Progress towards the Single Atom Microscope: measuring rare-reaction rates for nuclear astrophysics

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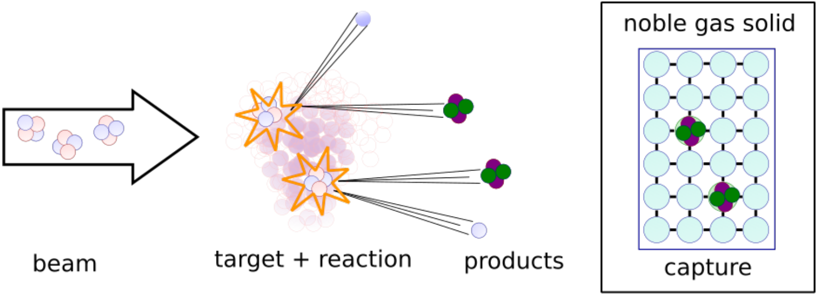
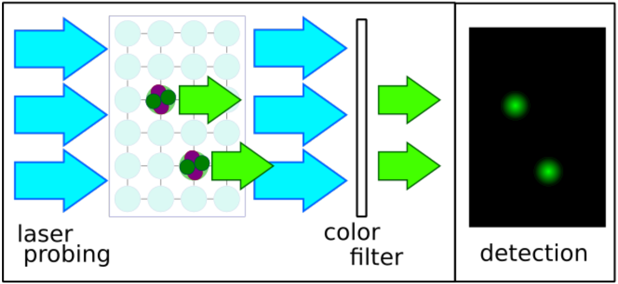
Rare Nuclear Processes - Optical Detection Scheme



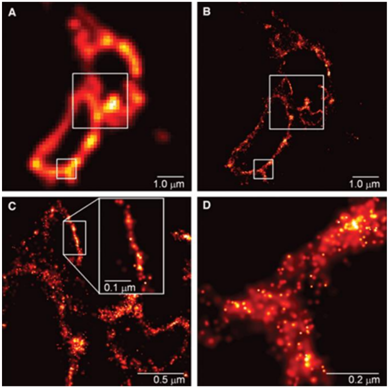


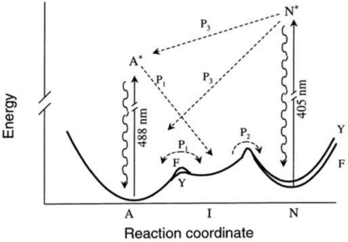
Advantages of noble gas solids:

1. Chemically inert
2. Easy to purify
3. Stable confinement of product species
4. Transparent for optical wavelengths

Superresolution Fluorescence Microscopy

- 2014 Nobel Prize In Chemistry
  - Eric Betzig, Stefan Hell, and W. E. Moerner
- Well developed techniques
- Utilized on a large scale in the biological sciences

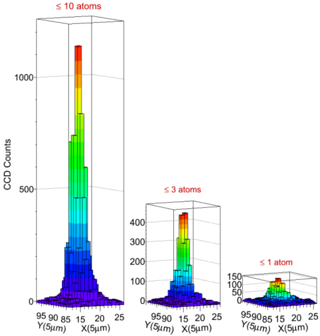




Betzig et al., Science, 2006, 313, 1642-1645; Dickson et al., 1997, Nature 388, 355-358

Demonstrated Single Atom Sensitivity

- *Imaging Single Barium Atoms in Solid Xenon for Barium Tagging in the nEXO Neutrinoless Double Beta Decay Experiment*, by Timothy Walton, Dissertation, Colorado State University (2016)
- *Demonstration of Single Barium Ion Sensitivity for Neutrinoless Double Beta Decay using Single Molecule Fluorescence Imaging*, A.D. McDonald et al., (2017), accepted by PRL



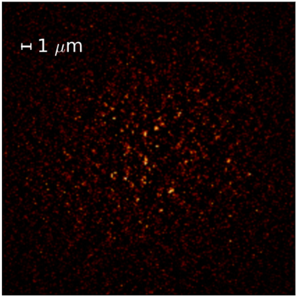
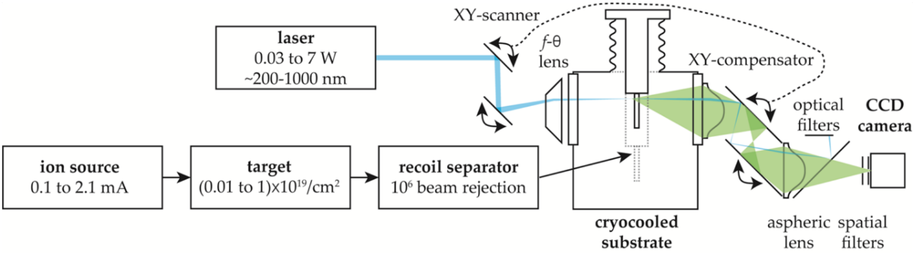


FIG. 3. A sample image from the EM-CCD in one of the barium-spiked samples showing both near-surface (bright) and deeper (dim) fluorescent molecules.

SAM Experiment Layout - Utilize Inverse Kinematics

- Heavier reactant beam, lighter reactant target.
  - Advantage: heavy atomic product scattered in forward tight cone.
  - no need for a large 4π detector
- Gather ALL products in a noble gas solid (Ne, Ar, Kr, Xe).
  - selectively identify products via laser fluorescense spectroscopy.
  - measure rate (count) by optically imaging product atoms.



JENSA: https://doi.org/10.1016/j.phpro.2015.05.057
HIPPO: https://doi.org/10.1016/j.nima.2011.10.039

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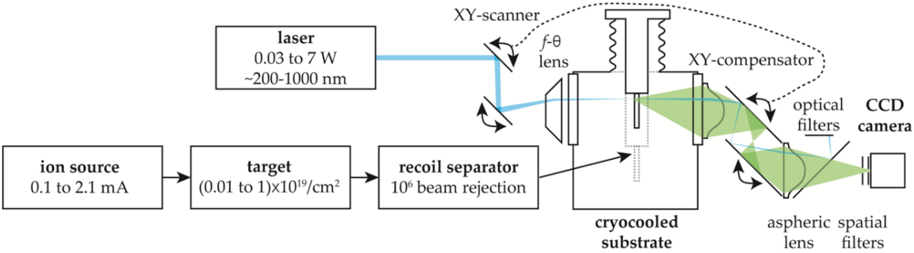

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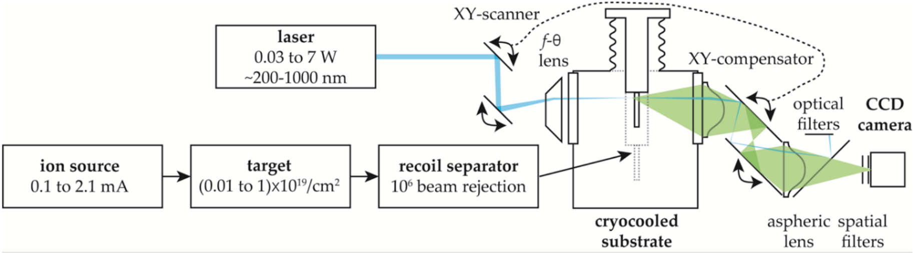
Advantages: Efficient, Selective, Sensitive

- Efficient: Unrejected beam and all product atoms are captured.
- Selective: Product atoms are identified via resonant laser excitation.
- Sensitive: Emission Spectrum is significantly shifted from Excitation Spectrum.



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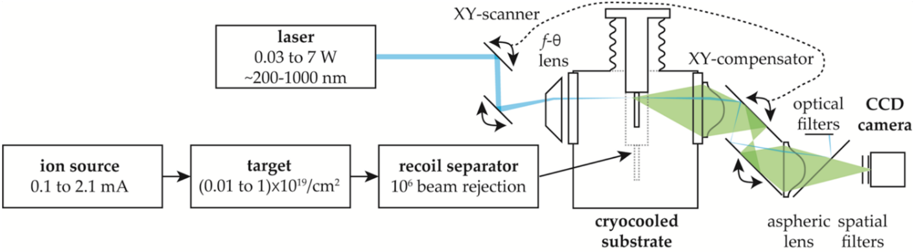

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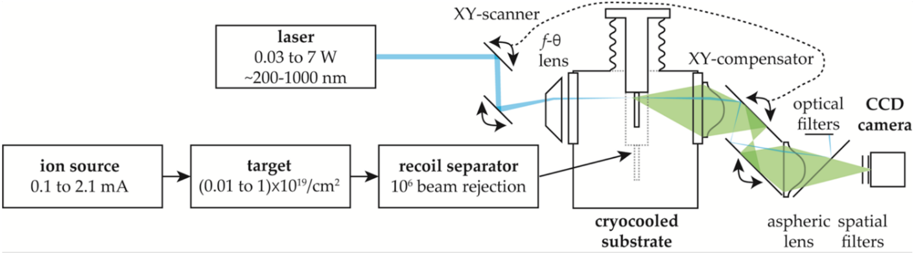

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How do we accomplish this?

Recoil Separators

- How large of a noble gas film is necessary to capture all products?
    - affects scanning/counting cycle time
- For which situations is beam supression a challenge?
    - generally not a problem for SAM
- What degree of isotopic selection is feasible?

Single Atom Sensitivity

- How to isolate the single atom signal from background sources?
    - excitation light
    - impurities in optics, windows, substrate
- What is the time dependence of signal and background?
    - photobleaching - atoms can go dark
- How can we maximize the signal size for a fixed fluorescence rate?
    - low noise detectors
    - high optical capture efficiency

Some Laser-Friendly Atoms

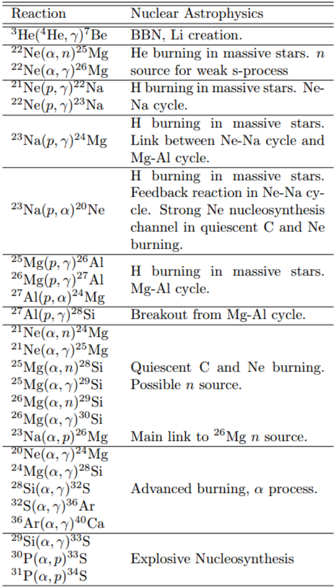
Species	Excitation (nm)	Emission (nm)	Brightness (Hz)	Medium	Notes
Li	670	890	5E7	Kr	[15]
Be	225	455 & 332	4.2E-1		*
		245	5.5E8		*
B	215	250*	1.7E8*	Ne	[14]
Na	595	720	6.3E7	Kr	[2]
Mg	275	472 & 518	2.5E1	Ar	[12]
		296	5.0E8	Ne	[8]
Al	291	404	5.9E7*	Ar	[1]
	338	414	9.8E7*	Ar	[1]
Si	232, 219, 227	390*	1.3E7*	Ar	[7]
		412*	4.4E5*		[7]
S	466	805	1E5	Xe	[10]
K	762	900	5E7	Kr	[3]
Ca	423	657 & 1953	2.6E3		*
Mn	355	586	2.6E2	He	[13]
	278	413	1.8E7	Ar	[6]
Rb	776	830	5E7	Ar	[4]
Sr	461	689 & 2739	4.7E4		*
Cd	220	228	7.9E8	Ne	[9]
	226	326	<1E6	Kr	[9]
Cs	834	970	5E7	Ar	[4]
Eu$^+$	409	467	2.2E8	Xe	[5]
Yb	388	410	1.9E8*	Ne	[11]
		546 & 1540*	1.1E6	Ne	[16]

* Vacuum values, NIST Atomic Spectra Database (physics.nist.gov)

Hyperfine Quenching Yb in s-Ne: Xu, Singh, et al. PRL 113, 033003 (2014)

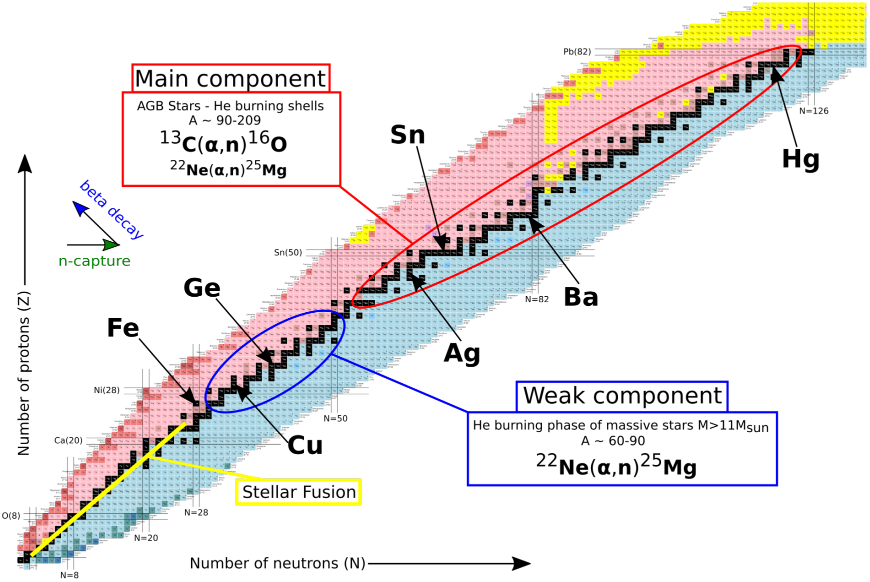
Some SAM-Friendly Nuclear Reactions

- Astrophysically relevant reactions.
- Optical transitions.
- Stable or *not too unstable* products/reactants.
- Compatible with inverse kinematics reaction scheme.
- Forward or reverse* channels.
- Low level of background products/reactants.



Reaction	Nuclear Astrophysics
^{3}He(^{4}He, γ)^{7}Be	BBN, Li creation.
^{22}Ne(α, n)^{25}Mg ^{22}Ne(α, γ)^{26}Mg	He burning in massive stars. n source for weak s-process
^{21}Ne(p, γ)^{22}Na ^{22}Ne(p, γ)^{23}Na	H burning in massive stars. Ne-Na cycle.
^{23}Na(p, γ)^{24}Mg	H burning in massive stars. Link between Ne-Na cycle and Mg-Al cycle.
^{23}Na(p, α)^{20}Ne	H burning in massive stars. Feedback reaction in Ne-Na cycle. Strong Ne nucleosynthesis channel in quiescent C and Ne burning.
^{25}Mg(p, γ)^{26}Al ^{26}Mg(p, γ)^{27}Al ^{27}Al(p, α)^{24}Mg	H burning in massive stars. Mg-Al cycle.
^{27}Al(p, γ)^{28}Si	Breakout from Mg-Al cycle.
^{21}Ne(α, n)^{24}Mg ^{21}Ne(α, γ)^{25}Mg ^{25}Mg(α, n)^{28}Si ^{25}Mg(α, γ)^{29}Si ^{26}Mg(α, n)^{29}Si ^{26}Mg(α, γ)^{30}Si	Quiescent C and Ne burning. Possible n source.
^{23}Na(α, p)^{26}Mg	Main link to ^{26}Mg n source.
^{20}Ne(α, γ)^{24}Mg ^{24}Mg(α, γ)^{28}Si ^{28}Si(α, γ)^{32}S ^{32}S(α, γ)^{36}Ar ^{36}Ar(α, γ)^{40}Ca	Advanced burning, α process.
^{29}Si(α, γ)^{33}S ^{30}P(α, p)^{33}S ^{31}P(α, p)^{34}S	Explosive Nucleosynthesis

S-Process Neutron Sources



Main component

AGB Stars - He burning shells
A ~ 90-209

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

$^{22}\mathbf{Ne}(\alpha,n)^{25}\mathbf{Mg}$

Weak component

He burning phase of massive stars $M>11M_{sun}$
A ~ 60-90

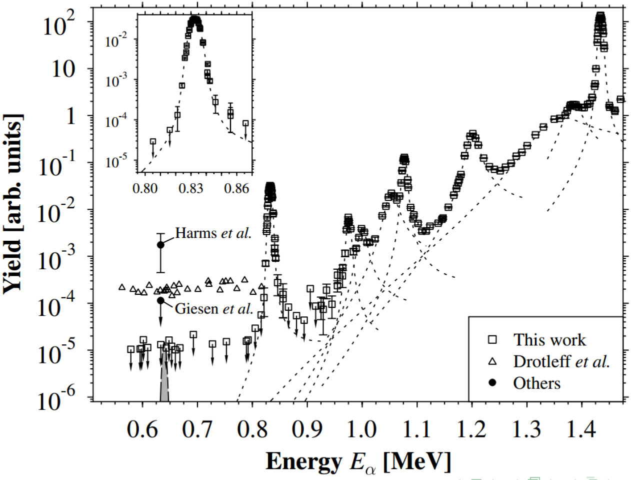
$^{22}\mathbf{Ne}(\alpha,n)^{25}\mathbf{Mg}$

Stellar Fusion

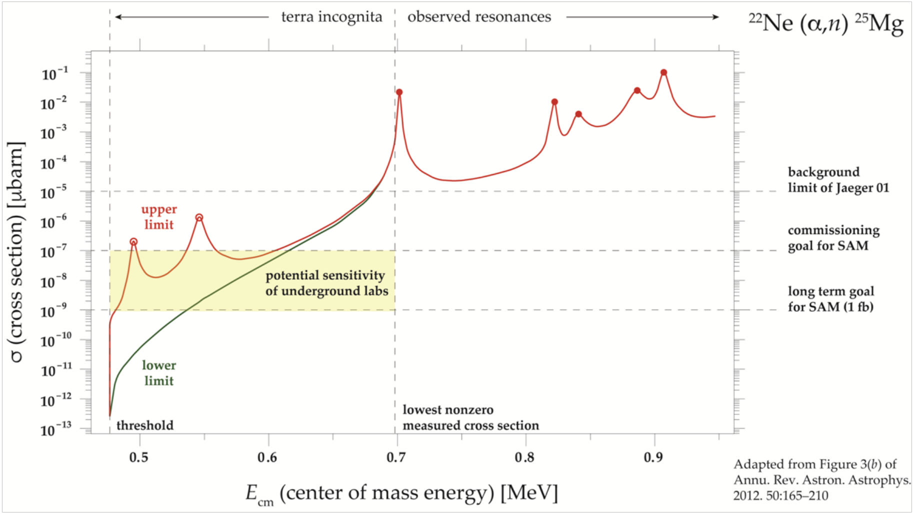
Adapted from: http://people.physics.anu.edu.au/~ecs103/chart/

^{22}Ne+α: The Key Neutron Source in Massive Stars, Jaeger et al., Phys. Rev. Lett. 87, 202501 (2001)

- Most recent direct measurement of ^{22}Ne(α,n)^{25}Mg in Gamow Window.
- 100-150 μA He$^+$ beam incident on a ^{22}Ne gas jet target.



Goal: Sub-Picobarn Sensitivity (Single Atom!)

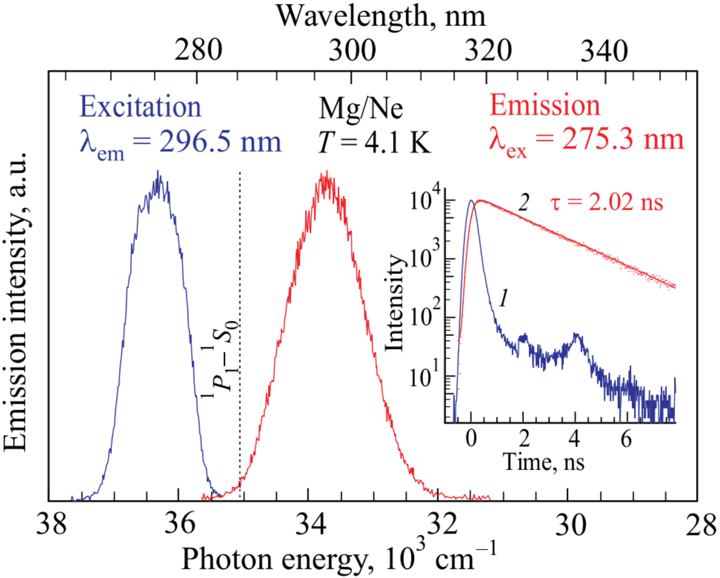


Adapted from Figure 3(*b*) of Annu. Rev. Astron. Astrophys. 2012. 50:165–210

(cross section)x(areal density)x(current)≈ (reaction rate)

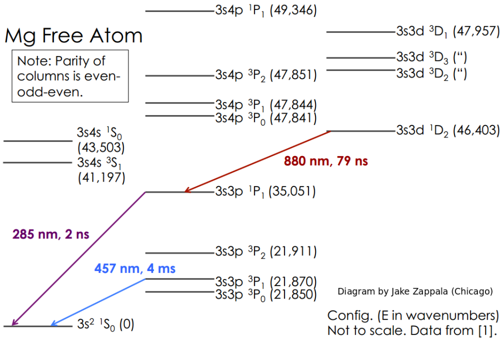
$$(1\ \text{fb}) \times (10^{19}\ \text{cm}^{-2}) \times (2.1\ \text{mA}) \approx \mathbf{7/day}$$

Matrix Isolated Magnesium Spectroscopy in Solid Neon



Metal atom (Zn, Cd and Mg) luminescence in solid neon, Healy, Kerins, McCaffrey LTP 38, 679(2012)

Magnesium Spectroscopy



Mg Free Atom

Note: Parity of columns is even-odd-even.

3s4p $^1P_1$ (49,346)

3s3d $^3D_1$ (47,957)

3s3d $^3D_3$ (")

3s3d $^3D_2$ (")

3s4p $^3P_2$ (47,851)

3s4p $^3P_1$ (47,844)

3s4p $^3P_0$ (47,841)

3s3d $^1D_2$ (46,403)

3s4s $^1S_0$ (43,503)

3s4s $^3S_1$ (41,197)

880 nm, 79 ns

3s3p $^1P_1$ (35,051)

285 nm, 2 ns

3s3p $^3P_2$ (21,911)

457 nm, 4 ms

3s3p $^3P_1$ (21,870)

3s3p $^3P_0$ (21,850)

$3s^2$ $^1S_0$ (0)

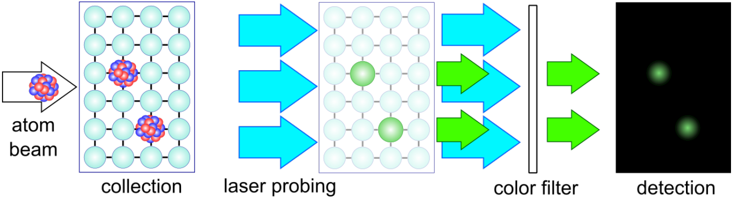
Diagram by Jake Zappala (Chicago)

Config. (E in wavenumbers)
Not to scale. Data from [1].

Medium	Excitation (nm)	Emission (nm)	Lifetime (ns)
Kr	283	297	1.25
Kr	283	324	2.15
Kr	283	472	8.91×10^6
Ar	283	297	1.12
Ne	275.3	296.5	2.02

Optical Dynamics of Yb in s-Ne: Xu, Hu, Singh, et al. PRL 107, 093001 (2011)

Single Atom Detection Scheme



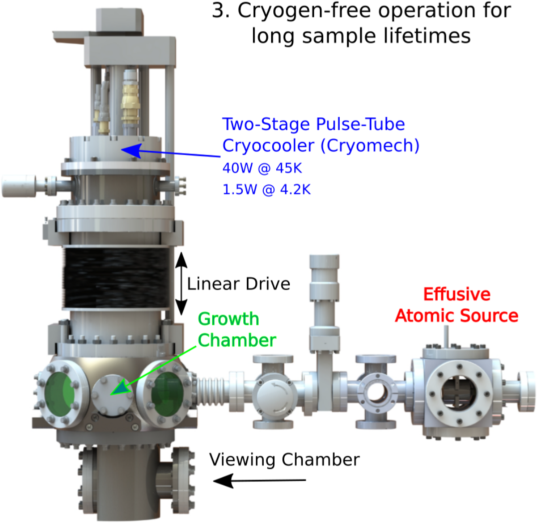
Light Collection Efficiency - Optimization

- Solid angle of the detector (fluorescing atoms emit isotropically)
- Optical filter transmission (need to filter out excitation light)
- Quantum efficiency of the camera

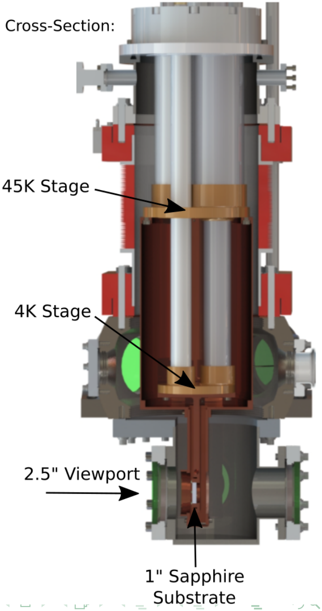
Andor Clara CCD Camera
Dark count rate per pixel: 2.3/hr/pixel
Quantum Efficiency: 0.65 @ 550nm

Prototype Single Atom Microscope

1. Maximized Light Collection Efficiency
2. Modular Design
3. Cryogen-free operation for long sample lifetimes



Cross-Section:



Summary and Future Plans

SAM is a novel method for measuring rare nuclear reaction rates.

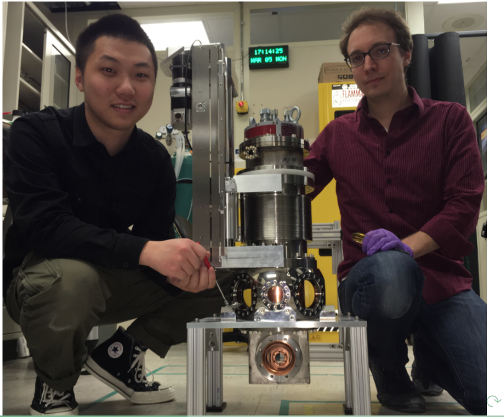
- $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$
- Other reactions w/laser friendly reactants or products.

Products are captured in a cryogenic noble gas solid.

- Utilize a recoil separator for isotopic selection and to minimize heat load.
- Identified and counted via resonant laser excitation.

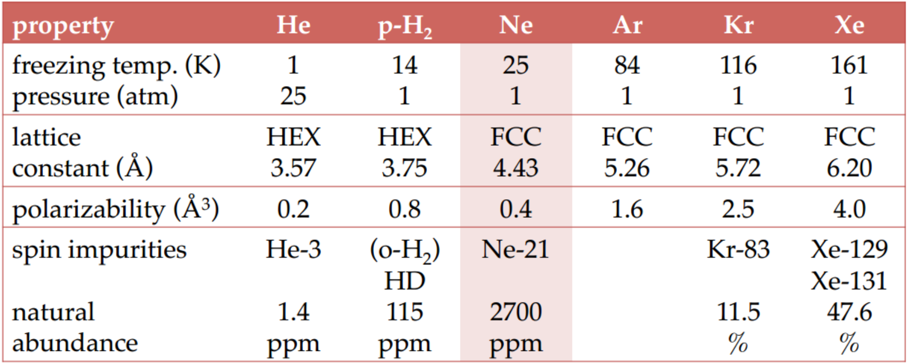
Plans for 2018:

- pSAM assembly and testing.
- Study and characterization of background signals.
- Single Atom Microscopy proposal paper with updated measurements.
- Mg in s-Ne Spectroscopy.
- Mg in s-Ne Fluorescence yield.



Backup/Extra Slides

Properties of Noble Gas Solids



property	He	p-H_2	Ne	Ar	Kr	Xe
freezing temp. (K)	1	14	25	84	116	161
pressure (atm)	25	1	1	1	1	1
lattice constant (Å)	HEX 3.57	HEX 3.75	FCC 4.43	FCC 5.26	FCC 5.72	FCC 6.20
polarizability (Å^3)	0.2	0.8	0.4	1.6	2.5	4.0
spin impurities	He-3	(o-H_2) HD	Ne-21		Kr-83	Xe-129 Xe-131
natural abundance	1.4 ppm	115 ppm	2700 ppm		11.5 %	47.6 %

Ashcroft & Mermin *Solid State Physics* (1976)
Cook *Argon, Helium and The Rare Gases* (1961)
Huiszoon & Briels *Chem. Phys. Lett.* **203** 49 (1993)

Nuclear Reaction Rates

- It is important to understand rate of $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$, and competing $^{22}\mathrm{Ne}(\alpha,\gamma)^{26}\mathrm{Mg}$ under stellar conditions.
- Rate uncertainties cause large abundance variations in simulations of s-process nucleosynthesis.

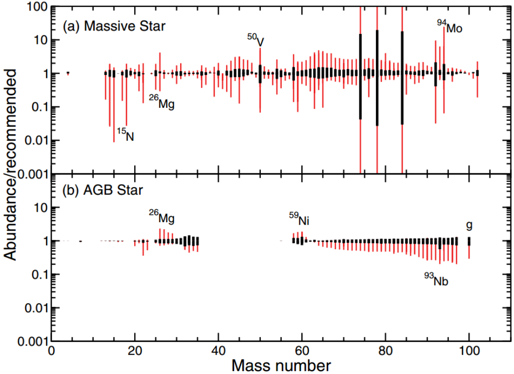
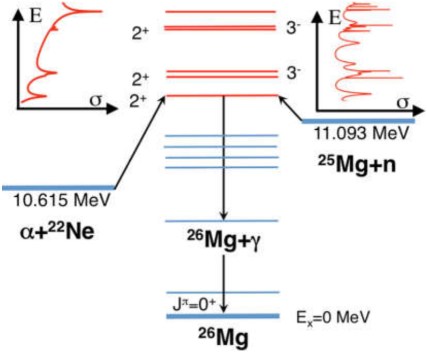


Figure: Abundance variations based on recent (black) and previous (red) $Ne + \alpha$ reaction rate uncertainties.

"Reaction rates for the s-process neutron source 22Ne+alpha", R. Longland *et al.* Phys. Rev. C 85,065809 (2012)

^{22}Ne+α - resonances

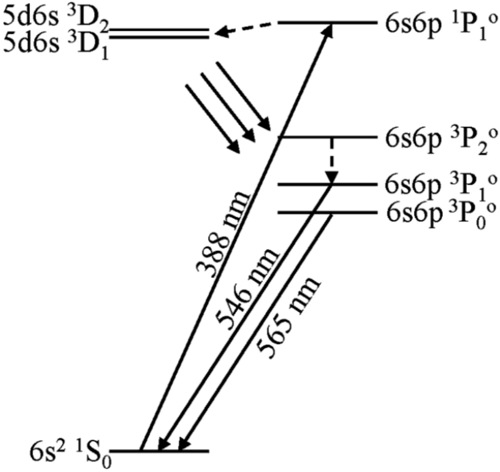
- Recent (2017!) study of excited states in ^{26}Mg via neutron resonance spectroscopy of ^{25}Mg+n.
- Crucial to assign correct spin parities, J^{π} to ^{26}Mg states.
- (α, n) can only populate natural-parity states in ^{26}Mg, as $J^{\pi} = 0^{+}$ for ^{22}Ne, α.
- Massimi et. al. (2017) identified 5 natural parity states below the $E_{\alpha}^{lab} = 832$ keV ($E_n \approx 235$ keV) resonance.



"Neutron spectroscopy of ^{26}Mg states: Constraining the stellar neutron source ^{22}Ne$(\alpha, n)^{25}$Mg" C. Massimi et. al. Physics Letters B 768 (2017)

Ytterbium as a Test Case

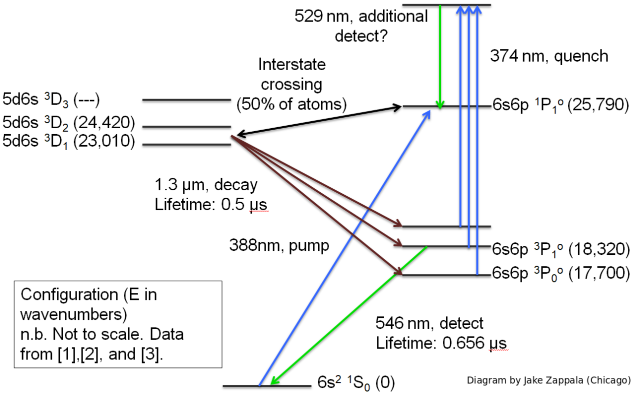
- Yb structure similar to Mg.
  - Yb: [Xe] $4f^{14}6s^2$
  - Mg: [Ne] $3s^2$
- Yb in Ne extensively studied.
  - has optically accessible transitions.
  - exhibits large shift between excitation and emission.
- Provides a good test case for Single Atom Detection.



Xu, Hu, Singh, et al. PRL 109 093001 (2011)

Single Atom Sensitivity - Ytterbium

- short lifetime - lots of light.
- large shift between excitation/emission



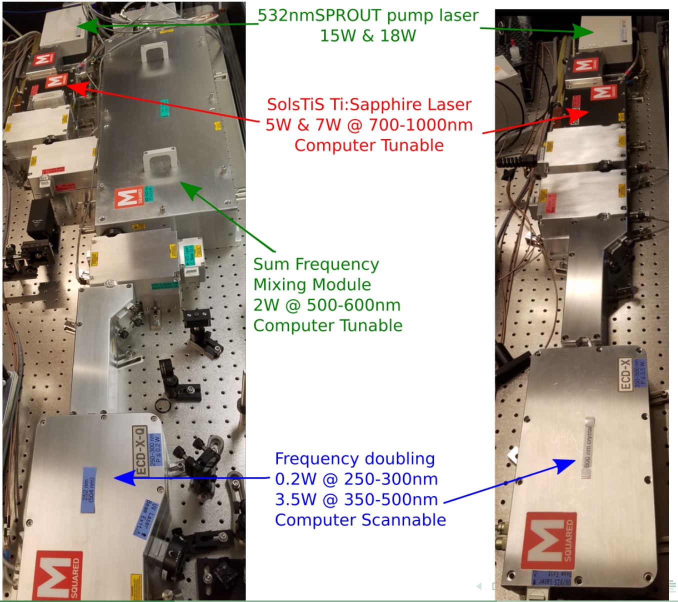
Configuration (E in wavenumbers)
n.b. Not to scale. Data from [1],[2], and [3].

Diagram by Jake Zappala (Chicago)

Yb fluorescence rate of 1 MHz, 2% solid angle efficiency, Yb Signal Rate ≈ 20 kHz

SpinLab High Power, Tuneable Lasers

GRUVY **BLUREI**



532nmSPROUT pump laser
15W & 18W

SolsTiS Ti:Sapphire Laser
5W & 7W @ 700-1000nm
Computer Tunable

Sum Frequency
Mixing Module
2W @ 500-600nm
Computer Tunable

Frequency doubling
0.2W @ 250-300nm
3.5W @ 350-500nm
Computer Scannable

Candidate Species References

Species	Excitation (nm)	Emission (nm)	Brightness (Hz)	Medium	Notes
Li	670	890	5E7	Kr	[15]
Be	225	455 & 332	4.2E-1		*
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* Vacuum values, NIST Atomic Spectra Database (physics.nist.gov)

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[1] H. Abe and D. M. Kolb. Optical spectra of matrix-isolated aluminium. *Berichte der Bunsengesellschaft für physikalische Chemie*, 87(6):523–527, 1983.

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