Lifetime measurement of ^{15}O excited state

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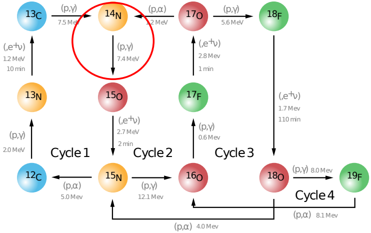
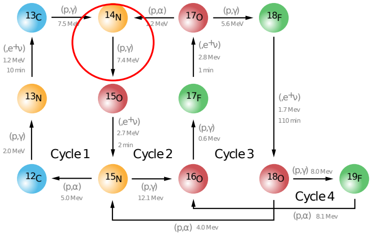
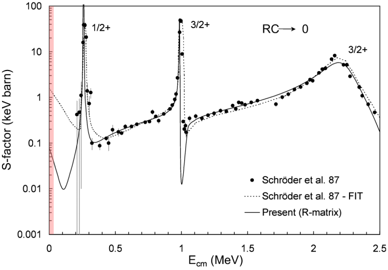
- The ^{14}N$(p,\gamma)^{15}$O: **slowest** reaction of the **CNO cycle.**



- The $^{14}N(p,\gamma)^{15}O$: **slowest** reaction of the **CNO cycle.**
- **Gamow Peak** between **10 – 30 keV**, the lowest measured energy is **117 keV**.

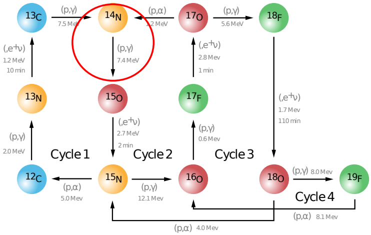


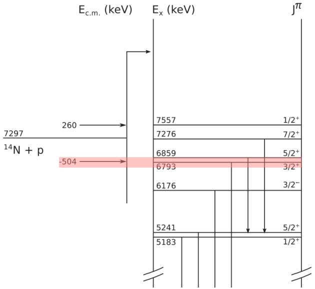


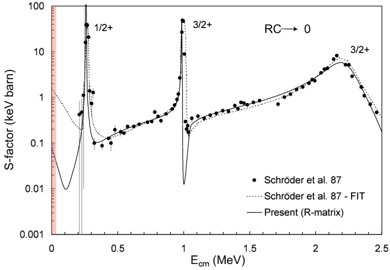
Astrophysical Motivation

^{14}N$(p,\gamma)^{15}$O Reaction

- The ^{14}N$(p,\gamma)^{15}$O: **slowest reaction of the CNO cycle.**
- **Gamow Peak** between **10 – 30 keV**, the lowest measured energy is **117 keV**.
- The extrapolation is **dominated by the subthreshold resonance at 6.79 MeV**.







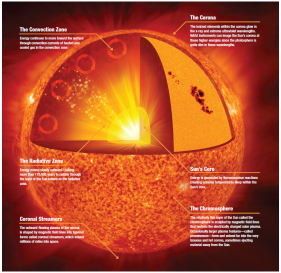
Astrophysical Motivation

Impact

Evolution of massive stars

The $^{14}N(p,\gamma)^{15}O$ governs the CNO cycle **equilibrium**:

- energy production
- star evolutionary path
- $\rightarrow$ **age of globular clusters**, oldest objects in the universe



Solar composition problem

Two estimates of solar metallicity **disagree**:

- **helioseismology**: density and sound velocity
- **solar model**: photosphere and luminosity

CNO ν-flux recently **measured by Borexino**:

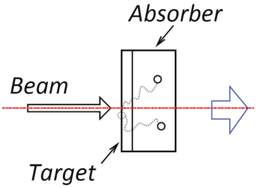
- the ν-flux depends **linearly** on the cross-section
- **independent estimate** by using $^{14}N(p,\gamma)^{15}O$ and $^{12}C(p,\gamma)^{13}N$ cross sections

^{15}O Lifetime - DSAM Measurement (1)

Previous Measurement

- Several attempts to measure **6.79 MeV state lifetime** in the past with the use of **Doppler Shift Attenutaion Method** (DSAM).
- The expected order of magnitude is $\mathbf{10^{-15}}$ **s**, at the lower edge of the DSAM applicability.
- Thus either **huge errors** or **upper limits** were obtained up to now.

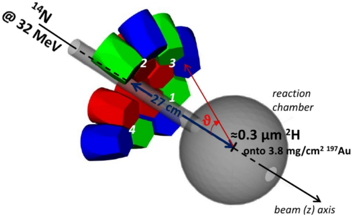
Dataset	τ_{obs} (fs)
Frentz et al. (2021)	0.6 ± 0.4
Bertone et al. (2001)	1.6 ± 0.75
Schurmann et al. (2008)	< 0.77
Galinski et al. (2014)	< 1.8
Sharma et al. (2020)	< 1.18



^{15}O Lifetime - DSAM Measurement (2)

Michelagnoli PhD. (2013)

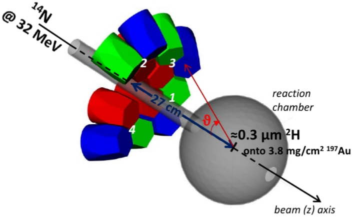
- DSAM with AGATA Demonstrator array
- ^{2}H(^{14}N,^{15}O)n reaction channel



^{15}O Lifetime - DSAM Measurement (2)

Michelagnoli PhD. (2013)

- DSAM with AGATA Demonstrator array
- ^{2}H(^{14}N,^{15}O)n reaction channel
- No particle detection
- $\rightarrow$ no Doppler correction
- Upper limit: $\tau < 1$ fs



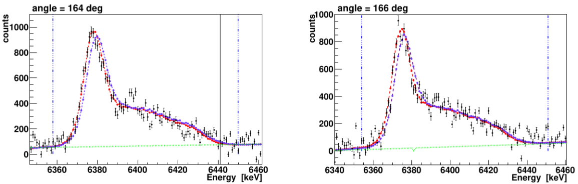


Figure 5.23: Lineshapes of the 6.79 MeV γ–ray in ^{15}O - Spectra mesured at different angles for the 6.79 MeV gamma line, compared with the lineshapes simulated for p_{fe}=20% and two different lifetimes, $\tau = 0.1$ fs (red spectrum) and 2.9 fs (violet).

Proposed Experiment

Reaction

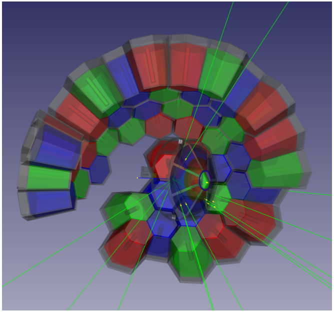
^{16}O(^{3}He,^{4}He)^{15}O @ 50 MeV

(**inverse kinematics**)

- Populating 6.79 MeV via *n*-**transfer**.
- ^{3}**He implanted in Au** backing to maximize $\frac{dE}{dx}$.
- Inverse kinematics lowers the uncertainty on $\frac{dE}{dx}$.
- ^{4}**He detection** greatly helps the DSAM.

Setup

AGATA + SPIDER

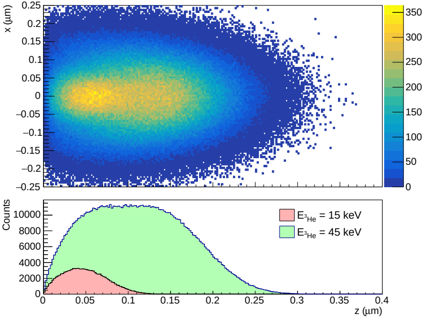


AGATA permits **continuous-angle DSAM**.

Target

Production

- ^{3}He **implanted** in Au layer
- Produced at HZDR institute
- $\sim 6 \times 10^{17}$ atoms/cm^2



Same target used in [1]:

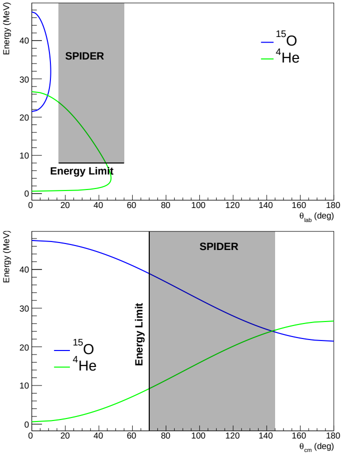
- **Stable** under 8 pnA $^{16}O^{+5}$ beam (4.8 pnA at LNL)
- Used in other studies [2,3]
- **Needs cooling**!

[1] Galinski et al. (2014), Phys. Rev. C 90, 035803
[2] Kanungo et al. (2006), Phys. Rev. C 74, 045803
[3] Mythili. et al. (2014), Phys. Rev. C 90, 035803

Reaction Study

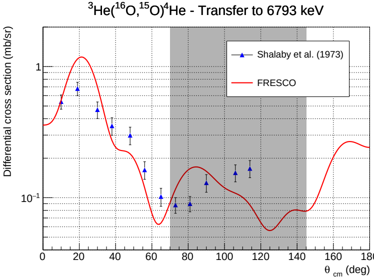
Kinematics

- 25 μm of Au $\rightarrow \Delta E_{He} \sim 8$ MeV
- ^{16}O completely stopped in target



Cross-Section

- DWBA calculation for transfer



$$\sigma_{tra} \sim 1.68 \text{ mb}$$

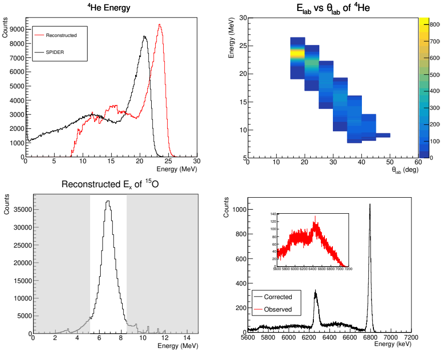
Details

- The Geant4 code with AGATA + SPIDER was used
- **Sensitivity**: transfer to $E_x = 6.791$ MeV with different τ
- **Feasibility**: transfer to all the excited states + elastic

Analysis:

1. Gate on γ-α coincidences
2. α reconstruction
3. E_x calculation
4. Gate on E_x
5. Doppler correction

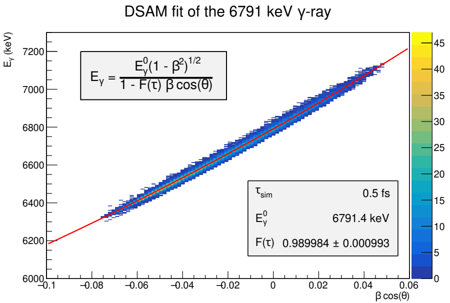
→ **No major background!**



Continuous DSAM Fit

Details

- Lifetimes from **0.1 fs** to **2 fs** were simulated.
- The Doppler-corrected peak was gated
- Then the **uncorrected spectrum was fitted**



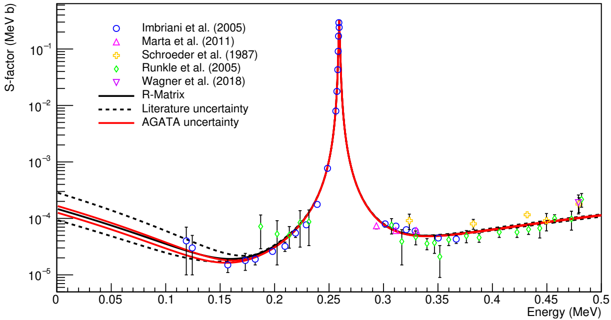
τ_{sim} (fs)	τ_{fit} (fs)
0.3	0.3 ± 0.1
0.5	0.5 ± 0.1
0.6	0.6 ± 0.1
0.9	1.0 ± 0.1
1.0	1.1 ± 0.1
1.2	1.4 ± 0.1
1.5	1.7 ± 0.1
1.8	1.9 ± 0.1
2.0	2.0 ± 0.1

AGATA + SPIDER guarantees 0.1 fs sensitivity!

Bonus: Extrapolation Improvement

Details

- **AZURE2**: R-Matrix code with user-friendly GUI
- All the nuclear information for the $^{14}N(p,\gamma)^{15}O$ are taken from Frentz et al. (2021)
- **Uncertainty reduced to 13 %** (from 65 %)



Expected Beamtime

$$R = 3760 \times I(\text{pnA}) \times \frac{t(\text{mg/cm}^2)}{A_\text{t}} \times \sigma(\text{mb}) \times \eta$$

- $I(\text{pnA}) = 4.8$ pnA (from TANDEM website)
- $t(\text{mg/cm}^2) = 3.1\ \mu\text{g/cm}$
- $\sigma_{tra} \sim 1.68$ mb
- $\eta = 0.1$ % (from simulation studies)

In order to accumulate 10^4 events:

100 h ($\sim$ 4 days)

Conclusions

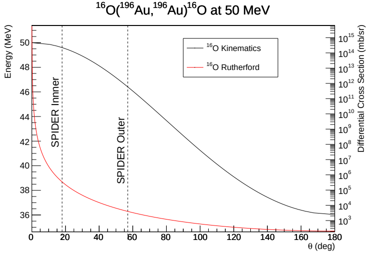
Closing Remarks

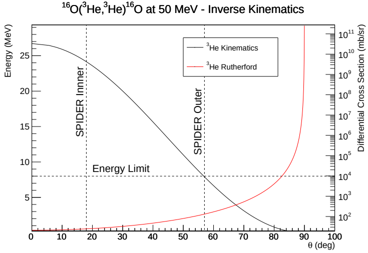
- **Stable target** and easy to make target
- State-of-the-art sensitivity for the DSAM
- Important **uncertainty reduction** for the $^{14}N(p,\gamma)^{15}O$
- Several important impacts for the nuclear astrophysics

Thank you for attention!

Background - Elastic Scattering

- Elastically scattered ^{16}O could create problems
- $\rightarrow$ stopped inside target
- The ^{3}He still detectable inside SPIDER
- $\rightarrow$ calculated 400 evt/s
- $\rightarrow$ α-γ coincidences





R-Matrix

Details

- Usually it is not possible to measure the cross-section at astrophysical energies, thus need for extrapolation
- The R-Matrix theory connects the cross-section to states
- It relies on the use of the collision matrix, U(E)

Ingredients:

- Incoming and outgoing channels for compound nucleus
- E_x, s, l for each state
- Resonance parameters for each channel (strength, width etc.)
- Subthreshold states: ANC, τ
- **Experimental data!**

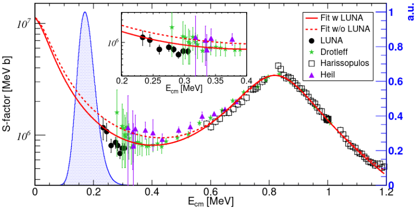


Figure: $^{13}C(\alpha, n)^{16}O$

DWBA - Elastic Scattering

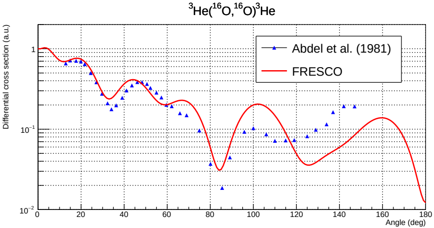


Figure: $E_{^{16}\mathrm{O}} = 74$ MeV

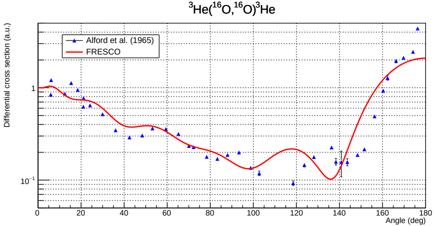
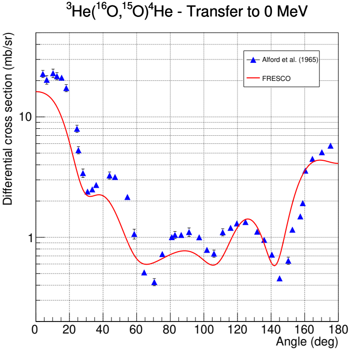
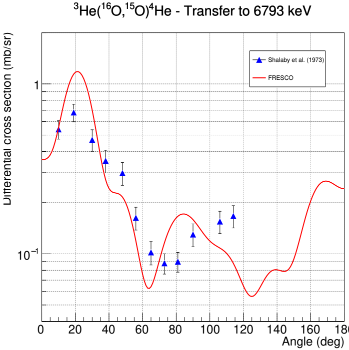


Figure: $E_{^{16}\mathrm{O}} = 50$ MeV

DWBA - Transfer





Conclusions

- $\chi^2/NDF = 321$, not great but data are very old
- Cross-sections used for the AGATA simulations