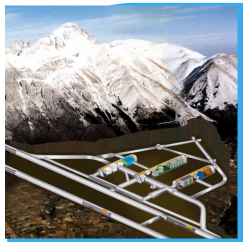
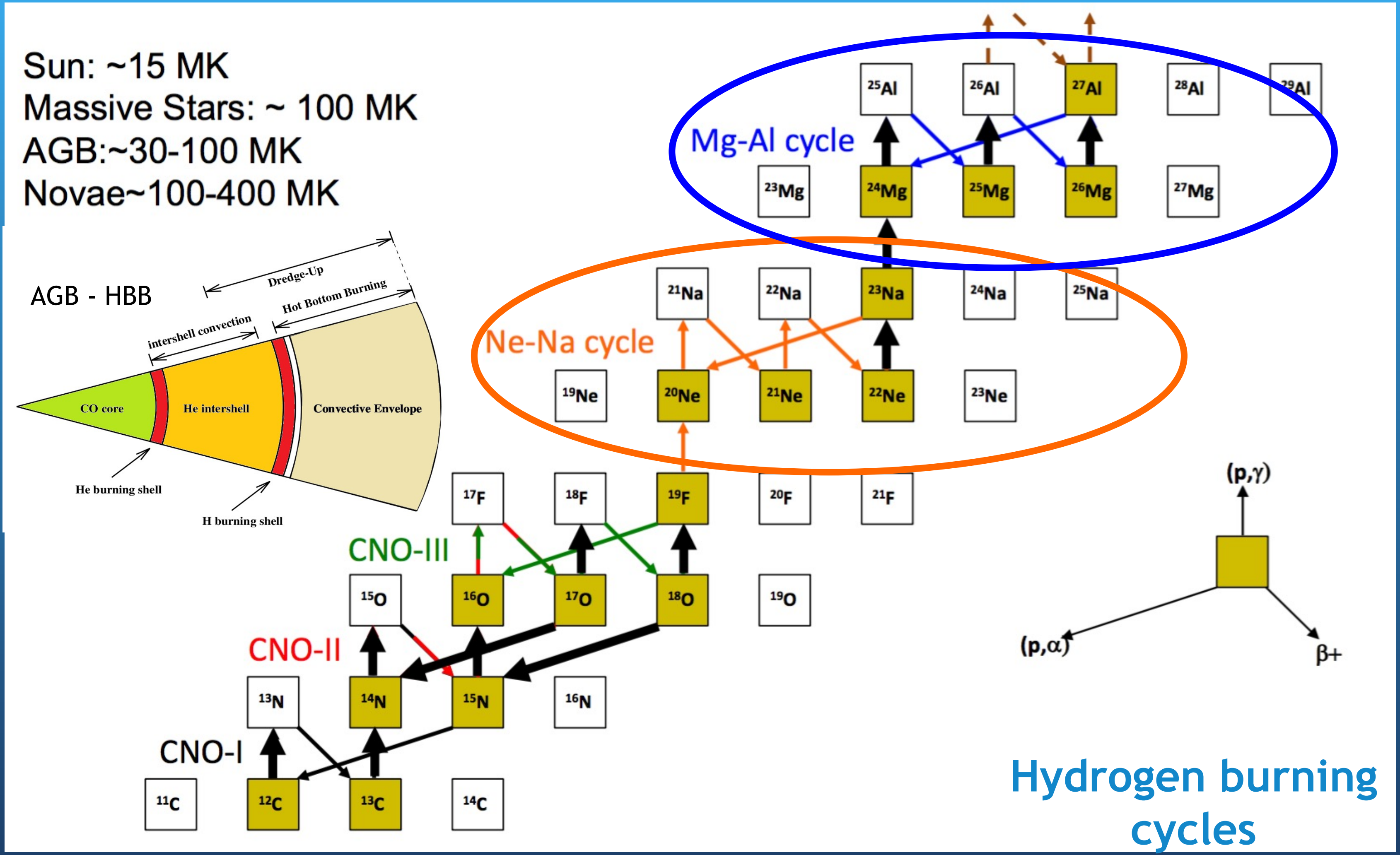
The study of the $^{21}Ne(p,\gamma)^{22}Na$ reaction at LUNA

S. Zavatarelli on behalf of the WG



Neon-Sodium cycle



NeNa cycle:

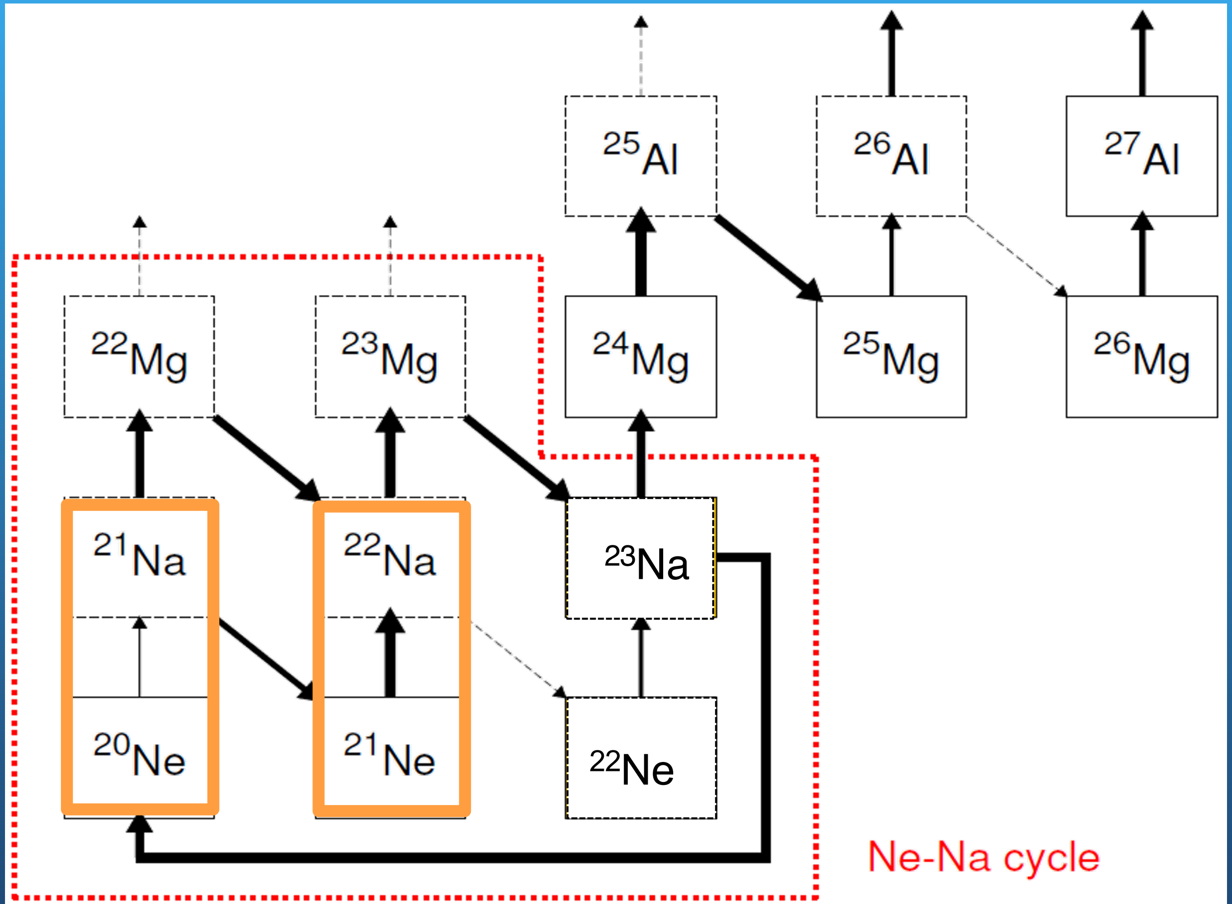
- slower reaction rate respect to hot CNO
- Less relevant for energy production
- Important for nucleosythesis : it determines neon and sodium isotopes abundances
- Though the $^{23}Na(p,\gamma)^{24}Mg$ reaction, it links to MgAl cycle influencing also Mg and Al isotopes production

NeNa cycle : astrophysical scenarios

Astrophysical sites:

- RGB stars (Red Giant Branch)
- AGB stars (Asymptotic Giant Branch)- HBB
- O-Ne Novae
- Massive stars

T ≅ 0.05-1 GK

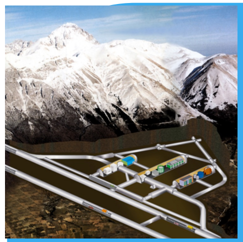


$^{20}Ne(p,\gamma)^{21}Na$: First and slowest reaction of the cycle

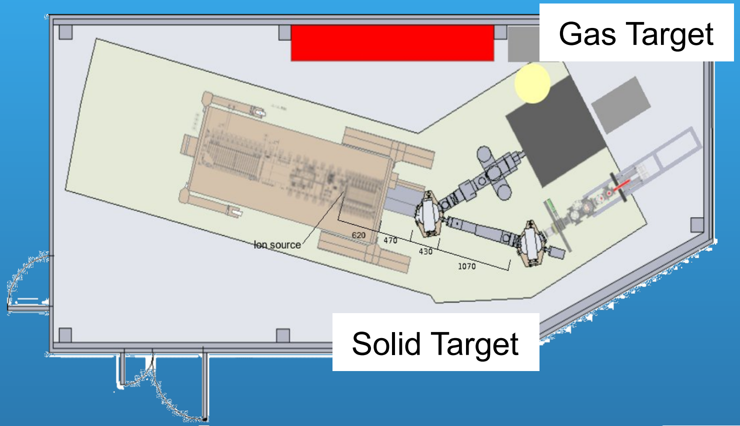
Bottleneck, impact on nucleosynthesis of involved elements (^{22}Na, ^{22}Ne..)

$^{21}Ne(p,\gamma)^{22}Na$: reasons of interest

- Radioactive isotope ^{22}Na ($t_{1/2}$ = 2.602 years) is produced in novae
- ^{22}Na decays into ^{22}Ne and could in future be observed via satellite telescope spectroscopy as a photon at 1.275 MeV is emitted
- ^{22}Na is specifically produced only in white dwarfs made of O and Ne



The LUNA 400 KV accelerator at LNGS



Radiation	LNGS/surface
Muons	10^{-6}
Neutrons	10^{-3}
Gammas	10^{-2}-10^{-5}

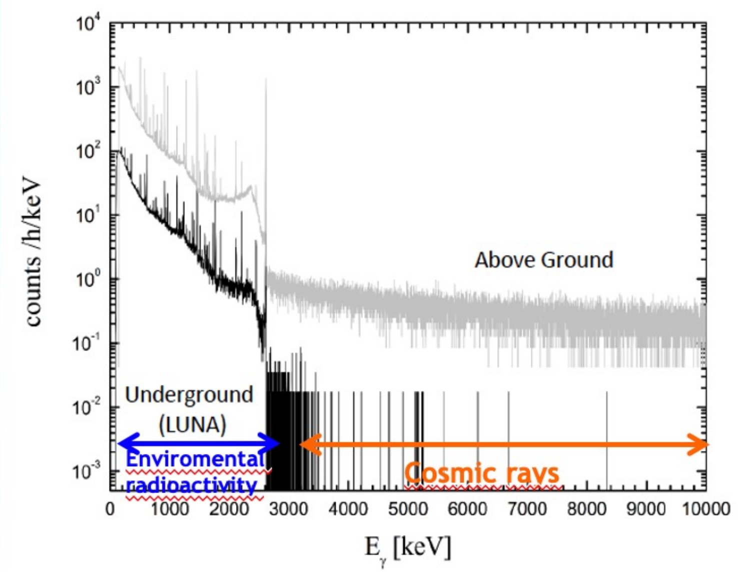
- Very stable, precise beam energy
- High beam currents
- Low backgrounds
- Best experimental techniques

→ **Key points for precision measurements!!**

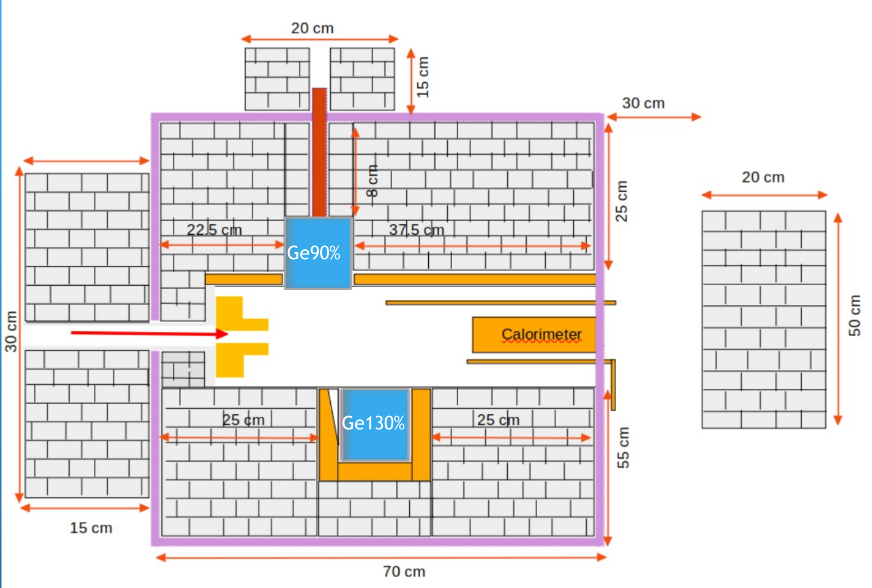
$E_{beam} \approx 50 - 400$ keV

$I_{max} \approx 500$ μA protons
$I_{max} \approx 250$ μA alphas

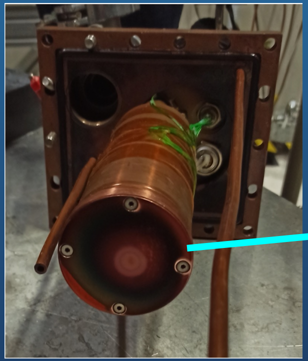
Energy spread ≈ 100 eV
Long term stability ≈ 5eV/h

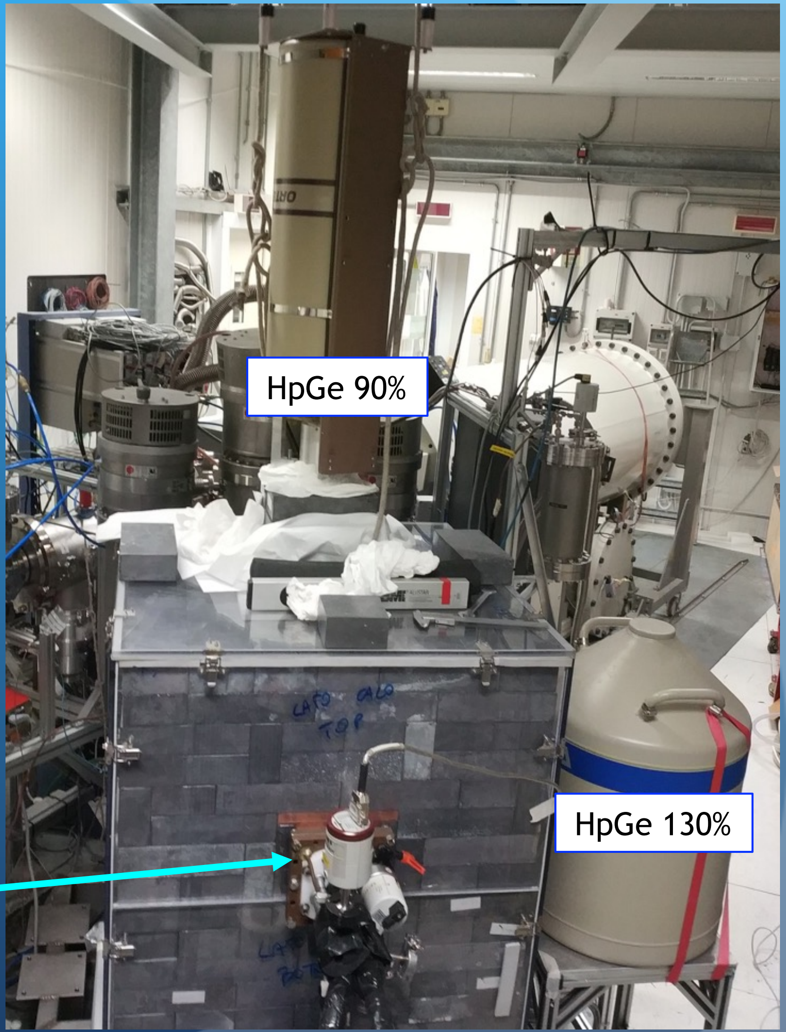


Experimental setup

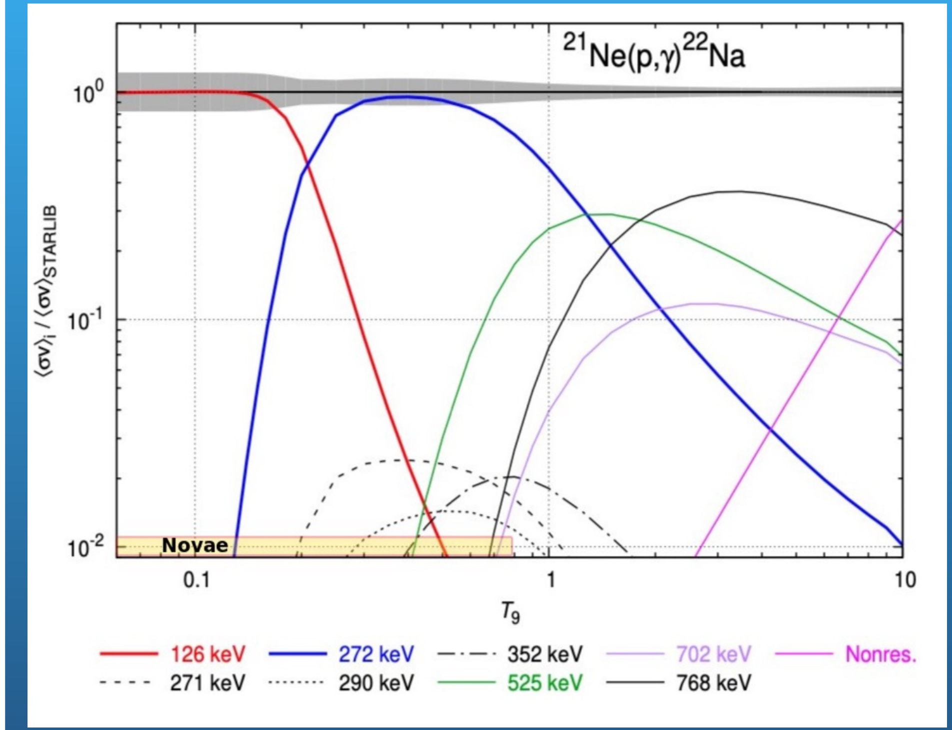


- Natural Ne windowless gas target (0.27% ^{21}Ne), enriched (59.1% ^{21}Ne)
- P = 2 mbar
- HPGe detectors:
  - Relative efficiency 130%
  - Relative efficiency 90%
- Lead + copper shielding
- Anti-Radon box





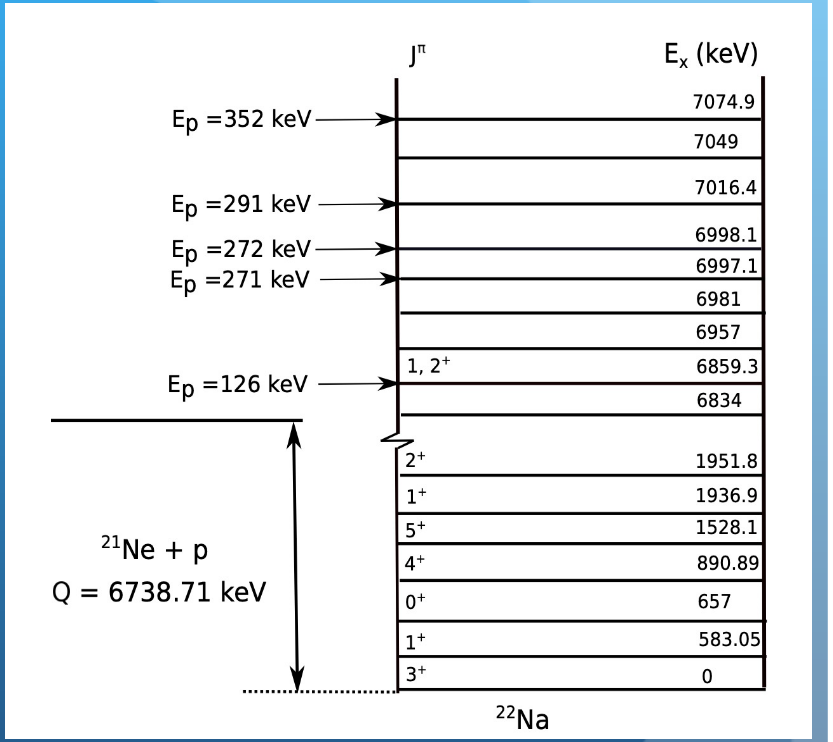
$^{21}Ne(p,\gamma)^{22}Na$



- *Q* value = 6739 keV
- Dominant resonances:
- *Ep* = 126 keV and 272 keV
- Other resonances:

  Ep = 271, 290 and 352 keV

(<%5 contribution to stellar rate)



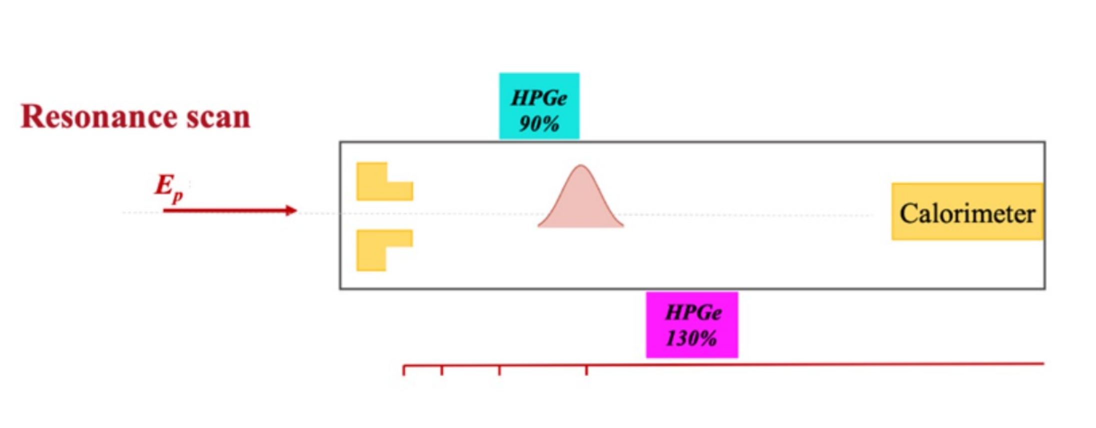
LUNA : Studied resonances E_p=126keV, 271keV, 272keV, 290keV, 352keV.

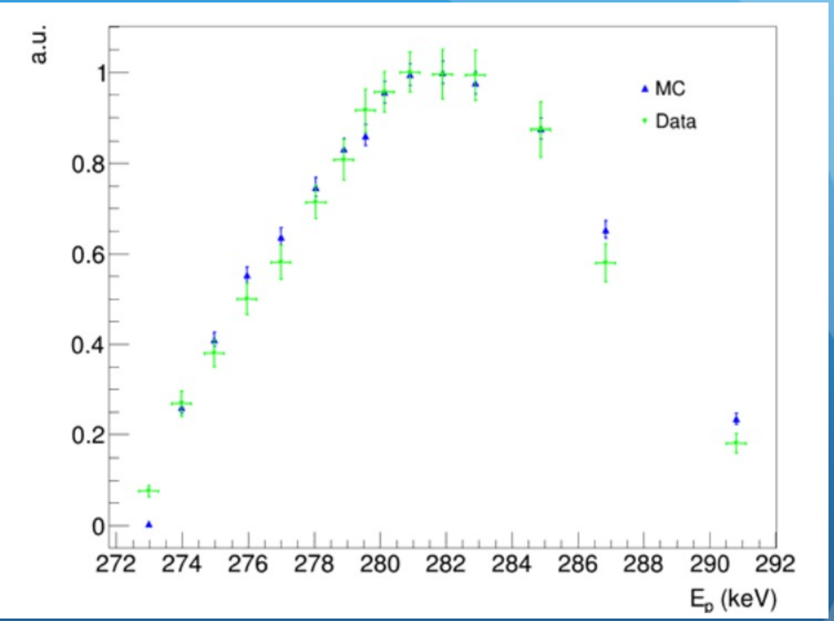
$^{21}Ne(p,\gamma)^{22}Na$: resonance at E_p=272keV

- Corresponding excited ^{22}Na level: Ex=6998 keV

By changing the beam energy, the resonance was populated in different points of the camera

- Detection efficiency and correction for summing effects has been estimated by a MC simulation



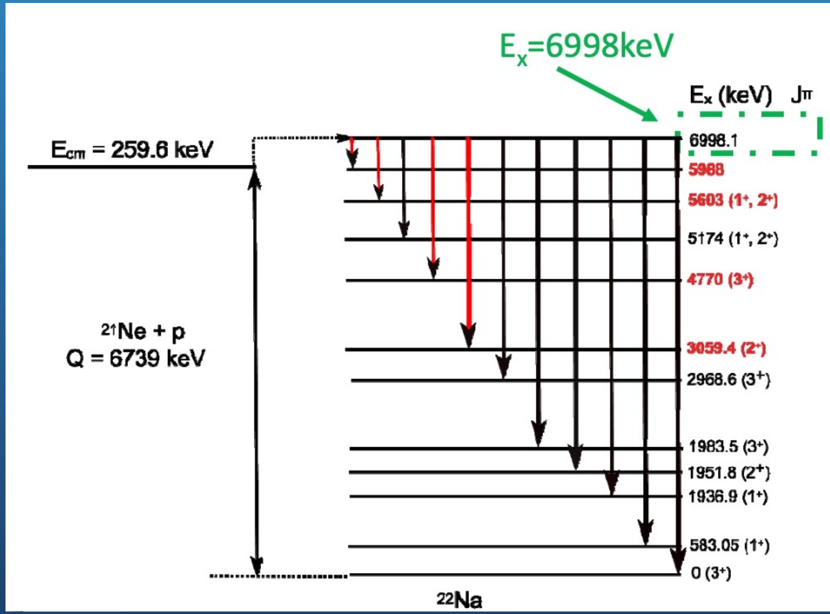


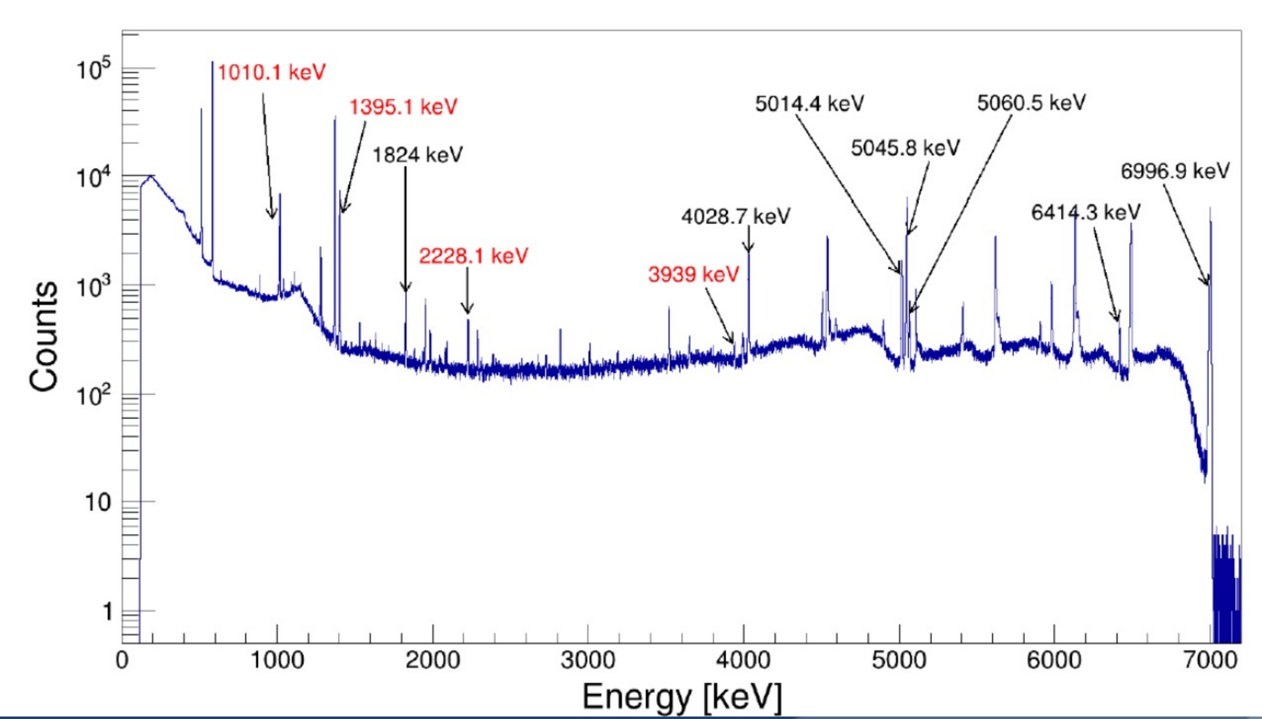
Ep=272 keV yields (HpGe130%)

$^{21}Ne(p,\gamma)^{22}Na$: resonance at E_p=272keV

Deexcitation scheme:

7 transitions already known, but observed 4 new ones (Eγ=1010.1, 1395.1, 2228.1 e 3939 keV).





$^{21}Ne(p,\gamma)^{22}Na$: resonance at E_p=272keV

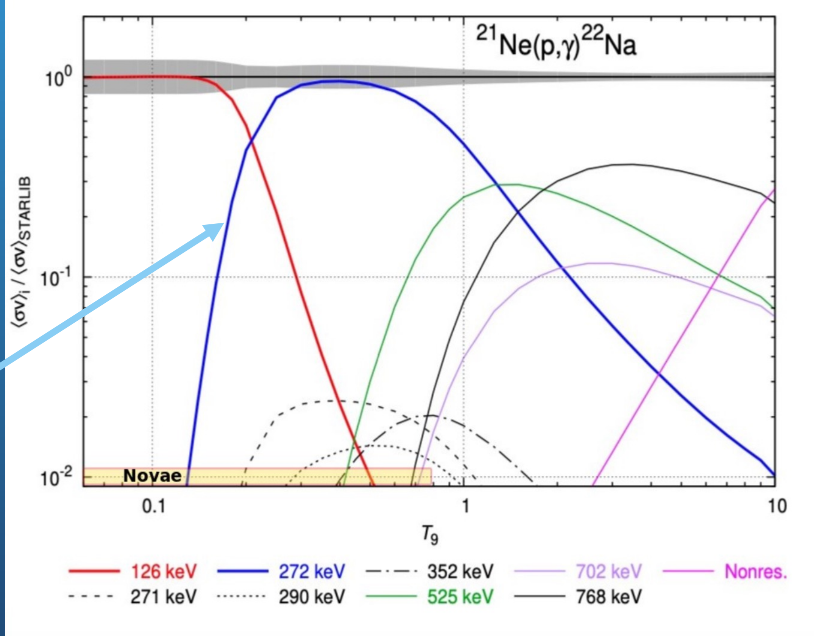
New transitions→higher resonance strenght.

Experimental yield

$$\omega\gamma \approx \frac{2}{\lambda_r^2} Y \epsilon_R \frac{m_t}{m_t + m_p}$$

Resonance strength

LUNA [meV]	Goerres et al. [meV]
$129.9 \pm 0.4_{stat} \pm 5.8_{syst}$	82±12



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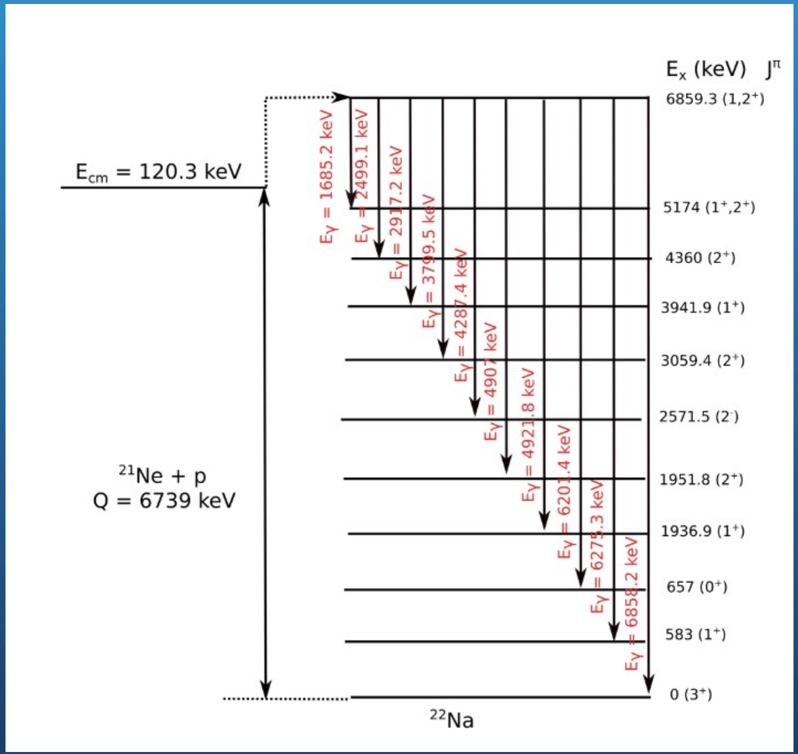
Reaction rate vs temperature

$^{21}Ne(p,\gamma)^{22}Na$: resonance at E_p=126 keV

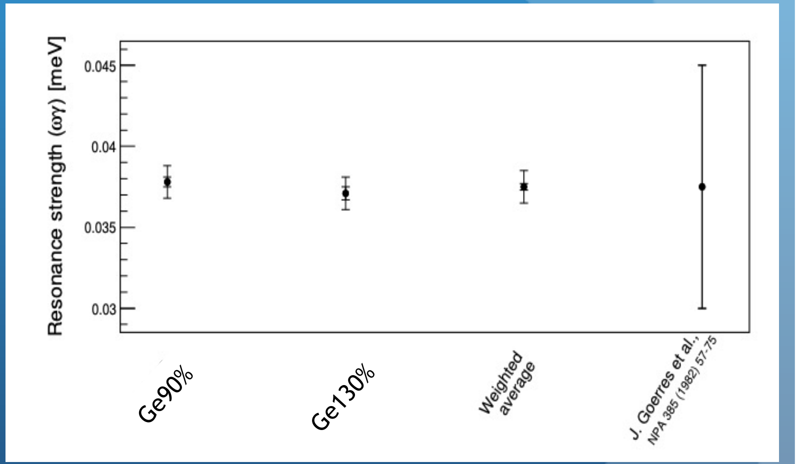
The E_p = 126 keV resonance corresponding to the 22Na state at E_x= 6859.3 keV was measured using enriched ^{21}Ne gas (59.1%).
Eight new primary gamma transitions observed + the two already known (4907 and 6201 keV primary γ)



Branching ratios (→ new!)

E_γ	BR [%]	stat. error [%]	syst. error [%]
1685.2	1.25	0.04	0.07
2499.1	1.16	0.05	0.06
2917.2	0.98	0.06	0.05
3799.5	1.09	0.08	0.07
4287.4	0.57	0.10	0.04
4907.0	64.2	0.4	3.0
4921.8	3.18	0.09	0.18
6201.4	19.6	0.2	1.0
6275.3	6.8	0.1	0.4
6858.2	1.16	0.05	0.06

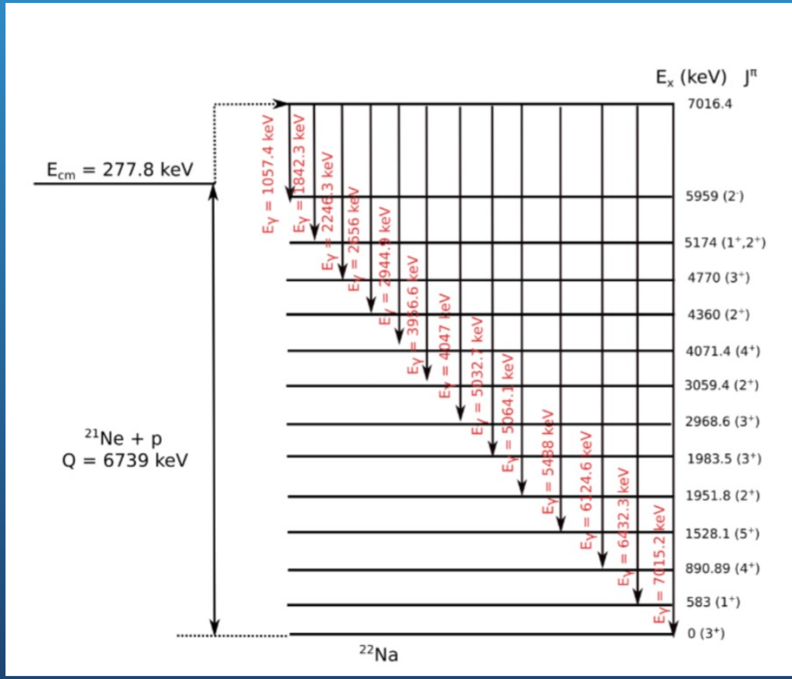
Resonance strength



$$\omega\gamma = 0.0375 \pm 0.0002_{stat} \pm 0.0017_{syst}$$

$^{21}Ne(p,\gamma)^{22}Na$: resonance at E_p=291 keV

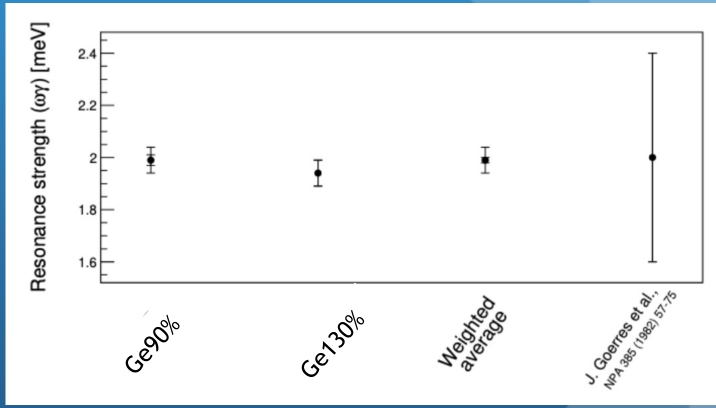
- The Ep = 291 keV resonance corresponding to the ^{22}Na state at Ex=7016.4 keV was measured byusing enriched ^{21}Ne gas (59.1%) .
- Three new primary gamma transitions besides the 10 already known



Branching ratios (→ new)

Primary gamma	BR [%]	stat. error [%]	syst. error [%]
1057.4	12.67	0.09	0.58
1842.3	4.69	0.04	0.21
→ 2246.3	0.09	0.02	0.01
2656.0	0.46	0.02	0.02
2944.9	9.50	0.07	0.42
→ 3956.6	0.41	0.03	0.02
4047.0	3.19	0.08	0.14
5032.7	3.20	0.06	0.14
5064.1	39.6	0.6	2.0
5488.0	0.50	0.03	0.02
6124.6	12.17	0.08	0.55
→ 6432.3	0.76	0.03	0.04
7015.2	12.7	0.1	0.6

Resonance strength

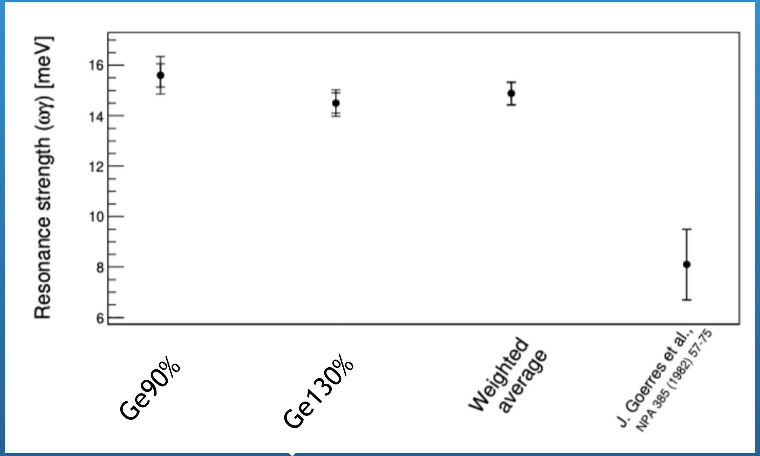


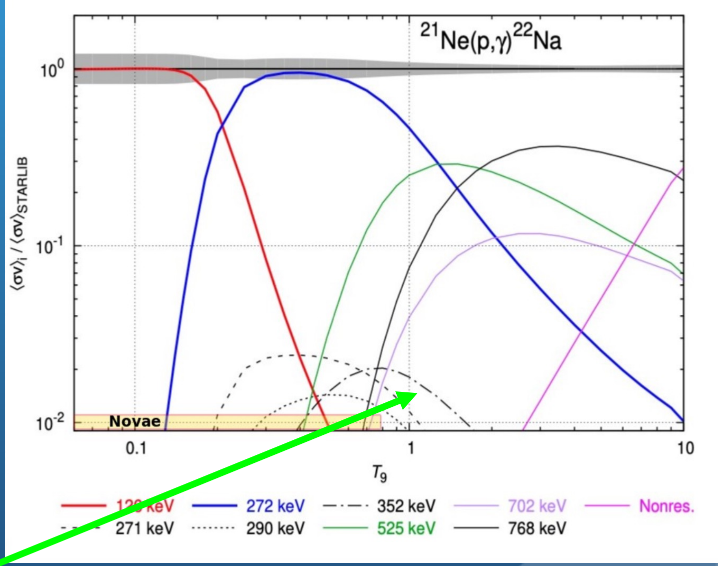
$\omega\gamma$ [meV]= $1.99 \pm 0.01_{stat} \pm 0.09_{syst}$

$^{21}Ne(p,\gamma)^{22}Na$: resonance at E_p=352 keV

The E_p = 352 keV resonance corresponds to the E_x = 7074.9 keV excited level in ^{22}Na was measured using natural Ne gas.
18 primary γ transitions observed as expected according to literature

Primary gamma	BR [%]	stat. error [%]	syst. error [%]
1080	5.43	0.03	0.24
1116	12.56	0.05	0.55
1337	0.582	0.002	0.027
1350	0.41	0.03	0.02
1375	2.72	0.01	0.14
1901	4.61	0.04	0.21
2013	0.75	0.03	0.03
2453	0.57	0.03	0.03
2492	0.67	0.03	0.03
2716.2	0.56	0.03	0.02
2779	0.50	0.04	0.02
3132	0.90	0.04	0.04
3555	1.31	0.04	0.06
4016.3	3.08	0.06	0.14
5124.3	5.7	0.1	0.3
6418.6	27.7	0.1	1.2
6492.8	31.9	0.1	1.4
7075.4	-	-	-





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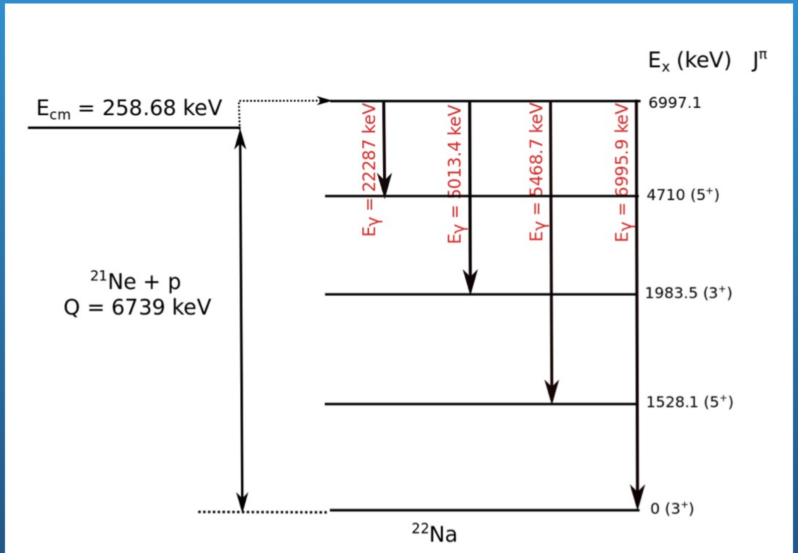
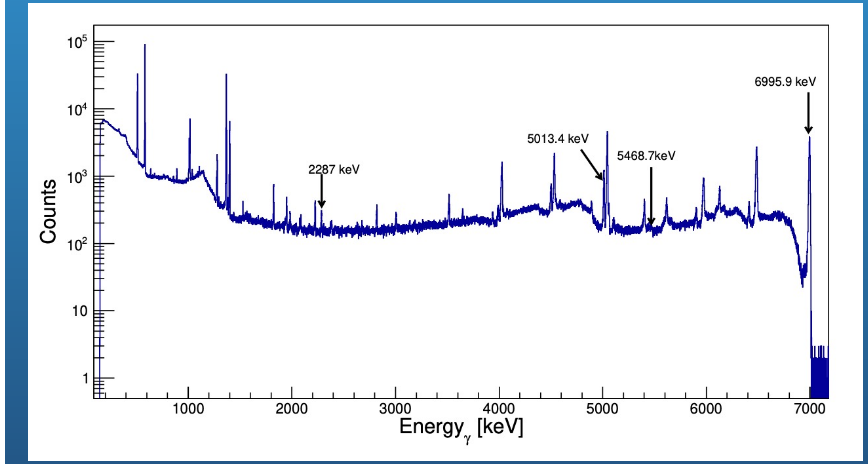
$\omega\gamma$ [meV]= $14.9 \pm 0.4_{stat} \pm 0.7_{syst}$

$^{21}Ne(p,\gamma)^{22}Na$: resonance at E_p=271 keV

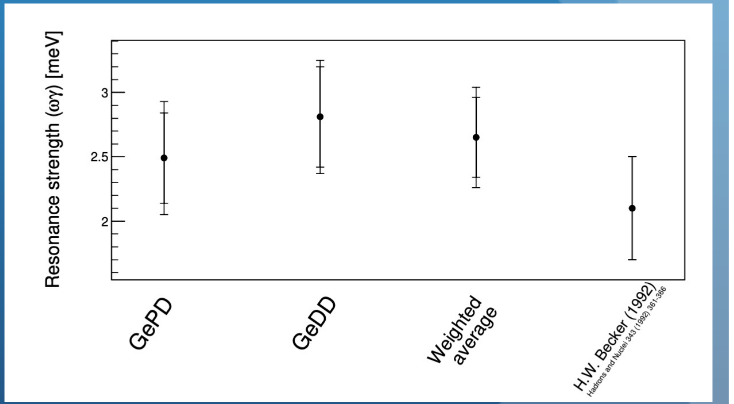
- The Ep = 271 keV resonance corresponding to the ^{22}Na state at Ex=2997.4 keV was measured byusing enriched ^{21}Ne gas (59.1%) . The only primary gamma that was used for the analysis is the 2287 keV gamma (the others are overlapped with other peaks and not clear)



Measured spectrum



Resonance strength



$\omega\gamma$ [meV]= 2.7 ± 0.3_{stat} ± 0.4_{syst}

$^{21}Ne(p,\gamma)^{22}Na$: conclusions

- ✅ The resonance strengths of all resonances of stellar interest for novae have been measured at LUNA with < 7% precision (precision for E_p = 271 keV resonance strength is ~ 19%).
- ✅ New primary gamma transitions found in E_p = 126, 272, and 291 keV resonances.
- ✅ The resonance strength of the E_p = 272 keV resonance, that is dominant at novae temperatures, is found to be 1.5 times larger than the previously measured value.

E_p [keV]	$\omega\gamma$ [meV]
126	$0.0375 \pm 0.0002_{stat} \pm 0.0017_{syst}$
271	$2.7 \pm 0.3_{stat} \pm 0.4_{syst}$
272	$129.9 \pm 0.4_{stat} \pm 5.8_{syst}$
291	$1.99 \pm 0.01_{stat} \pm 0.09_{syst}$
352	$14.9 \pm 0.4_{stat} \pm 0.7_{syst}$

Papers

- Technical paper (Masha E. et al) -> ready, to be sent to the WG and very soon to the EB
- Report on the analysis sent (in May) to the collaboration
- Physical paper (Sidhu R. et al) -> stellar rate under computation (Ragan), Maria Lugaro will investigate the stellar scenario where our results could have the largest impact and we will decide if PRL or PRC, and if they are needed further astrophysical consequence computations

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