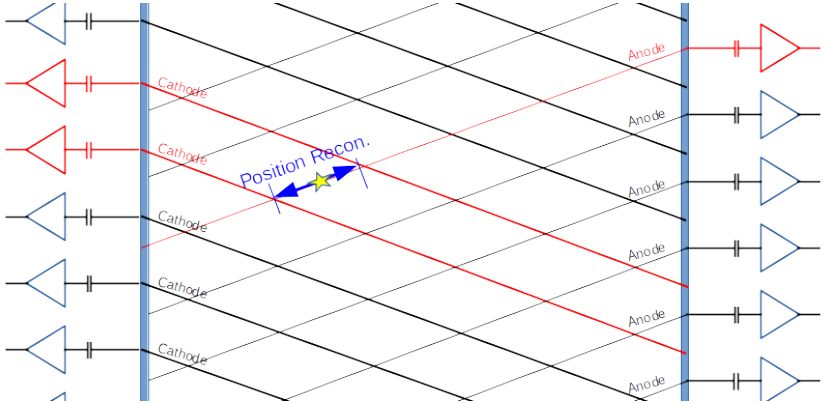
- The obvious: more beam at lower energy. (TRIUMF-approved experiment)
- Figure shows HF cross section folded with 1.45 MeV / 0.3 MeV FWHM gaussian
- Data was corrected for this effect, but
- Better resolution is needed to push towards lower cross sections. The ^{18}Ne experiment was limited by resolution as much as by statistics
- Achieving 0.3 MeV resolution is "good enough", not limiting anymore.
- Can be reached by ANASEN with better tracking resolution !



Ongoing / Proposed ANASEN upgrades

1) New digital Data Acquisition system using CAEN digitizers (FSU/LSU)
2) New silicon-tracker detectors replacing PC (LSU funds)
3) Redesigned PC – tracking detector (FSU) (Thesis V. Sitaraman Y0)





Original ANASEN:
charge division on resistive anode,
Position over Dynamic range: L

Redesigned: conductive anodes,
mirror-charge pick up on cathodes,
capacitive division, Dynamic Range: L/6

Proposed Research on (α,p) Reactions with ANASEN

Anasen has now reached the sensitivity to measure (α,p) reactions to E_{CM}~ 2.5 MeV. With the recent upgrades, we expect the experimental sensitivity only limited by statistics.
Here, we propose one experiment at TRIUMF and several at FSU.

1) $^{17}F(\alpha,p)^{20}Ne$ at FSU (GS Vignesh Sitaraman, Y1)

2) $^{13}N(\alpha,p)^{16}O$ at FSU (PD Ruchi Mahajan LSU, Y1)
   Both of these experiments inform the ^{44}Ti and/or the ^{56}Ni yield in CCSN.
   Both aim to improve on data taken at Argonne National Lab with MUSIC and weak beams, 3000 / 1000 pps.
   We expect 50000 / 20000 pps from RESOLUT.

3) Approved $^{18}Ne(\alpha,p)$ experiment at TRIUMF (S1773) (PI J. Blackmon +GS, Y2)
   Expect to improve sensitivity wrt the FSU measurement by a factor of ~20 and reach into the Gamow window at 0.8 GK.

Proposed Research on (α,p) Reactions with ANASEN

Anasen has now reached the sensitivity to measure (α,p) reactions to E_{CM}~ 2.5 MeV. With the recent upgrades, we expect the experimental sensitivity only limited by statistics. Here, we propose one experiment at TRIUMF and several at FSU.

4) ^{39}K(p, α)^{36}Ar at FSU. (GS, Y2)

This stable-beam experiment was identified as having a major impact on the production of ^{36}Ar in the outer Helium-layers of SN TIa. The reaction has never been measured to the precision required, although studies of resonance parameters from ^{39}K(p,γ) have been performed [207]. ANASEN is capable of measuring beams at 10^5 pps. (See also: ^{44}Ti(α,p) by SAC))

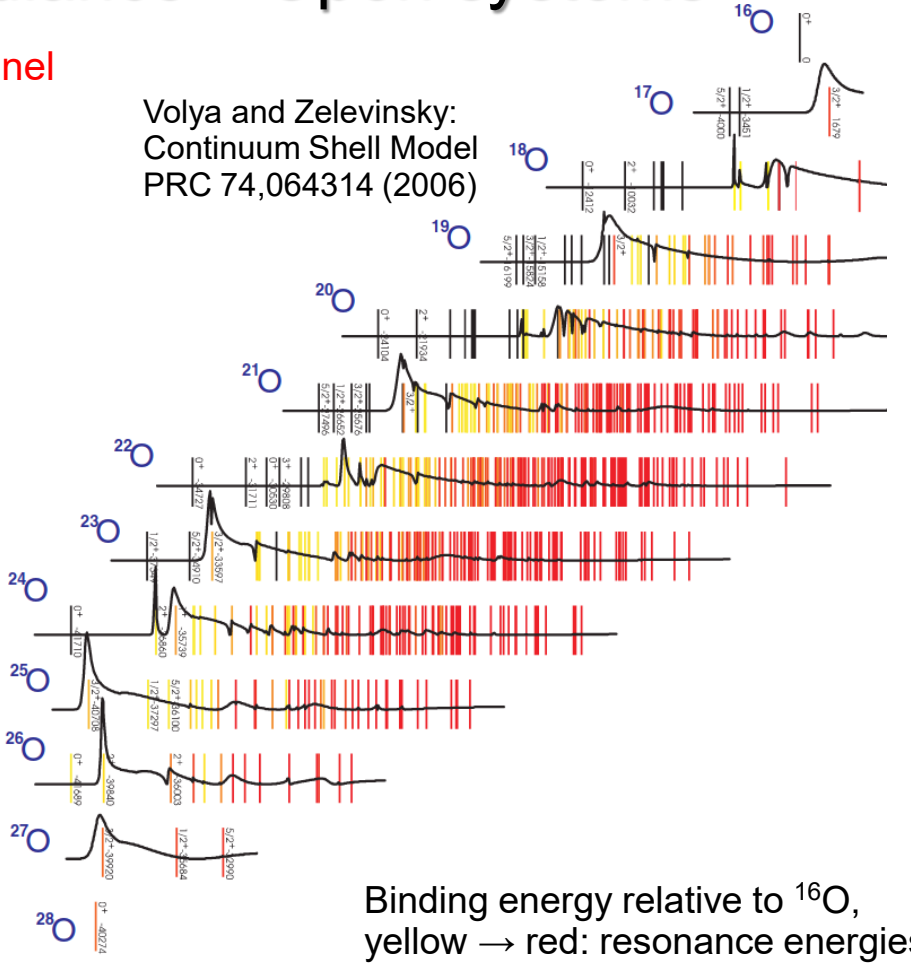
5) ^{26}Si(α,p)^{29}P (GS, Y3)

This reaction has been identified as a high-impact reaction impacting the time scale of the (α,p) process in X-ray bursts by Parikh et al. [188] and Cyburt et al. [203] and has never been measured before. The ^{26}Si beam will be produced through the ^{24}Mg(^{3}He,n) reaction at 30 mbarn [204], which leads us to expect a beam quality comparable to the one in the ^{18}Ne(α,p) experiment.

Topic 3: Superradiance – Open systems

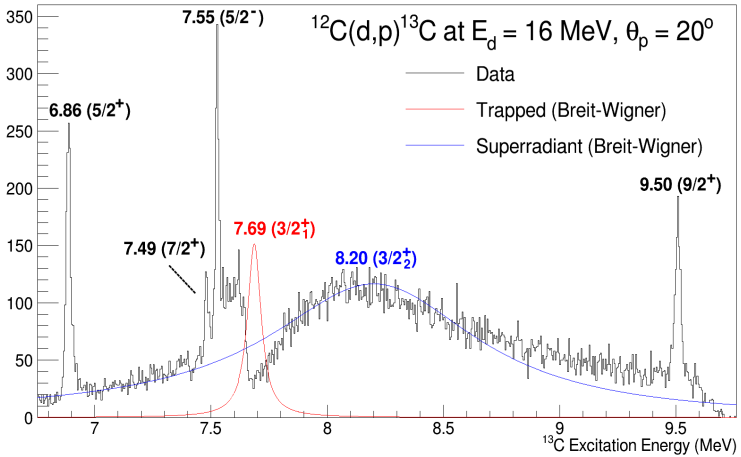
- Unbound states mix through decay channel
- Decay-width concentrates in few states, "Superradiance"
- General property in the quantum mechanics of open systems;
- Q: What happens to wave-function of bound states ?
- Central ingredient in structure and stability of exotic nuclei !?
- Natural ingredient of continuum shell model
- Part of FSU program to study the impact of the continuum on shell evolution.

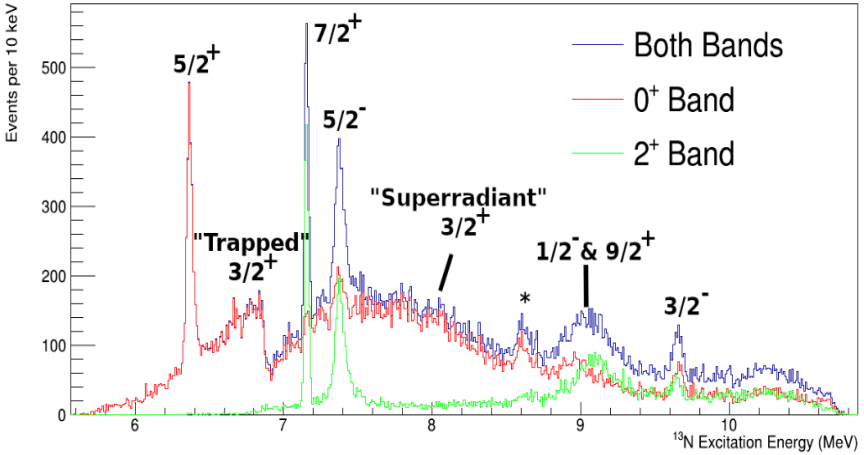
Volya and Zelevinsky:
Continuum Shell Model
PRC 74,064314 (2006)



Binding energy relative to ^{16}O,
yellow → red: resonance energies

Superradiant states in ^{13}C, ^{13}N

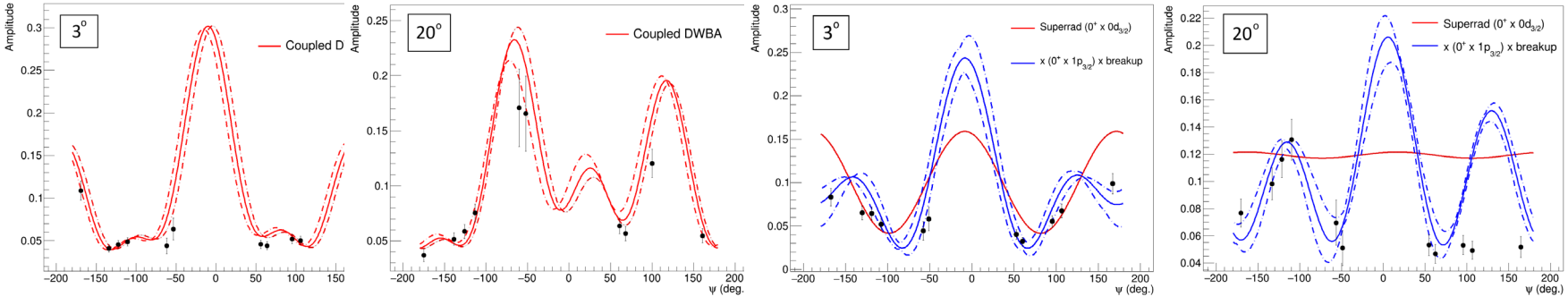




- Left: ^{12}C(d,p)^{13}C, $3/2^+_1$ and $3/2^+_2$ (SE-SPS)
- Right: ^{12}C(^{3}He,d)^{13}N(p), $3/2^+_1$ and $3/2^+_2$ (SE-SPS + Sabre)
- The non-continuum shell model predicts very similar configurations for $3/2^+_{1,2}$.
- Super-radiance (CSM): n- (p-) decay strength: concentrated in $3/2^+_2$, removed from $3/2^+_1$

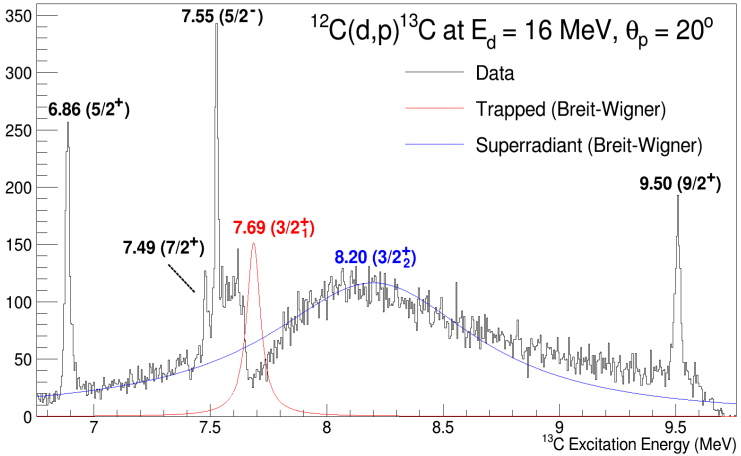
Angular Correlation Measurements in $^{12}C(^{3}He,d)^{13}N$ (p)

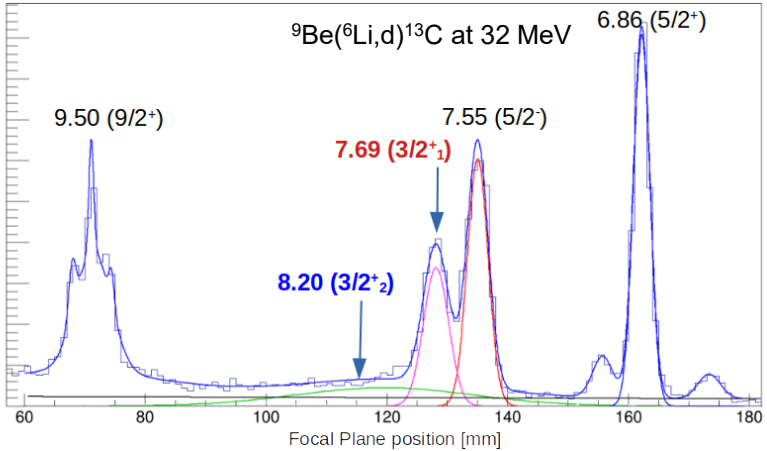
- SE-SPS at 3, 20 deg., protons detected in coincidence.
- Reaction-plane coordinates: Beam at “0 deg”. Absolutely normalized !
- Reaction theory developed, based on FRESCO + decay coupling.



- Left: Data for $3/2^-$ / $5/2^+$ “true” doublet at E_{ex}= 3.52 MeV:
  Strong forward-backward asymmetry from $3/2^-$ / $5/2^+$ interference.
- Right: Data for “superradiant” $3/2^+_2$ at E_{ex}= 7.9 MeV:
  Strong forward-backward asymmetry from *l*-mixing in broad-state decay.
  1.5 MeV FWHM means $\tau \sim 3 \cdot 10^{-21}$ s, on the “direct reaction” time scale
- Fit with (0^+ x $d_{3/2}$) & (0^+ x $p_{3/2}$) & breakup, very sensitive to the parameters.

Proposed Research: Superradiant States in ^{13}C





- Proposal: Y2, GS C. Esparza: Measure neutron-decay correlations for $3/2^+_{1,2}$ states in ^{13}C with (d,p) (left) and α-transfer reaction (right).
- The superradiant $3/2^+_2$ dominates (d,p), but vanishes in (^{6}Li,d), orthogonalization due to decay space ?
- Angular Correlations to be analyzed with formalism of K. Hanselman will provide stringent test for continuum shell model and clustering (A. Volya)

FLORIDA STATE UNIVERSITY

Summary

- The sensitivity of ANASEN for is now unsurpassed and will likely lead to high-profile projects measuring thermonuclear reaction rates at FSU and elsewhere.
- Interpretation / application in collaboration with FSU astrophysics group and UNC.
- The SE-SPS + Sabre at FSU re-instates the facility for coincident transfer-reaction & decay spectroscopy of resonances
  - (Not shown here) For Nuclear Astro (C. Deibel): $^{27}Al(^{3}He,t)\,^{27}Si(p)^{26}Al_{g,m}$
  - For super-radiance program:
    Study of ^{13}C vs. ^{13}N (n vs. p decay of resonances)
    Interpreted in collaboration with FSU nuclear theory