Probing neutrons and purported fission daughter products from gas-loaded, laser-irradiated metal-hydrogen targets

Principal Investigator: Yet-Ming Chiang, Professor, MIT

Presentation by Florian Metzler, Research Scientist, MIT

Washington, DC
September 8, 2023

ARPA-E LENR: Massachusetts Institute of Technology

Massachusetts Institute of Technology

Project Title:

Probing neutrons and purported fission daughter products from gas-loaded, laser-irradiated metal-hydrogen targets

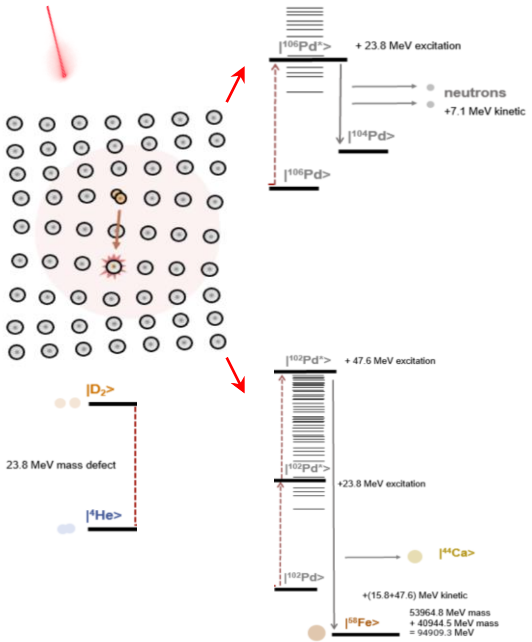
PI:

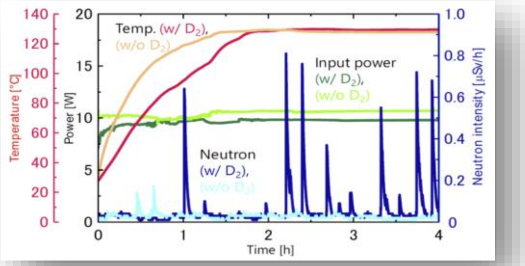
Yet-Ming Chiang
ychiang@mit.edu

Project Outcomes:

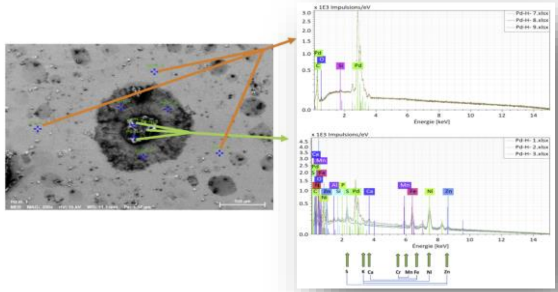
Unequivocal demonstration of the presence or absence of LENR phenomena through replication experiments with additional characterization and detection methods

Laser irradiation





Neutron bursts



Elemental production

Key takeaway: anomalous emitted radiation and surface isotopes have been reported in metal deuterides under low power laser irradiation and should be revisited with improved radiation detection and isotopic characterization

Hypothesis

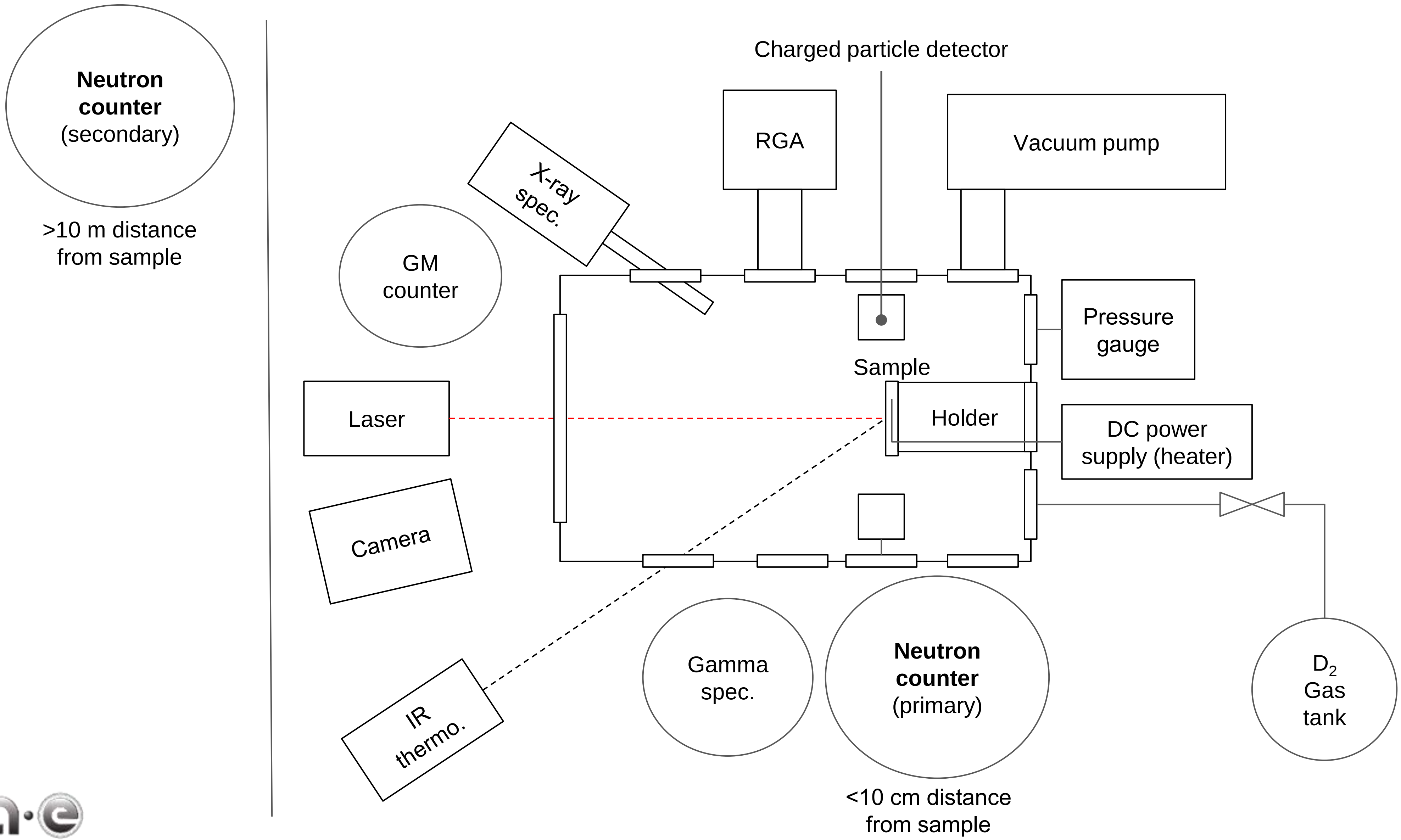
Hypothesis:

Nuclear reactions can occur in metal deuterides at near-ambient temperature and pressure conditions under low-power laser irradiation
(Beltyukov 1991; Nassissi 1999; Mastromatteo 2016; Ushikoshi 2020; Barrowes 2022)

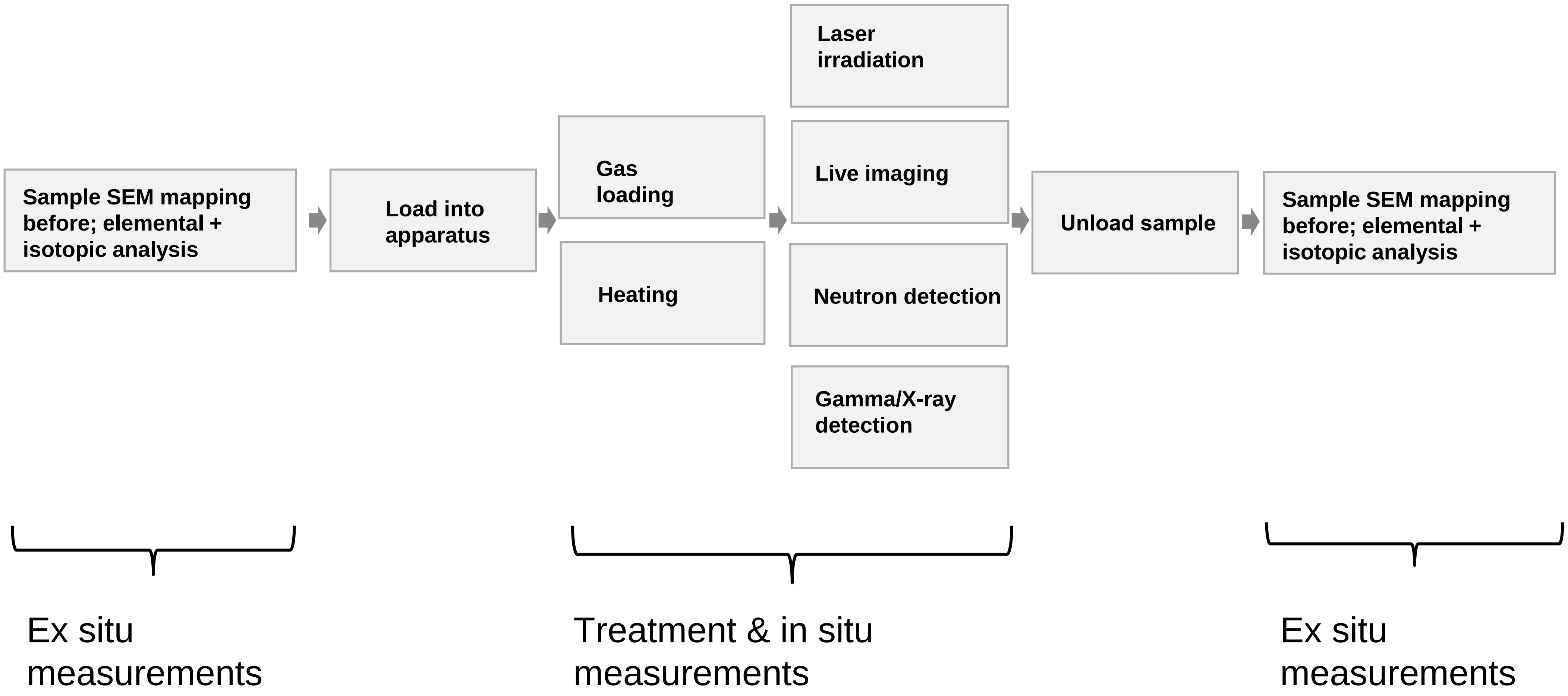
More specifically:

- DD and HD fusion reactions can be accelerated by nonradiatively transferring corresponding transition energies (23.8 MeV and 5.5 MeV respectively) to resonant excited states of heavy lattice nuclei (e.g. Pd and Ti isotopes).
- Such transfer is enabled by shared phonon and plasmon modes that cause temporary delocalization of nuclear states in a coherence domain (delocalized nuclear excitons).
- Dicke enhancement can accelerate what are initially low transfer probabilities due to weak couplings.

Overview of experimental setup



Key steps



Laser irradiation
Gas loading
Live imaging
Sample SEM mapping before; elemental + isotopic analysis
Load into apparatus
Unload sample
Sample SEM mapping before; elemental + isotopic analysis
Heating
Neutron detection
Gamma/X-ray detection
Ex situ measurements
Treatment & in situ measurements
Ex situ measurements

Variables overview

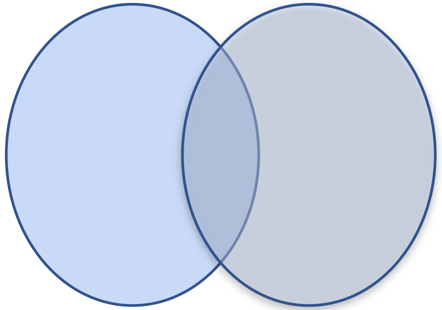
Independent variables → **Observables** → **Causes**

- **target material** (Pd, Ti);
- **target temperature** (25–175 °C)
- **chamber gas** (vacuum, H2, D2, Ar)
- **chamber pressure** (0.01–4 bar);
- **laser wavelength** (405, 594, 640, 1064 nm);
- **laser type** (pulsed or continuous-wave)
- **laser strength** (up to 1 J/pulse or 5-50 mW for CW);
- **spot size** (0.01–1 cm2).

+ potentially many hidden variables

Spots with low-Z elements

Bursts in neutron and gamma detectors



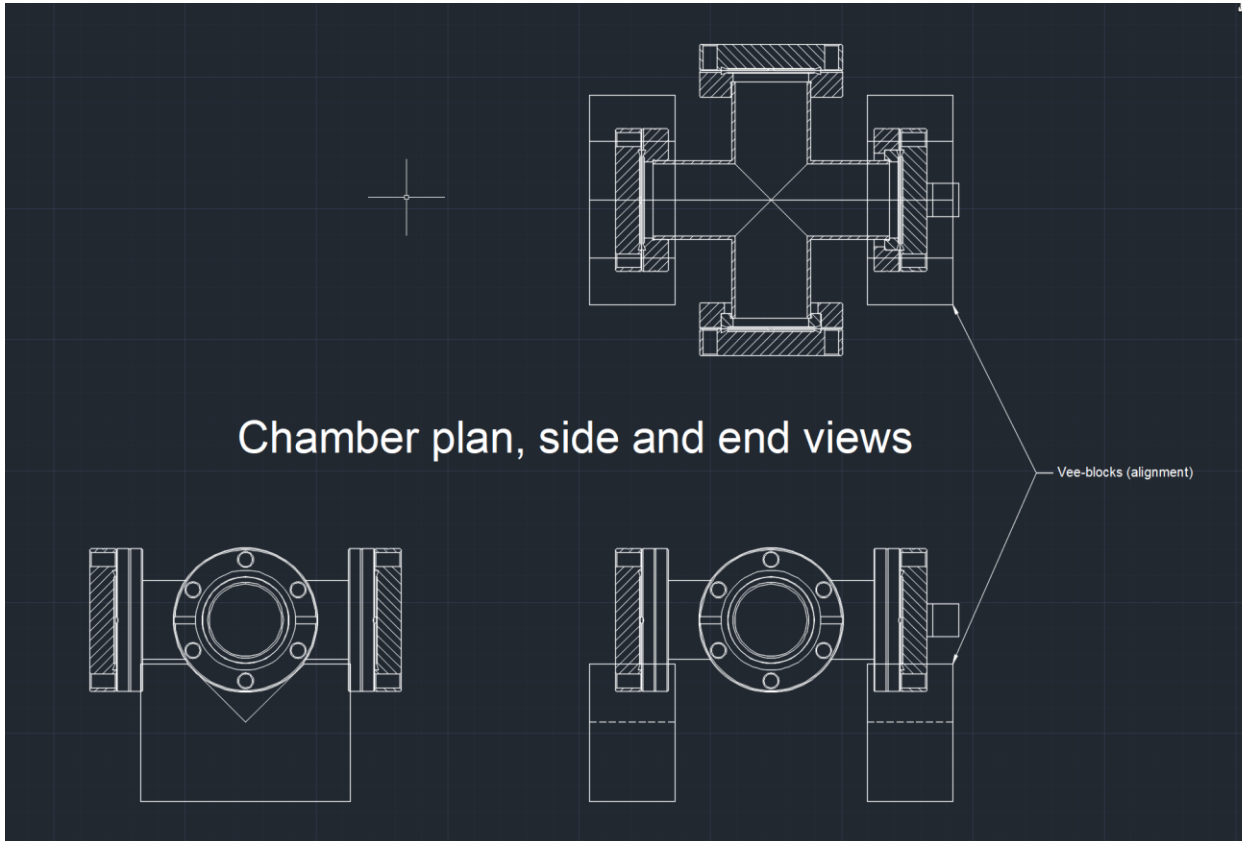
Prosaic?

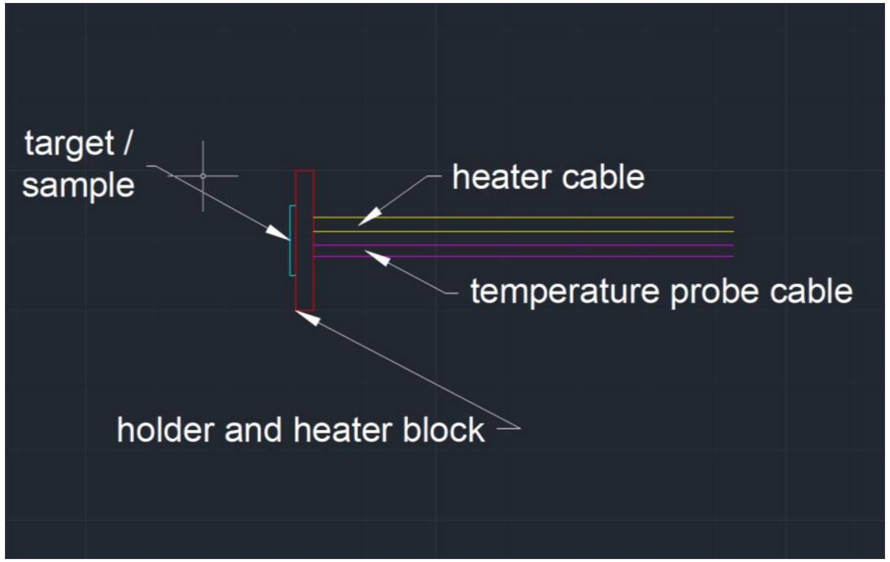
Nuclear?

- **neutron** counts (He-3 counter detectors; efficiency ~20%)
- **gamma** counts >100 keV (NaI gamma spectrometers)
- **isotopic ratios** of sample surface materials (mass spectrometer + NAA; goal is accuracy ±10%)

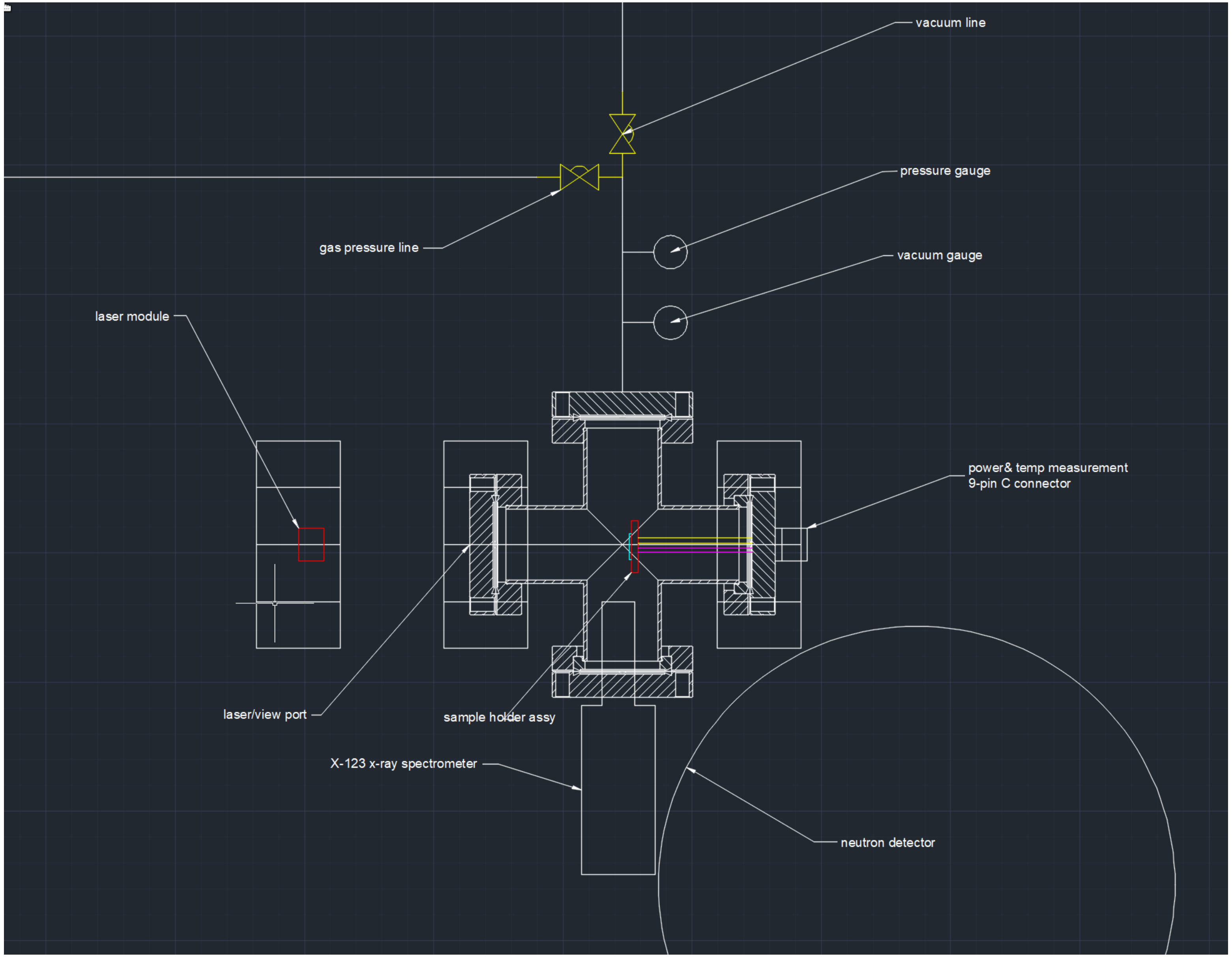
CHANGING WHAT'S POSSIBLE

Reactor design

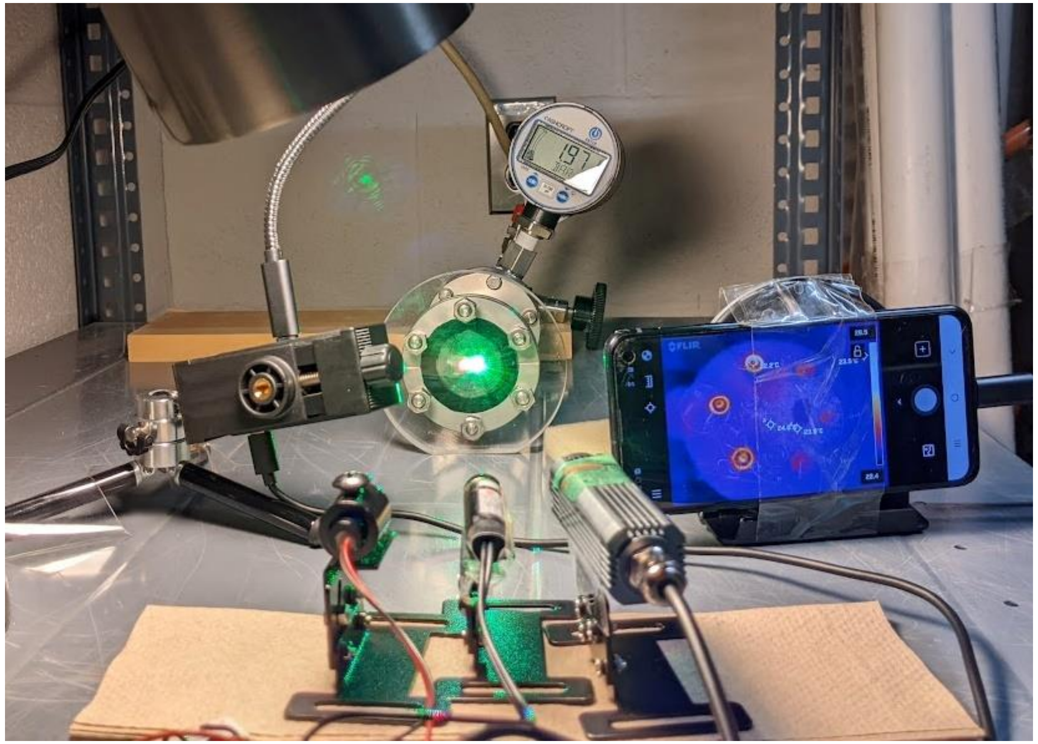




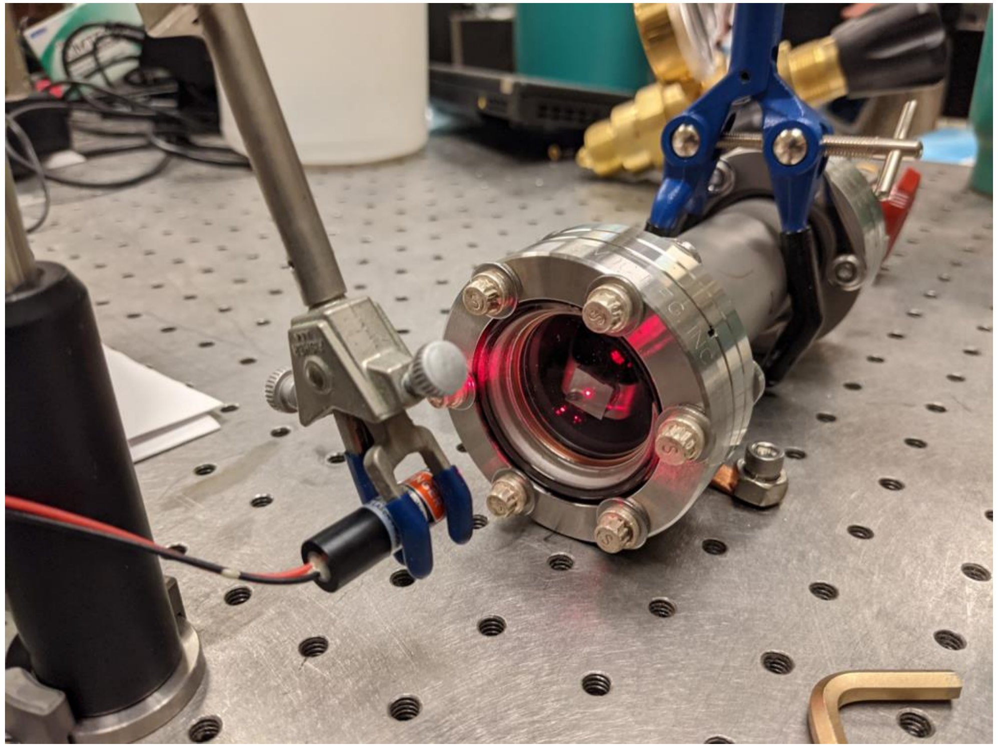
Reactor design (cont'd)



Preliminary experiments



At US Army EDRC



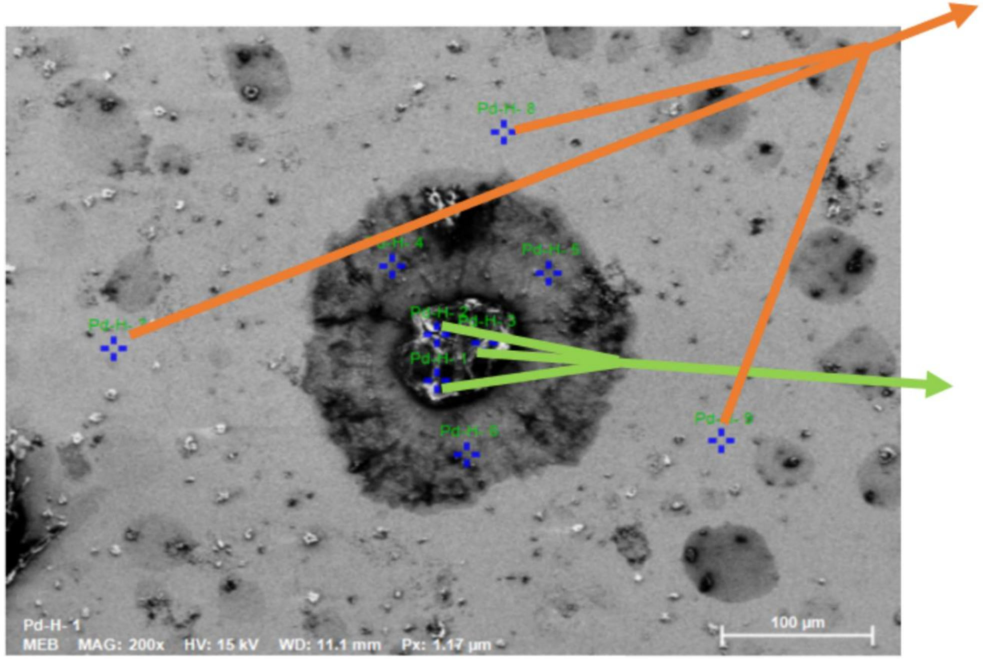
At MIT

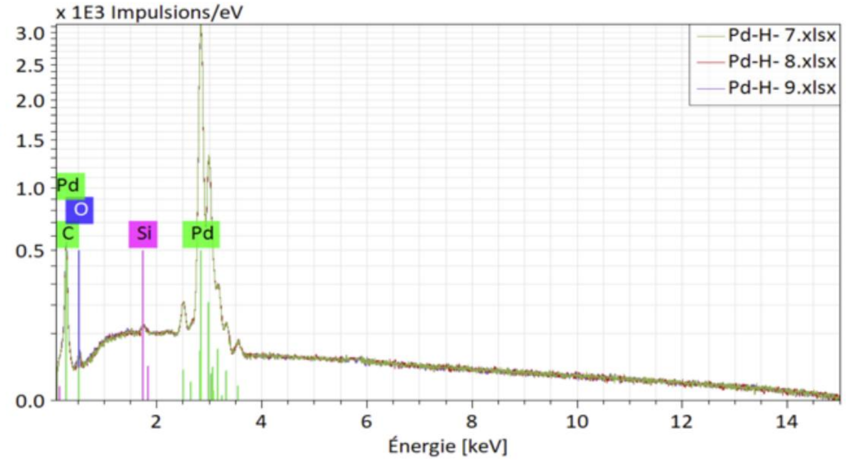
Data Acquisition

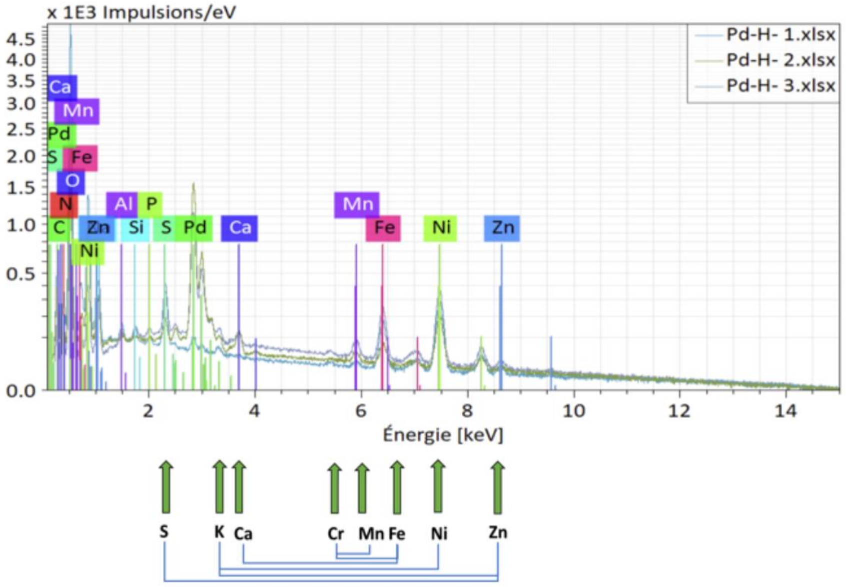
Measurement	Recording Method	Settings	Latency	Storage Media
SEM-EDS surface maps	Bitmaps	TBD	Before and after each experiment	Dropbox or Google Drive
Isotopic detection	Gamma spectra from Neutron activation analysis (NAA) and mass spectra from MS	TBD	Before and after each experiment	Dropbox or Google Drive
Radiation detection (*n*)	Neutron counts per second from ^3He proportional counter & liquid scintillation detector	Use of moderator to optimize sensitivity for 1-10 MeV neutrons	Continual data collection w/ time resolution of counts per second or higher	Local computer + Postgres time series database on an MIT-based server; Dropbox or Google Drive backup
Radiation detection (γ)	Spectra and counts >100 keV from HPGe and NaI spectrometers	Focus on 100 keV to 5 MeV range	Continual data collection w/ time resolution of counts per min or higher	Local computer + Postgres time series database on an MIT-based server; Dropbox or Google Drive backup

Reports of surface changes in the literature

SEM-EDS analysis of spots







Selection of possible stable daughter pairs from the fission of Pd isotopes:

Pd-102: Ni + K

Pd-104: Zn + S

Pd-105: Fe + Ca, Ni + K

Pd-106: Fe + Ca, Zn + S, Fe + Cr

Pd-108: Zn + K, Fe + Cr, Mn + Cr

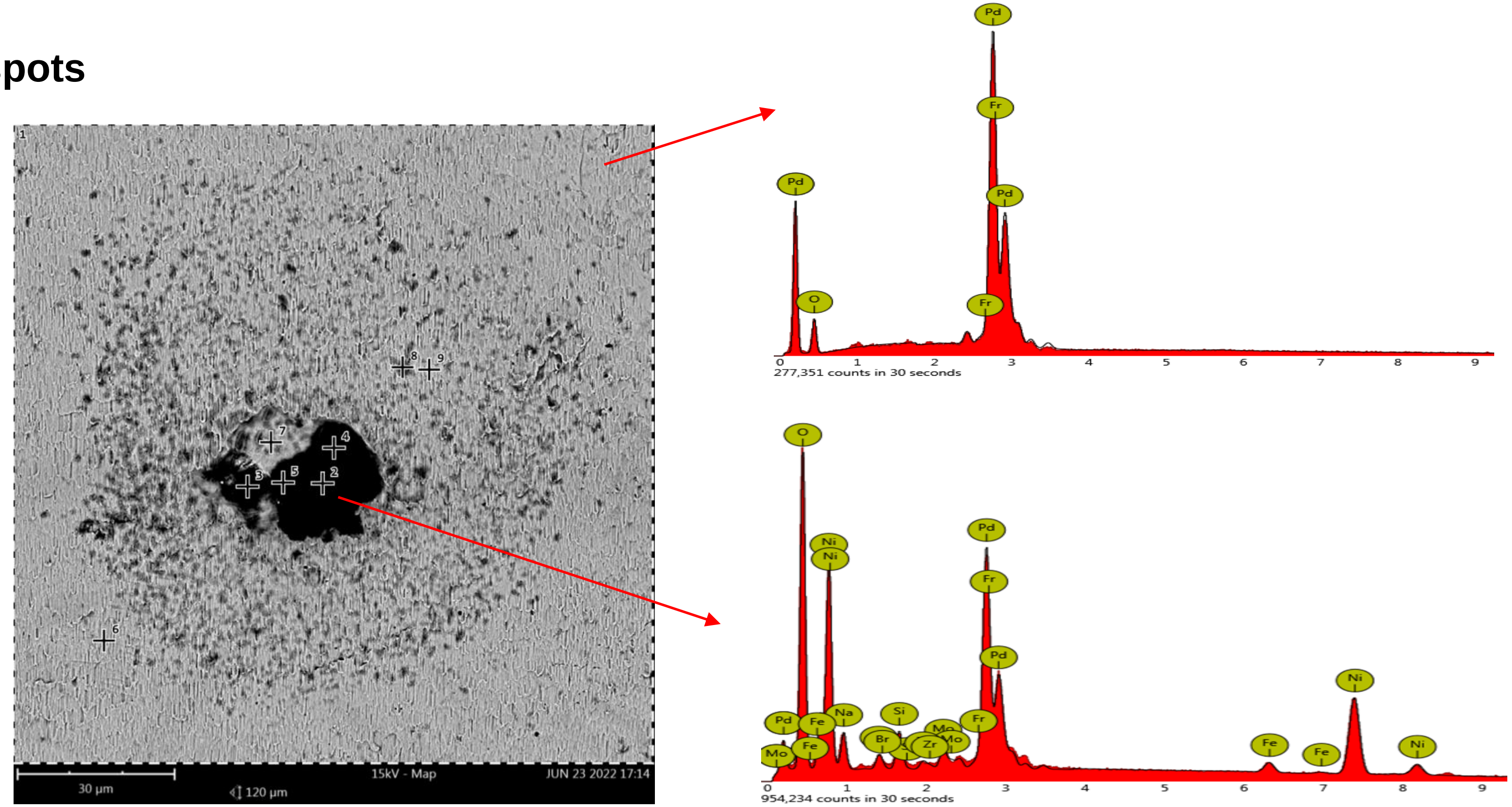
Pd-110: Fe + Cr, Mn + Mn

Biberian 2020, SFSNMC

arpa·e
CHANGING WHAT'S POSSIBLE

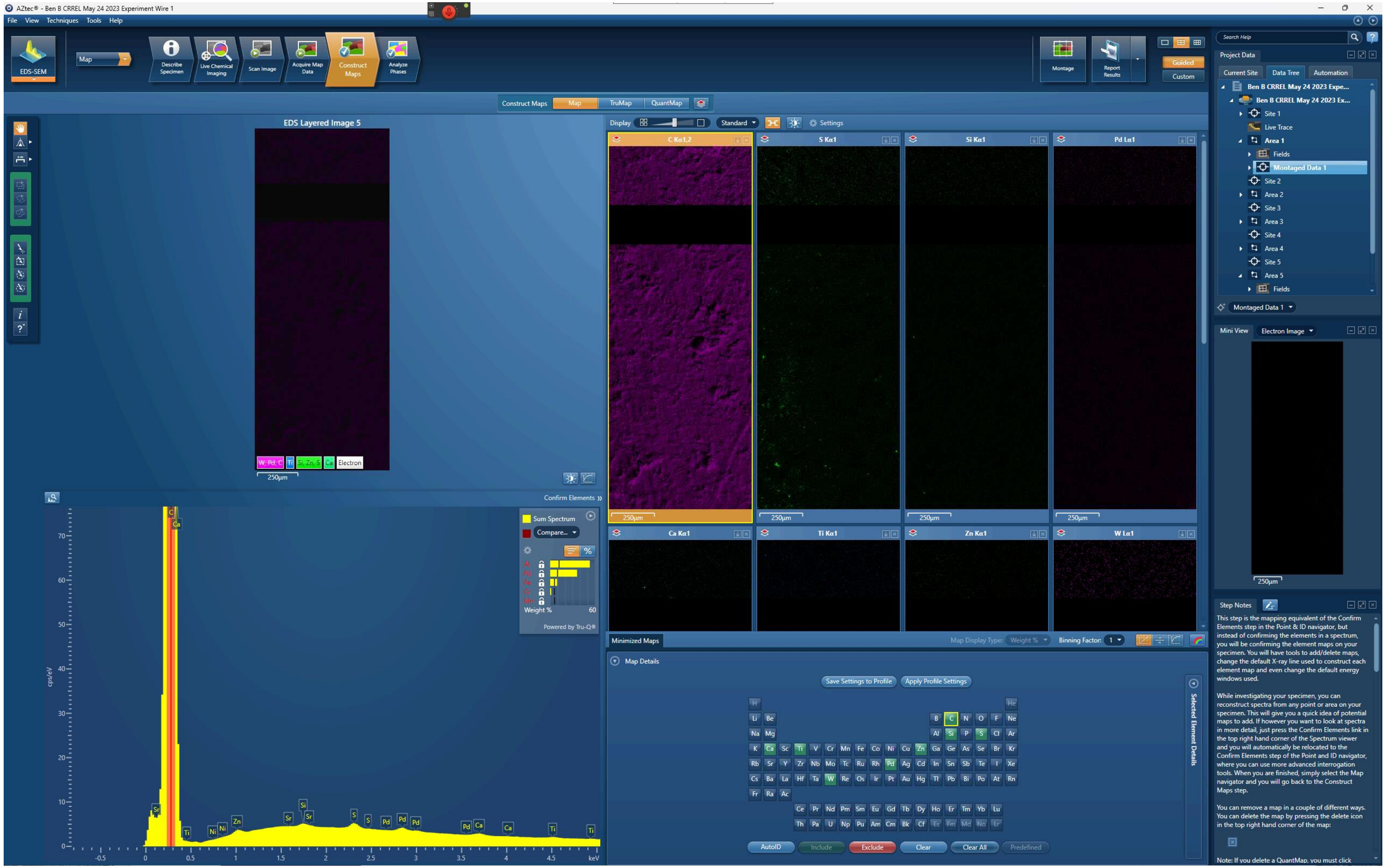
Reports of surface changes in the literature (cont'd)

SEM-EDS analysis of spots



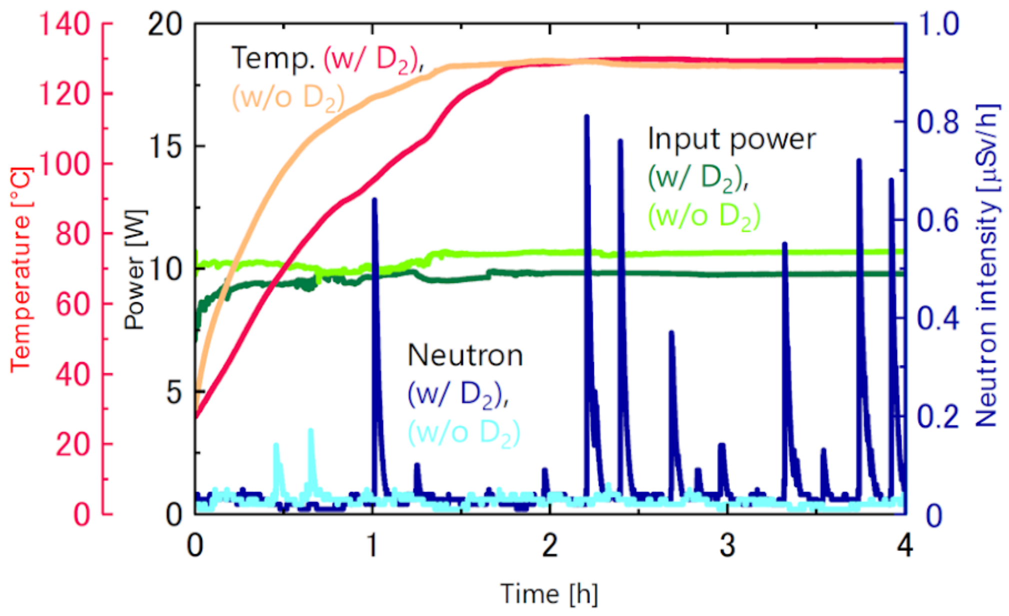
Barrowes 2022, ICCF24

SEM-EDS surface mapping in collaboration with Texas Tech

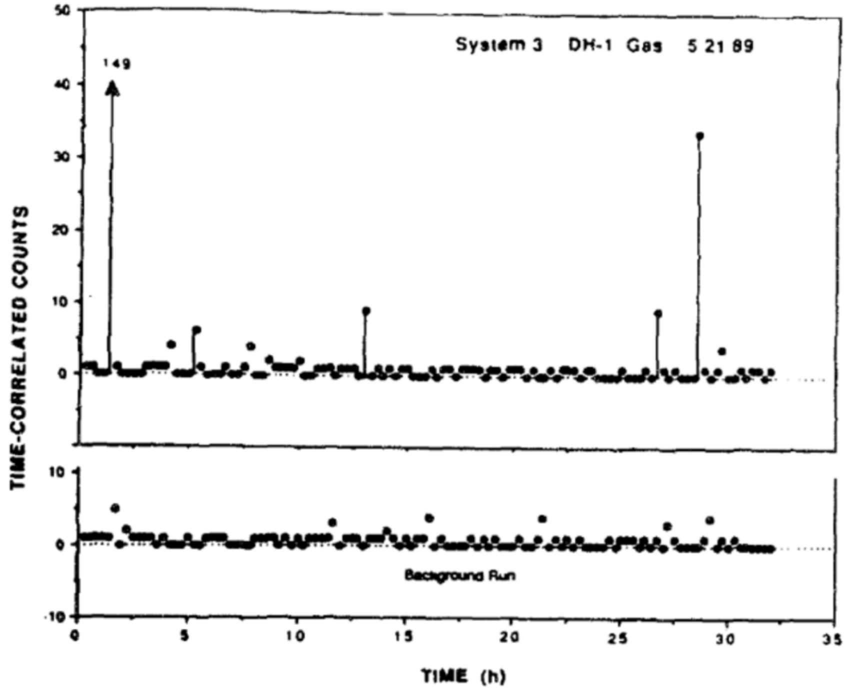


arpa·e
CHANGING WHAT'S POSSIBLE

Reports of neutron bursts in the literature



Uchikoshi 2020, Kyoto University



Menlove et al. 1990, Journal of Fusion Energy

Reports of neutron bursts in the literature (cont'd)

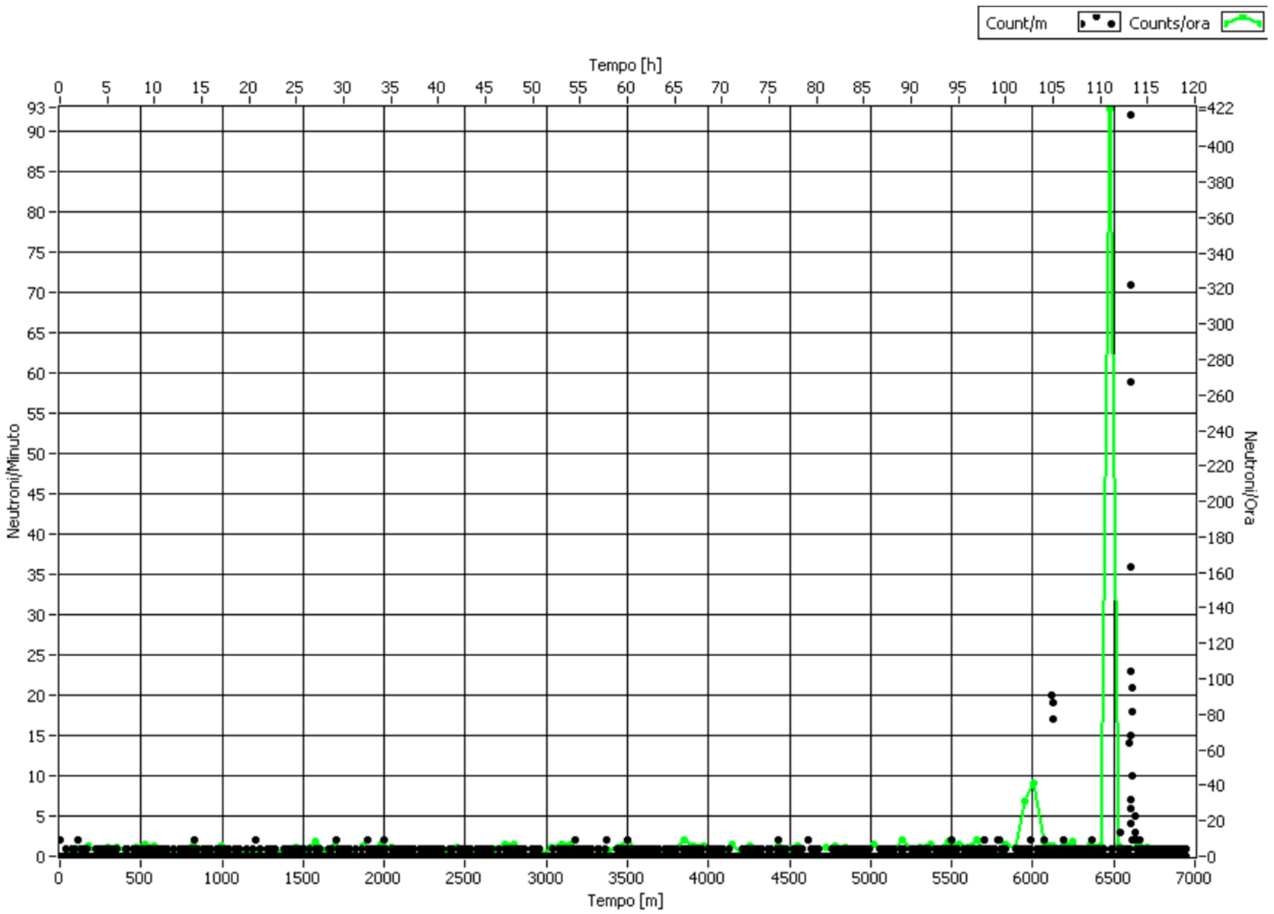
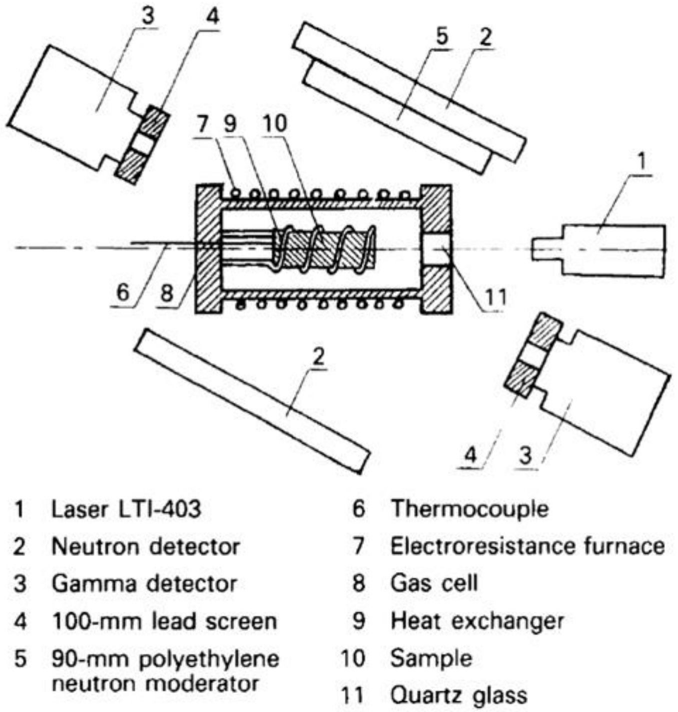


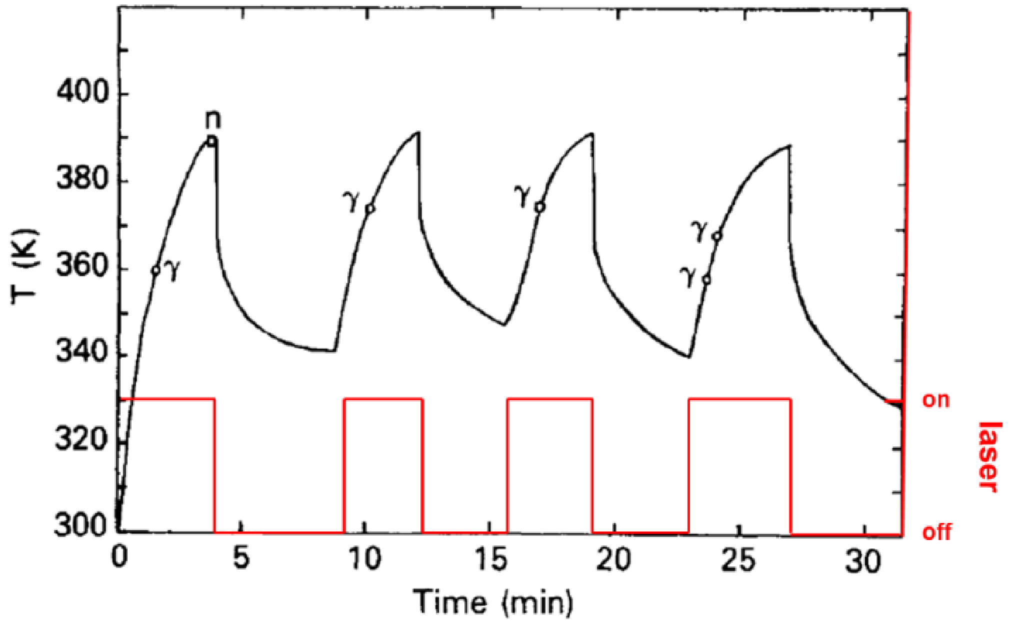
Figure 14. Screen shot of the neutron monitoring PC showing a massive neutron emission from reactor 1 after the experiment with a 405 nm laser.

Mastromatteo 2020, JCMNS

CHANGING WHAT'S POSSIBLE

Reports of neutron and gamma bursts correlated with irradiation



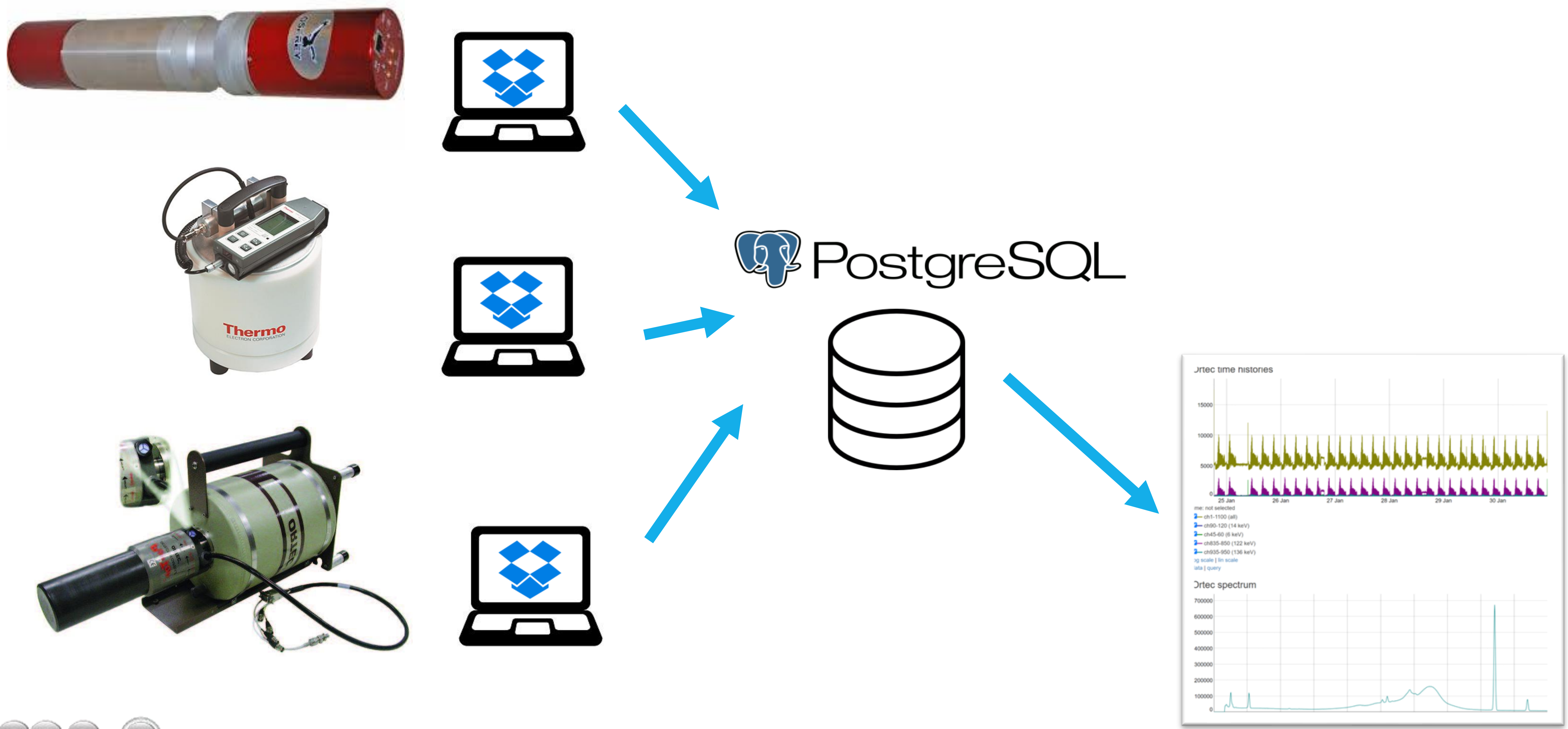


Beltyukov et al. 1991, Fusion Technology

Gamma emission on the order of 5 x 10^3/s
and neutron emission on the order of 2 x 10^2 n/s
in bursts of <0.5 s

(exceeding gamma background by 2x and neutron background by 18x)

24/7 data streaming with universal time stamps



CHANGING WHAT'S POSSIBLE

Cloud-based time series optimized Postgres database

Adminer 4.7.3 4.8.1

DB: experiments
Schema: public

SQL command Import
Export Create table

select codep_ps
select codep_ps2
select cp_a
select cp_r
select current1
select digtempsensors2
select digtempsensors3
select fukai_ps1
select gas_flow_1
select gm1
select gm2
select h_d_lvl_1
select hydrogen1
select keithley_ps
select multimeter1
select multimeter2
select multimeter3
select multimeter_trackers1
select multimeter_trackers2
select neutron1
select neutron_sean
select optimaloadcell
select ortec
select osprey
select phprobe
select precisionscale1
select pressure
select rotstage
select rotstage2
select target_amps_1
select target_temp_1
select tempandlight
select tempcontrol1
select temps_fukai1
select thermistor1
select x123
select x123sdd
select x123sdd2

Select: neutron1

Select data Show structure Alter table New item

Select | Search | Sort: time ☑ descending; ☐ descending | Limit: 51 | Action: Select !

`SELECT * FROM "neutron1" LIMIT 51` (0.001 s) Edit

Modify	time	channels	id
edit	2020-01-10 15:52:44.533429	{0}	180119
edit	2020-01-10 15:53:07.17187	{0}	180120
edit	2020-01-10 15:53:12.445233	{0}	180121
edit	2020-01-10 15:53:17.704783	{0}	180122
edit	2020-01-10 15:53:22.985357	{0}	180123
edit	2020-01-10 15:53:28.272824	{0}	180124
edit	2020-01-10 15:53:33.535181	{0}	180125
edit	2020-01-10 15:53:38.80538	{0}	180126
edit	2020-01-10 15:53:44.107407	{0}	180127
edit	2020-01-10 15:53:49.365995	{0}	180128
edit	2020-01-10 15:53:54.643854	{0}	180129
edit	2020-01-10 15:53:59.901735	{0}	180130
edit	2020-01-10 15:54:05.169946	{0}	180131
edit	2020-01-10 15:54:10.43189	{0}	180132
edit	2020-01-10 15:54:15.722133	{0}	180133
edit	2020-01-10 15:54:21.082643	{0}	180134
edit	2020-01-10 15:54:26.377788	{0}	180135
edit	2020-01-10 15:54:31.642518	{0}	180136
edit	2020-01-10 15:54:36.955902	{0}	180137
edit	2020-01-10 15:54:42.221534	{0}	180138
edit	2020-01-10 15:54:47.497802	{0}	180139
edit	2020-01-10 15:54:52.755105	{0}	180140
edit	2020-01-10 15:54:58.023233	{0}	180141

Page: 1 2 3 4 5 ... last | Whole result: ☐ ~ 1,266,176 rows | Modify: Save | Selected (0): Edit Clone Delete | Export (~ 1,266,176)

CHANGING WHAT'S POSSIBLE

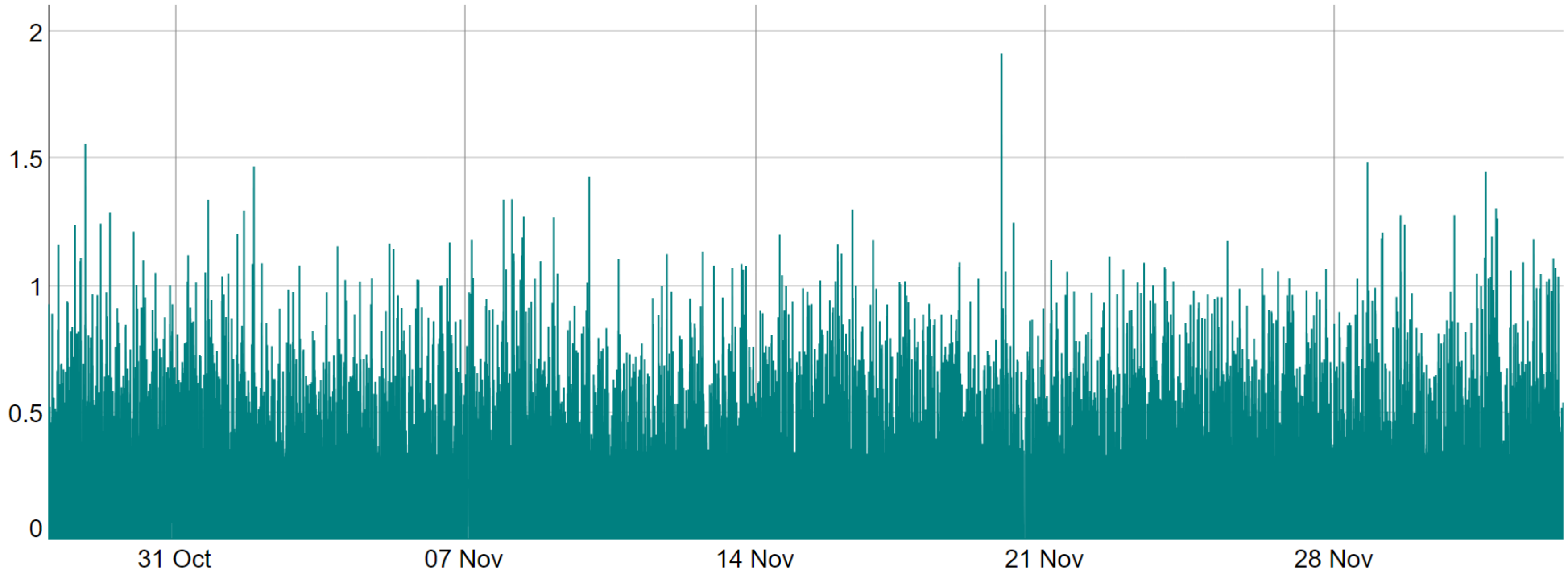
Database can accommodate scalar and vector data

Example: neutron background

show editor | hide editor | clear cache and refresh

Neutrons lab

Neutron counts



time: not selected

Neutrons

log scale | lin scale

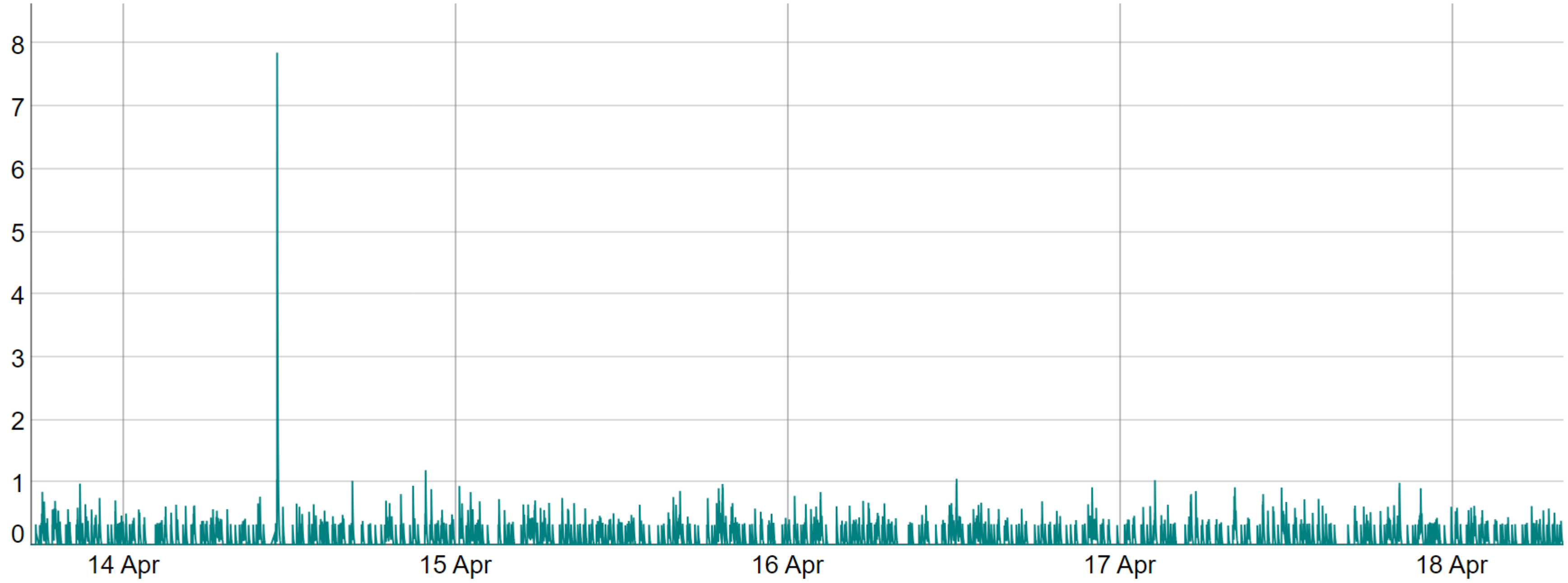
data | query

Example: neutron burst

show editor | hide editor | clear cache and refresh

Neutrons lab

Neutron counts



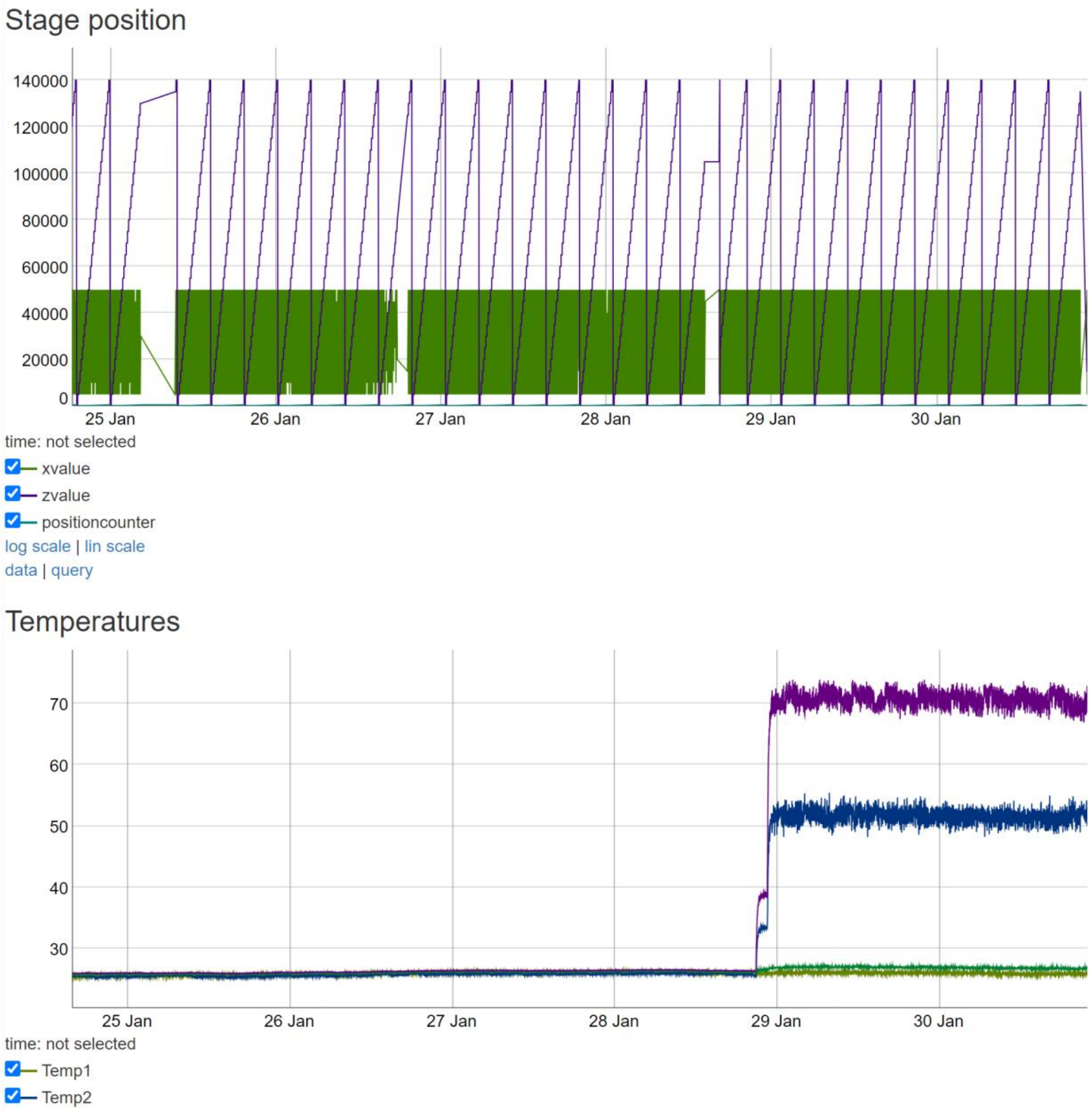
time: not selected

Neutrons

log scale | lin scale

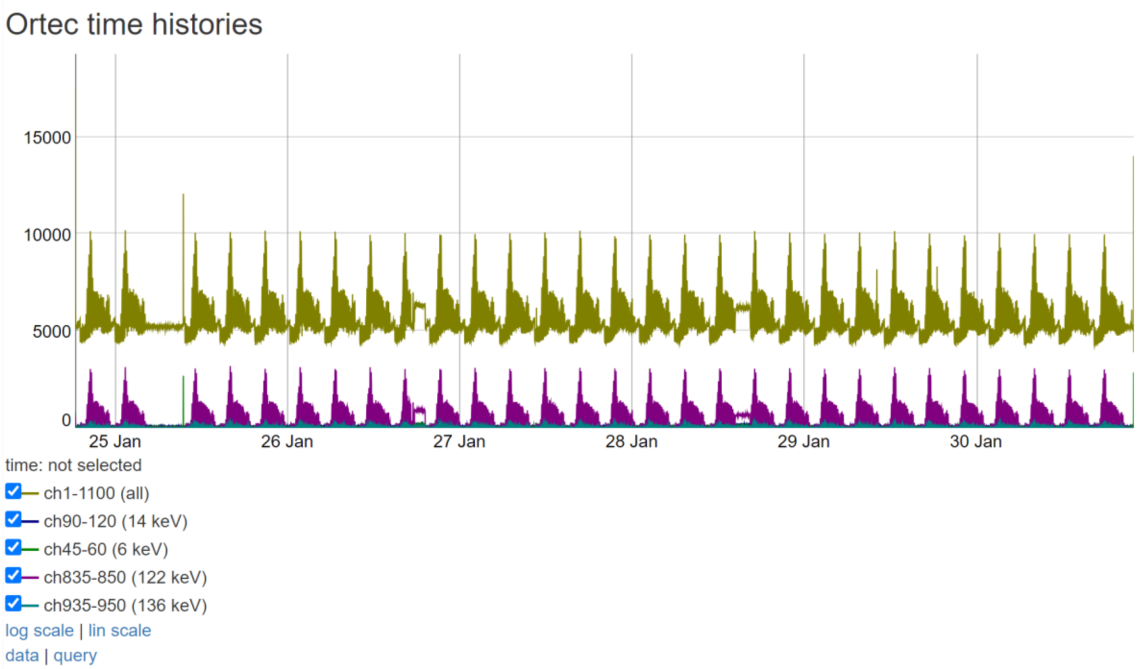
data | query

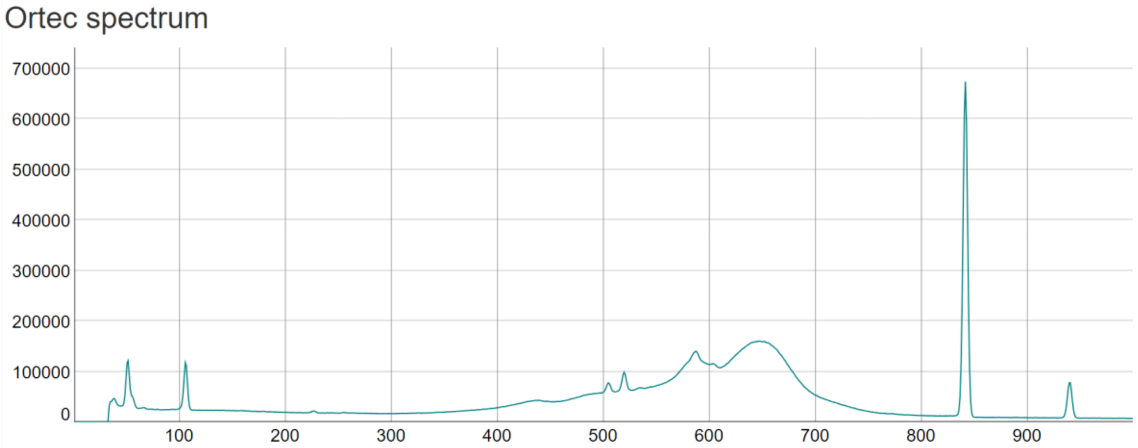
Example: plotting data from different data source



arpa·e
CHANGING WHAT'S POSSIBLE

Example: plotting data from different data source (cont'd)





Obtaining low-cost large-area He-3 neutron detectors

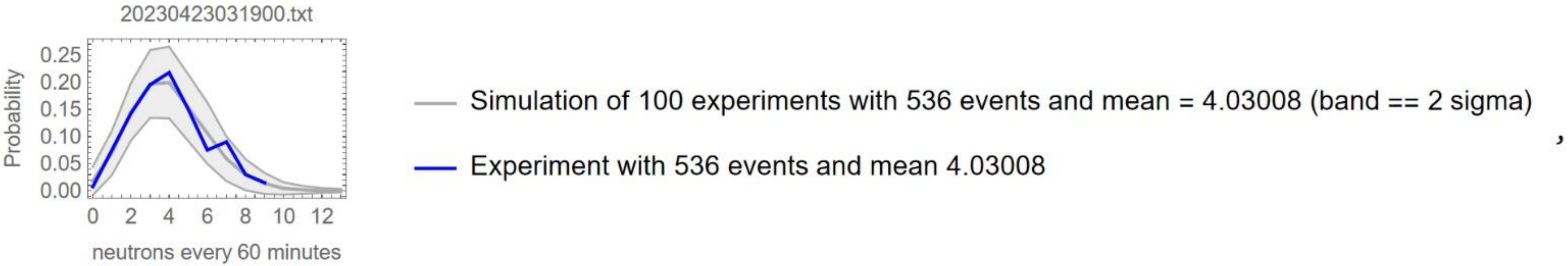
10x ^{3}He Neutron Detector Bank

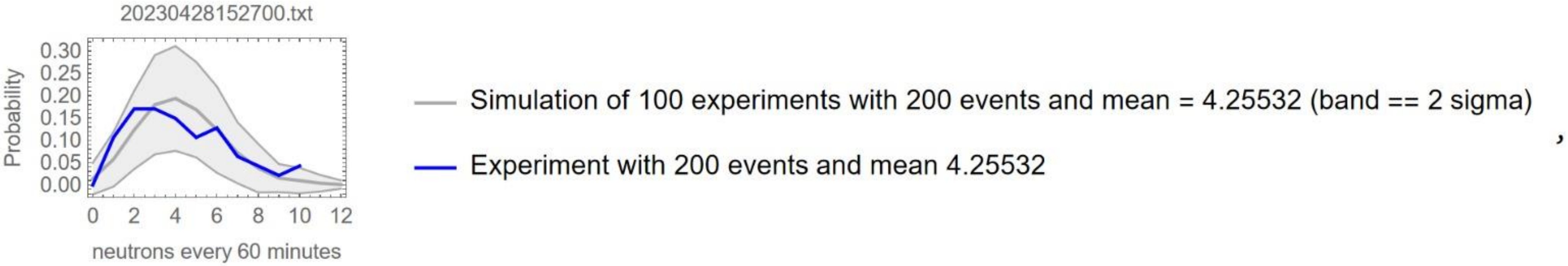
$5,995.00

Shielding to reduce background (neutrons, gammas)

- Working with Igor

Toward a statistical framework for neutron/gamma detection

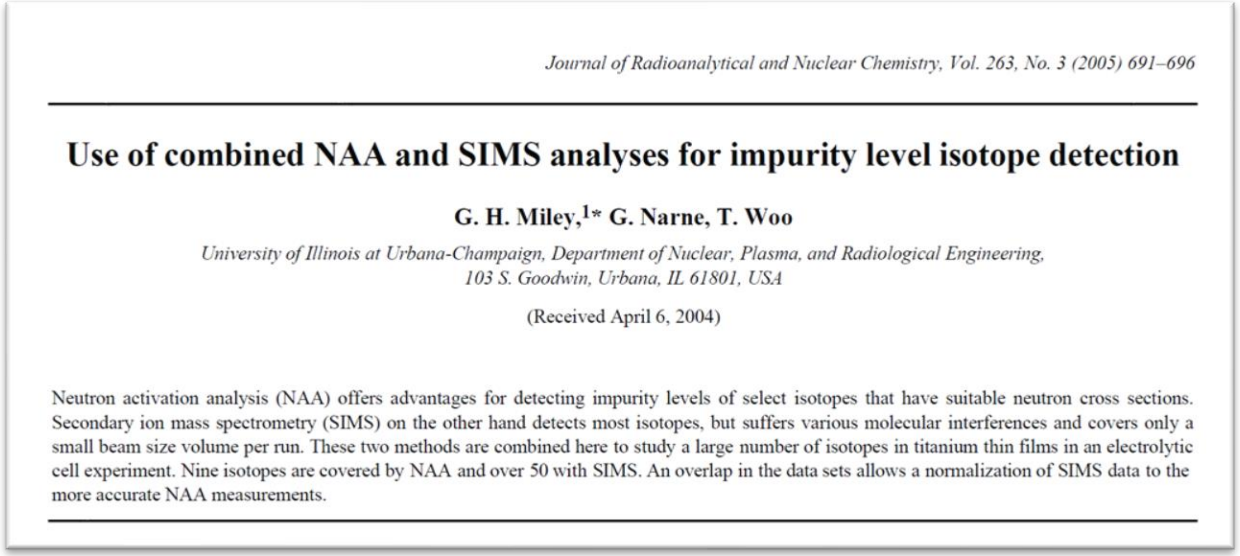




arpa·e
CHANGING WHAT'S POSSIBLE

Toward a statistical framework for isotopic analysis

Building on:


Journal of Radioanalytical and Nuclear Chemistry, Vol. 263, No. 3 (2005) 691–696

Use of combined NAA and SIMS analyses for impurity level isotope detection

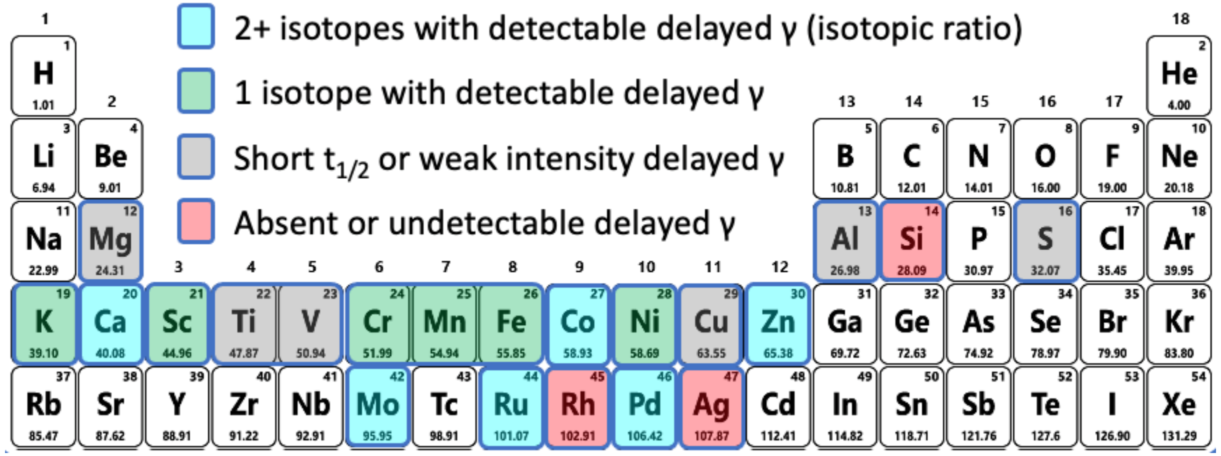
G. H. Miley,[1]* G. Narne, T. Woo

University of Illinois at Urbana-Champaign, Department of Nuclear, Plasma, and Radiological Engineering, 103 S. Goodwin, Urbana, IL 61801, USA

(Received April 6, 2004)

Neutron activation analysis (NAA) offers advantages for detecting impurity levels of select isotopes that have suitable neutron cross sections. Secondary ion mass spectrometry (SIMS) on the other hand detects most isotopes, but suffers various molecular interferences and covers only a small beam size volume per run. These two methods are combined here to study a large number of isotopes in titanium thin films in an electrolytic cell experiment. Nine isotopes are covered by NAA and over 50 with SIMS. An overlap in the data sets allows a normalization of SIMS data to the more accurate NAA measurements.

Promising isotopes:



CHANGING WHAT'S POSSIBLE

Toward a statistical framework for isotopic analysis (cont'd)

OAK RIDGE National Laboratory | 80

Science Areas ∨ Work With Us ∨

Nuclear Analytical Chemistry Section

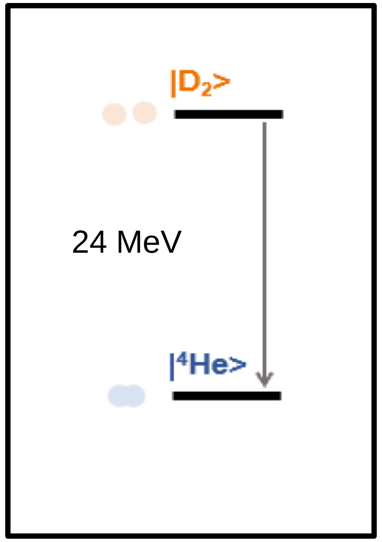
Chemical and Isotopic Mass Spectrometry Group

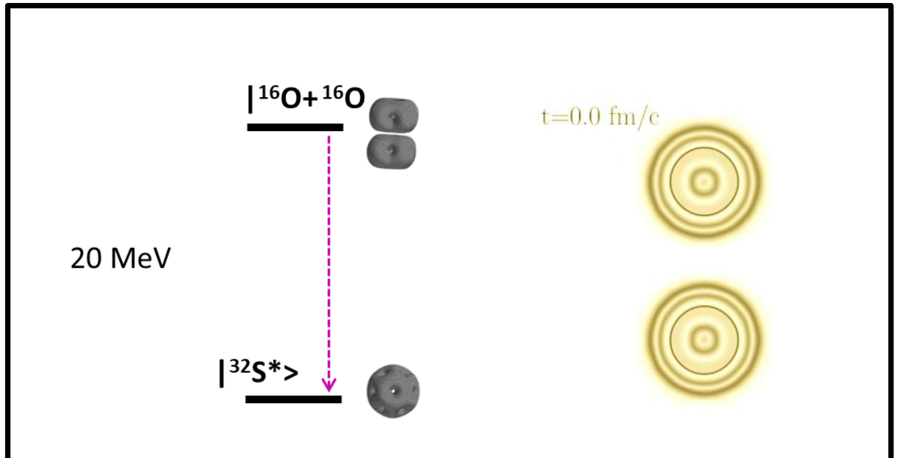
About Facilities Instrumentation Projects Publications Staff

The Chemical and Isotopic Mass Spectrometry (CIMS) Team in ORNL's Nuclear Analytical Chemistry and Isotopics Laboratory Group specializes in ultra-trace analytical measurements. We develop methods and technologies and make measurements in support of national and international nuclear safeguards, security, nonproliferation, verification, and forensics missions. We perform vital measurements in support of the stable and radioisotope production efforts at ORNL. The CIMS team leads the multi-lab DOE/DOS program to provide analytical support to the IAEA's Network of Analytical Laboratories for analysis of samples collected during onsite inspections of nuclear facilities and heads the analytical laboratory in the Mobile Uranium Facility, which helps secure nuclear material worldwide. In recent years members of the CIMS team have been recognized for their important national and international contributions with multiple Secretary of Energy Achievement Awards and the coveted DOE/NNSA Joule.

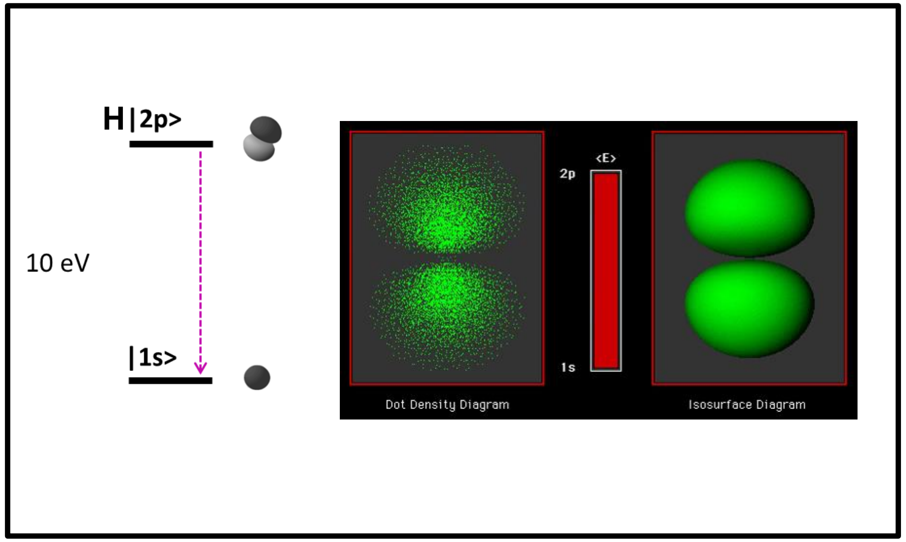
Framing

Fusion reaction viewed as a state transition to a lower energetic state, hindered by the reconfiguration of nucleons.





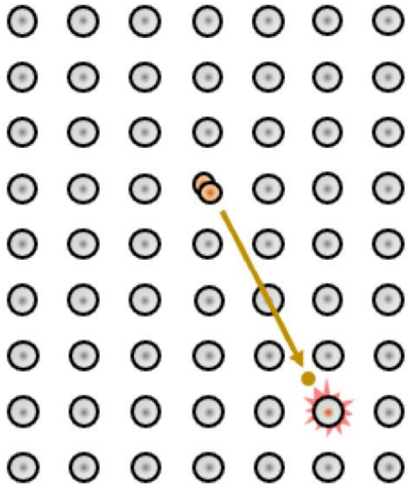
Schuetrumpf & Nazarewicz 2017

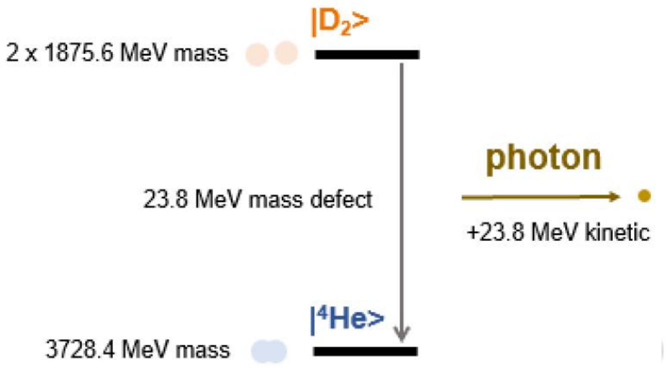


Analogous to how a state transition at the atomic level is hindered by the reconfiguration of electrons.

Fusion-fission hybrid reactions

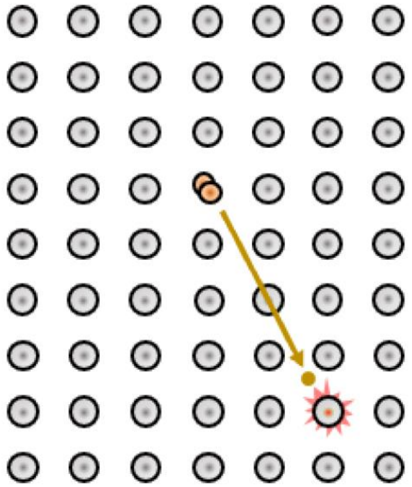
Conventionally expected but hopelessly slow:

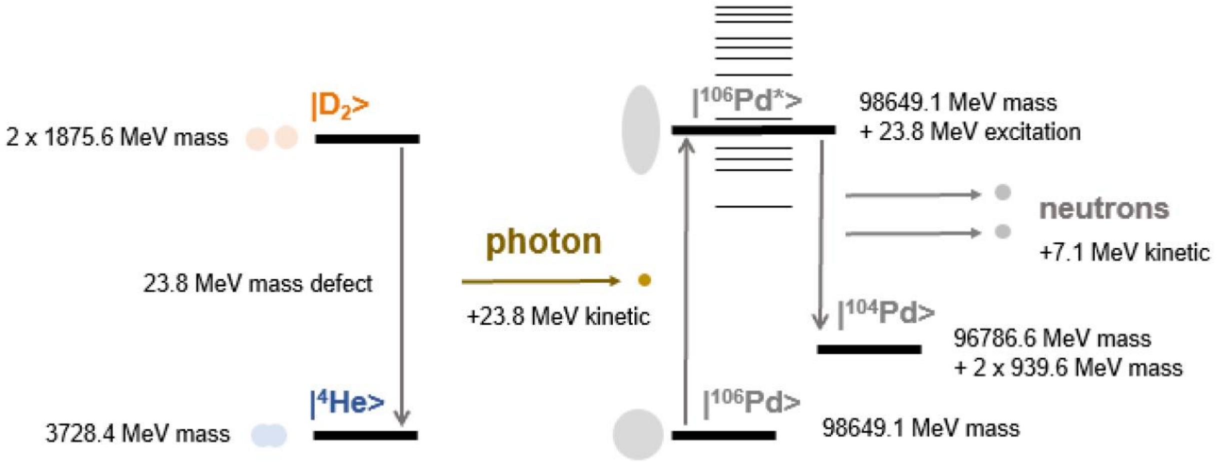




Fusion-fission hybrid reactions

Conventionally expected but hopelessly slow:





arpa·e
CHANGING WHAT'S POSSIBLE

Terhune & Baldwin PRL 1965

NUCLEAR SUPERRADIANCE IN SOLIDS*

J. H. Terhune and G. C. Baldwin

Advanced Technology Laboratories, General Electric Company, Schenectady, New York

(Received 16 February 1965)

A general theory of coherent spontaneous gamma-ray emission from an assemblage of isomeric nuclei in a perfect crystalline solid has been developed. The solid, characterized by internal energy states of the nuclei, by the lattice vibrations, and by the electromagnetic field, is treated as an integrated quantized system rather than as a number of noninteracting nuclei.[1-4] Transition probabilities are calculated by the usual methods of first-order time-dependent perturbation theory.

Coherent spontaneous emission of radiation from a gas has been discussed by Dicke.[5] It was shown that transitions exist for which the radiation rates, line shapes, and linewidths are all different from the corresponding quantities for an assemblage of noninteracting radiators. In particular, certain states were predicted that possess radiation rates much greater than normal because of correlations among the internal motions of the various molecules composing the system.

In a solid composed of N identical two-level nuclei in a perfect crystal lattice at a uniform and low temperature, correlations in the internal motions of the radiators are more probable than in the case of a gas. Furthermore, the interactions among members of the solid system are much stronger than in the gas, because of the coupling between neighbors in the lattice. The usual assumption[1-4] that each nucleus radiates independently of the states of other nuclei in the system is incompatible with the coupling of the nuclei through the common electromagnetic and phonon fields. Calculations of the spontaneous radiation rate for a solid system in which the nuclei are a priori assumed independent preclude the possibility of coherent spontaneous gamma emission by assumption. The present analysis is free from this inconsistency. Finally, the wavelength of the radiation is comparable with the spacing of nuclei in the lattice.

Using the method of Dicke,[5] the nuclear states are described by a vector model in which the vector orientation is quantized in energy space in analogy with fermion spin. The nuclei are assumed identical, in a uniform and field-free environment, with only two nondegenerate internal energy states coupled by a radiative transition. The lattice is assumed harmonic with nearest-neighbor interactions only; the phonon spectrum is approximated by the Debye model. The crystal is considered in the adiabatic approximation, and is assumed to be at rest with respect to the observer.

In the Hamiltonian for this system,

$$H = H_{\text{nuclei}} + H_{\text{lattice}} + H_{\text{radiation}} + H',$$

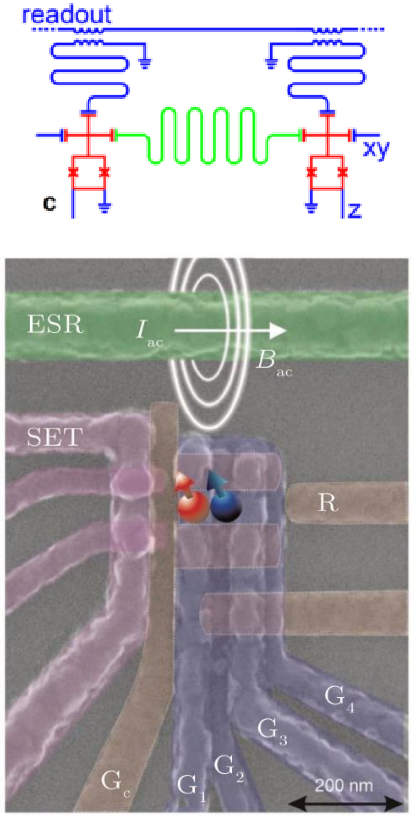
all terms except the interaction term H' are independent of the time. The latter is

$$H' = -\tfrac{1}{2}\sum_k [(\vec{a}_k \cdot \vec{e})R_{k+} + (\vec{a}_k{}^* \cdot \vec{e}^*)R_{k-}],$$

in which $\vec{a}_k{}^*$ and $\vec{a}_k$ are photon creation and destruction operators, respectively, k characterizes a mode of the electromagnetic field, $\vec{e}$ and $\vec{e}^*$ were defined in reference 5, and the nuclear excitation and de-excitation operators

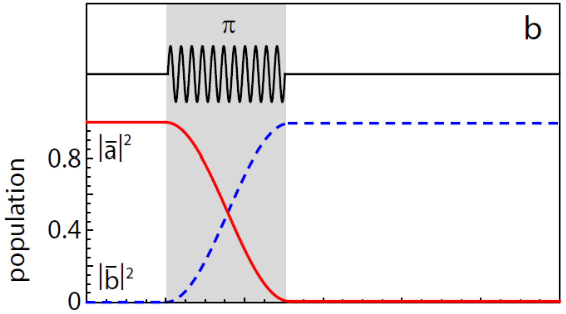
Excitation transfer

Quantum state transfer through activation of couplings



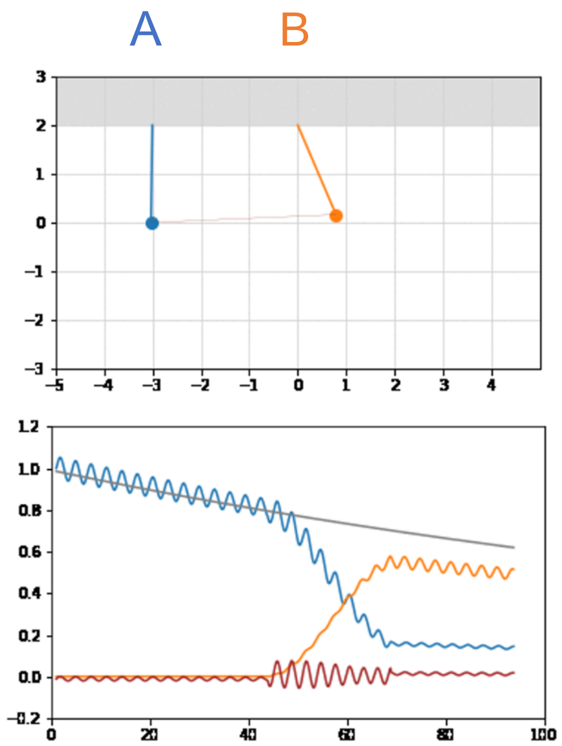
Two qubits implemented in silicon.

Zhang et al. (2018) *Chinese Physics B*



Frimmer & Novotny (2014)
Am. Journal of Physics

kinetic energy (classical) ≙ state occupation probability (quantum)



Classical analog to two coupled quantum systems

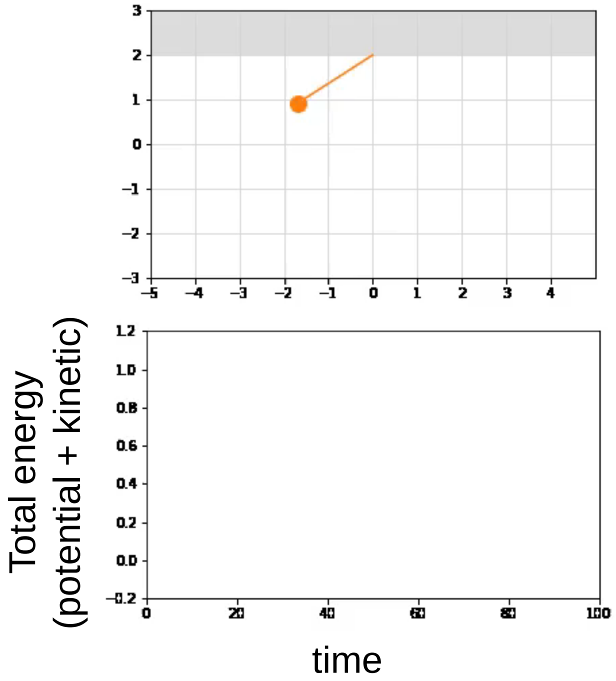
Briggs et al. (2011) *Physical Review E*
Eisfeld et al. (2012) *Physical Review E*

CHANGING WHAT'S POSSIBLE

Mechanical analogs for excitation transfer

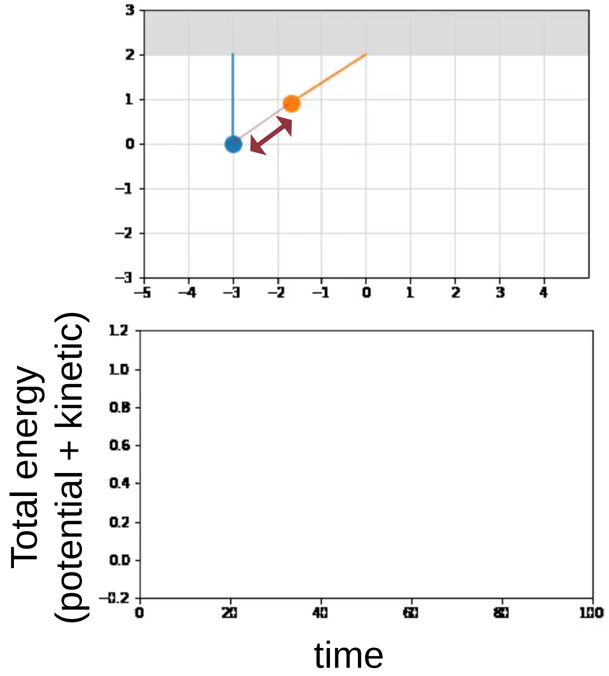
Damped oscillations

Start: Orange **excited**



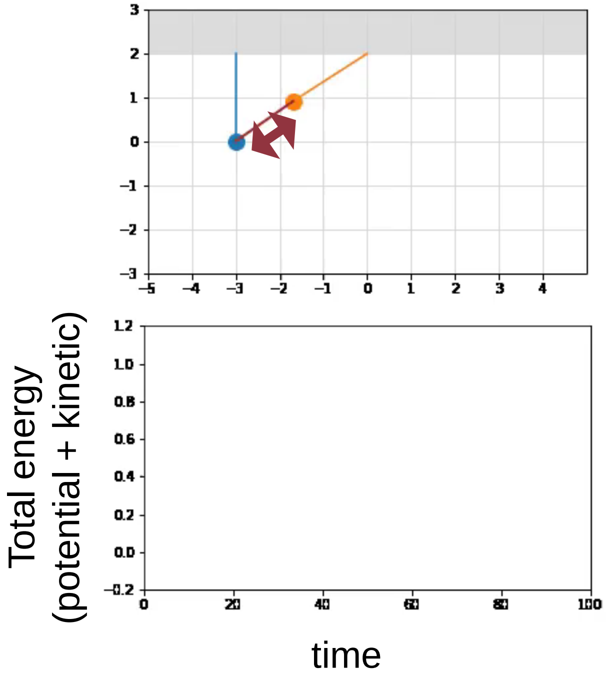
Weak coupling ⟷

Start: Blue **non-excited**



Strong coupling ⟷

Start: Blue **non-excited**



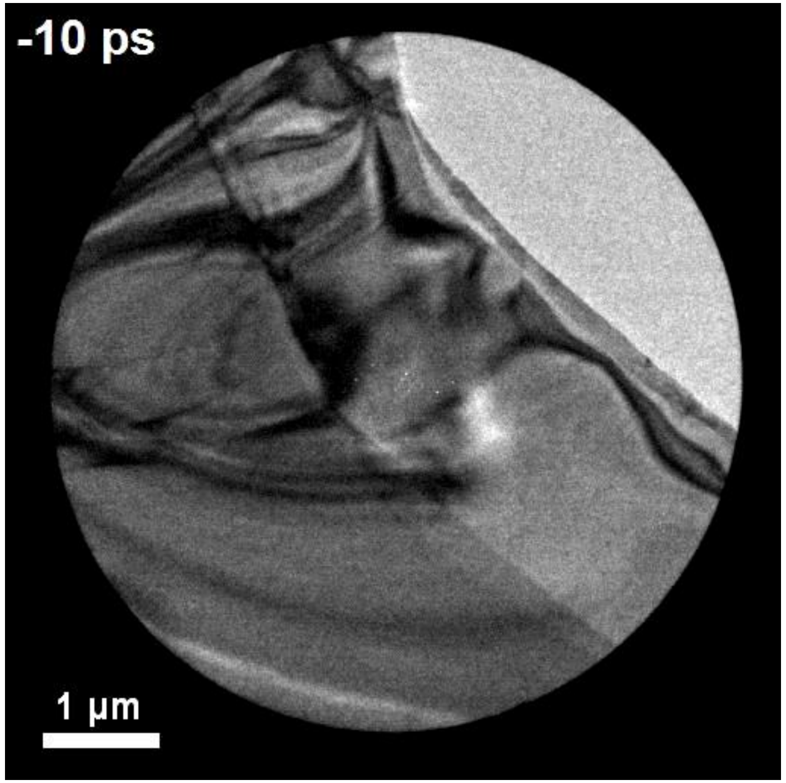
Energy (total)
Energy of orange pendulum
Energy of orange pendulum
Energy in the elastic string

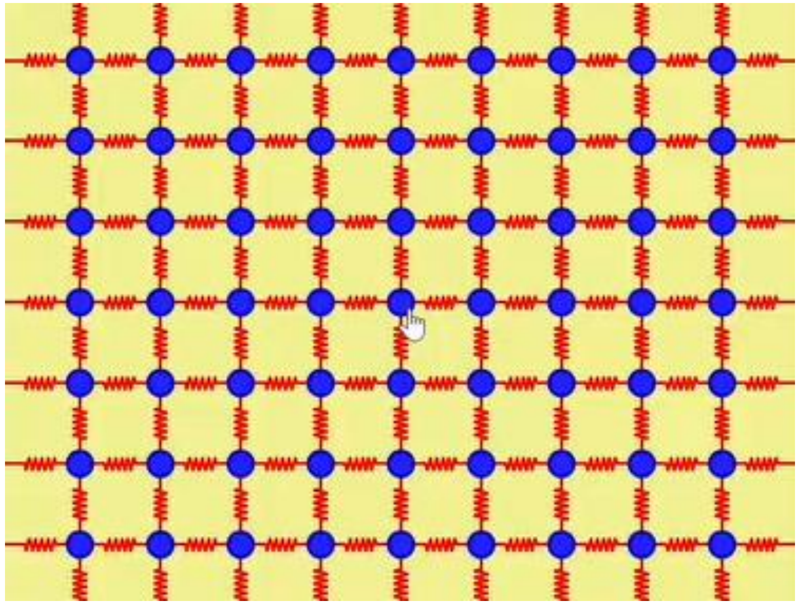
Briggs and Eisfeld, *PRA* (2013)
Zimanyia and Silbey, *J. Chem. Phys.* (2010)

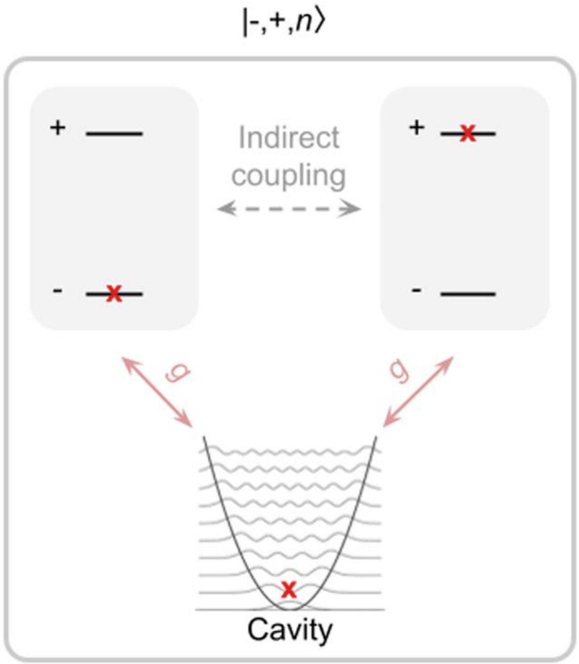
CHANGING WHAT'S POSSIBLE

Phonons/plasmons as source of couplings

Phonons in Ge

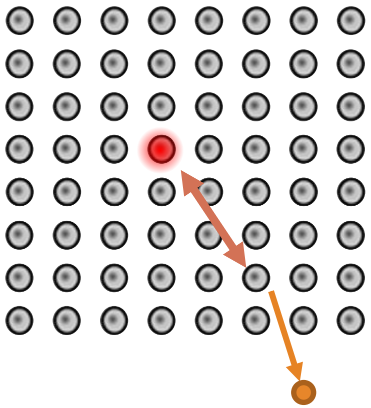






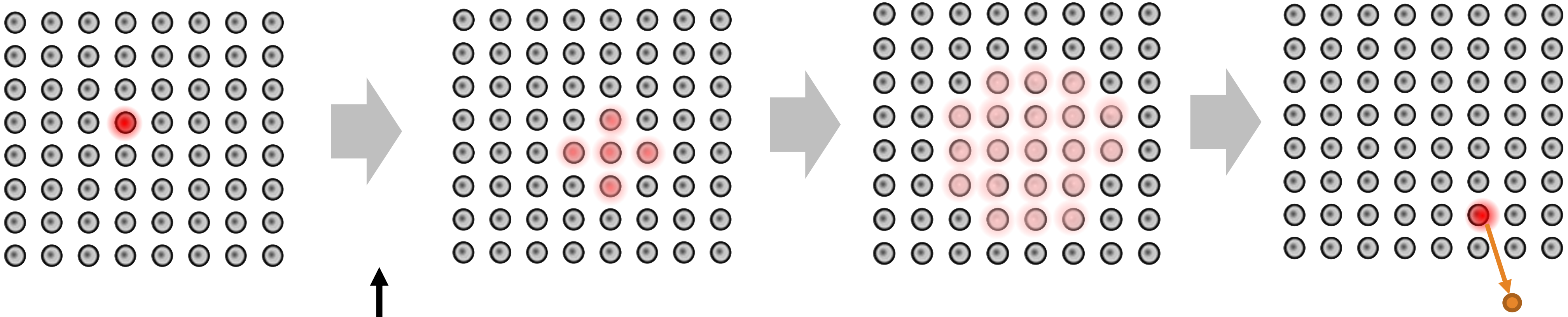
Cremons et al. 2016, *Nat. Commun.*

Delocalized excited states as intermediate steps



(one possible pathway of many)

$$|\Uparrow\rangle=\frac{1}{\sqrt{N}}\left(|\uparrow\downarrow\downarrow\ldots\downarrow\rangle+|\downarrow\uparrow\downarrow\ldots\downarrow\rangle+\ldots+|\downarrow\downarrow\downarrow\ldots\uparrow\rangle\right)$$

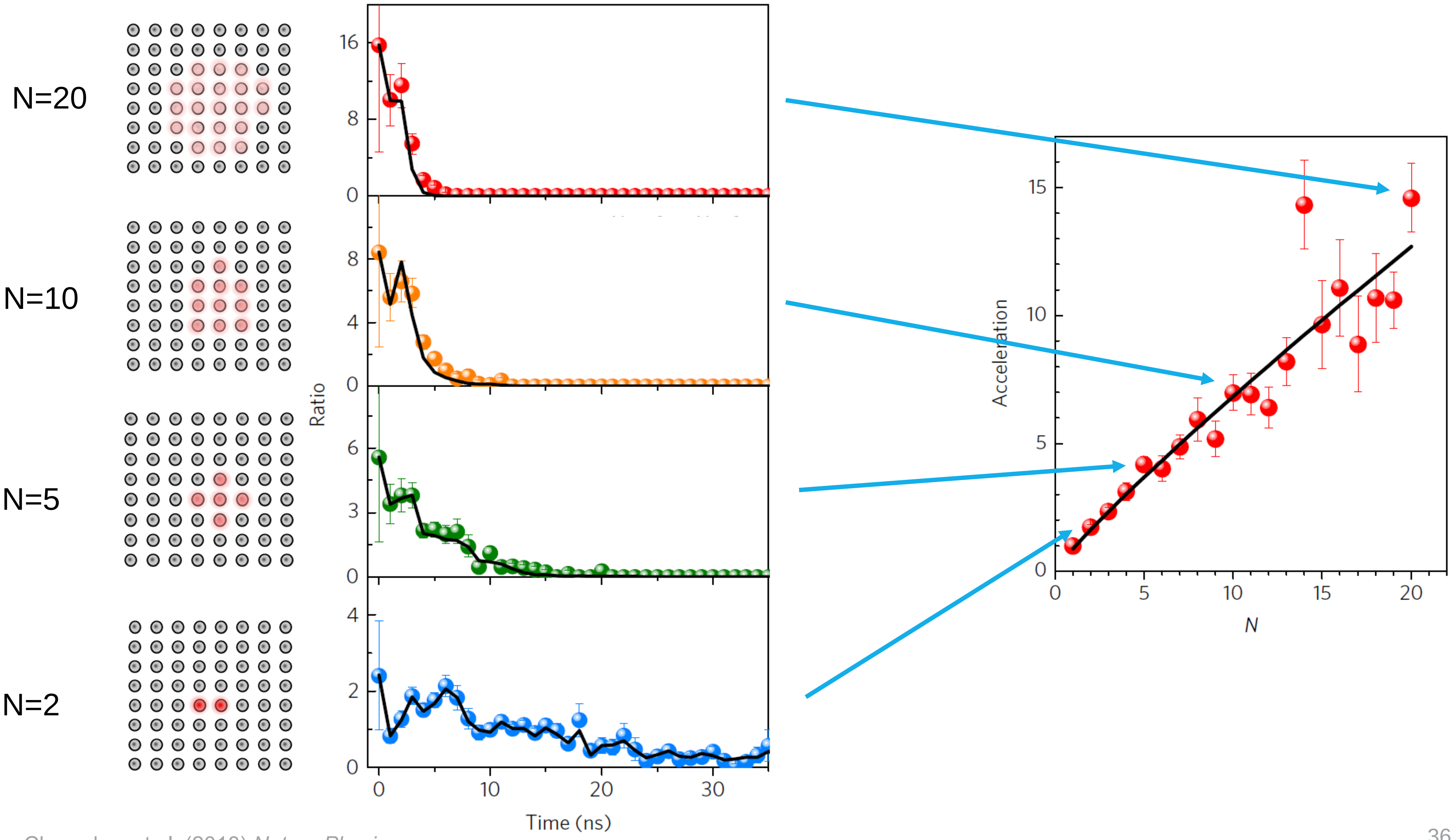


coupling activated

incoherent | coherent | incoherent

Superradiance: coherent acceleration of emission

Couplings associated with delocalized states

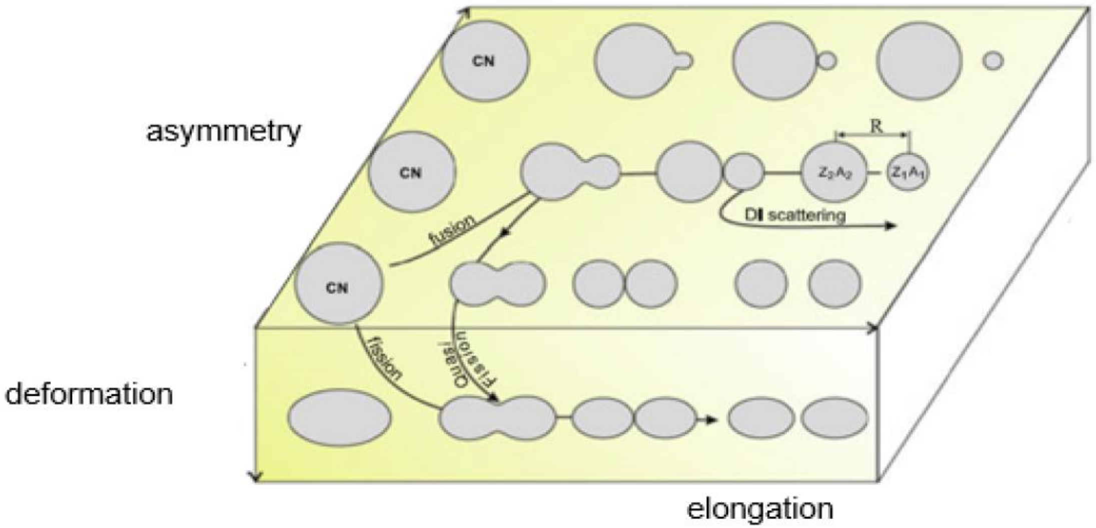


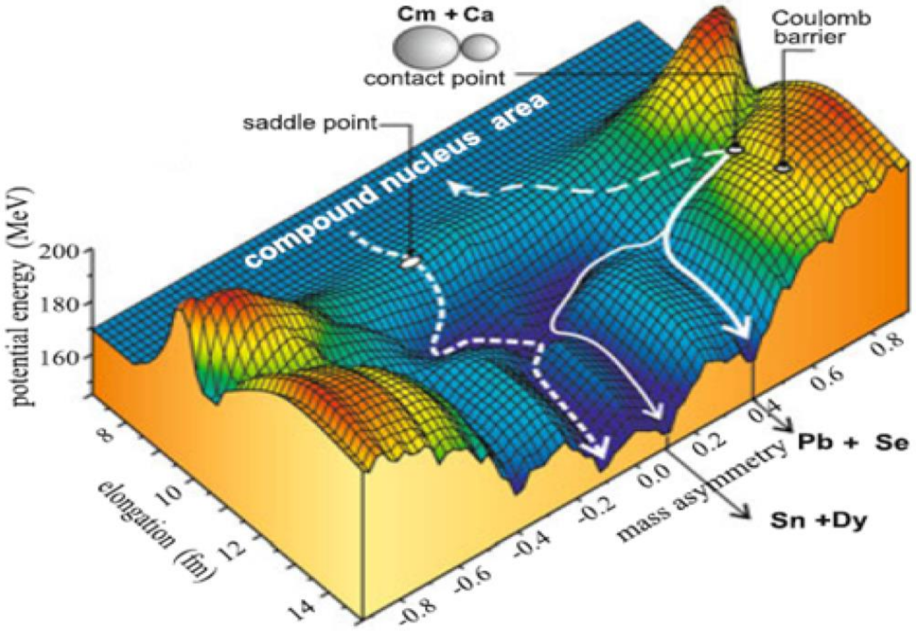
Chumakov et al. (2018) *Nature Physics*

arpa·e
CHANGING WHAT'S POSSIBLE

What determines nuclear energy levels & reaction products

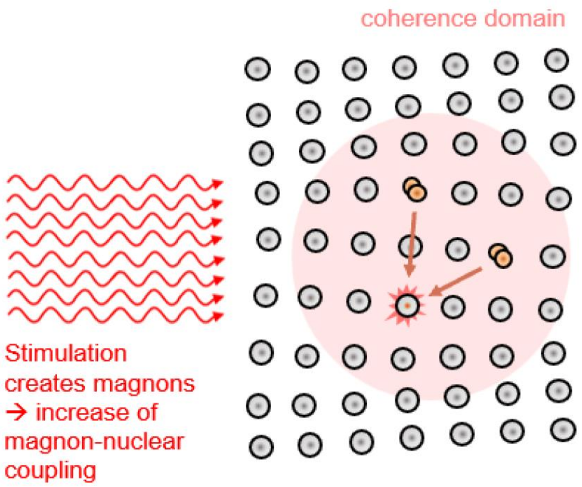
Nuclear molecule literature:

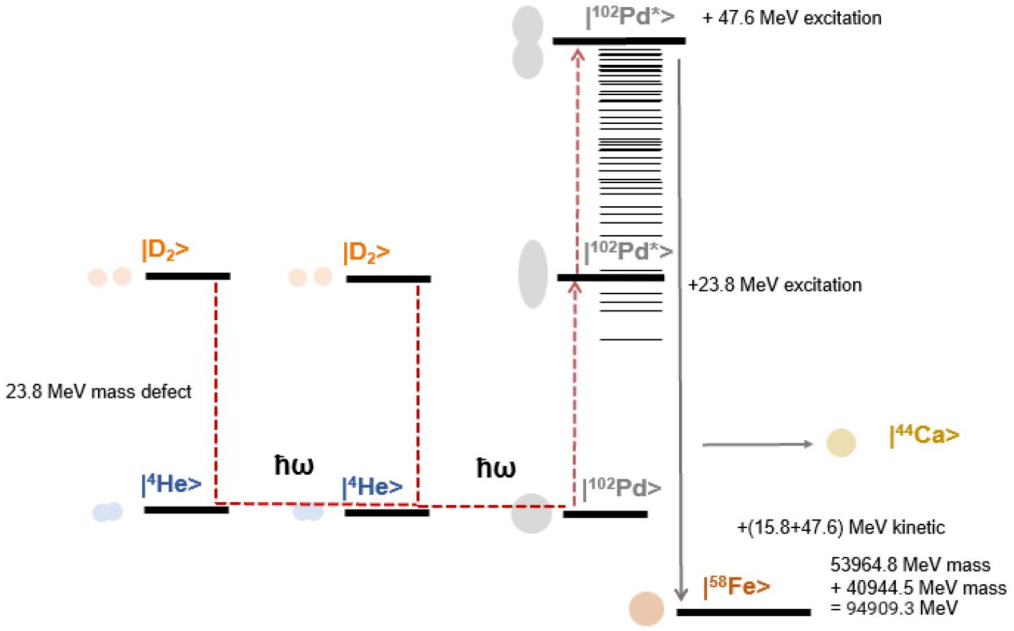


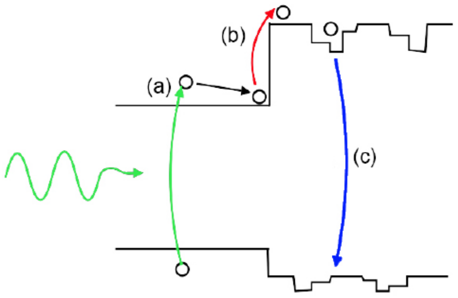


Zagrebaev & Greiner 2010, *Springer*

Low-Z elements from near-symmetric Pd fission





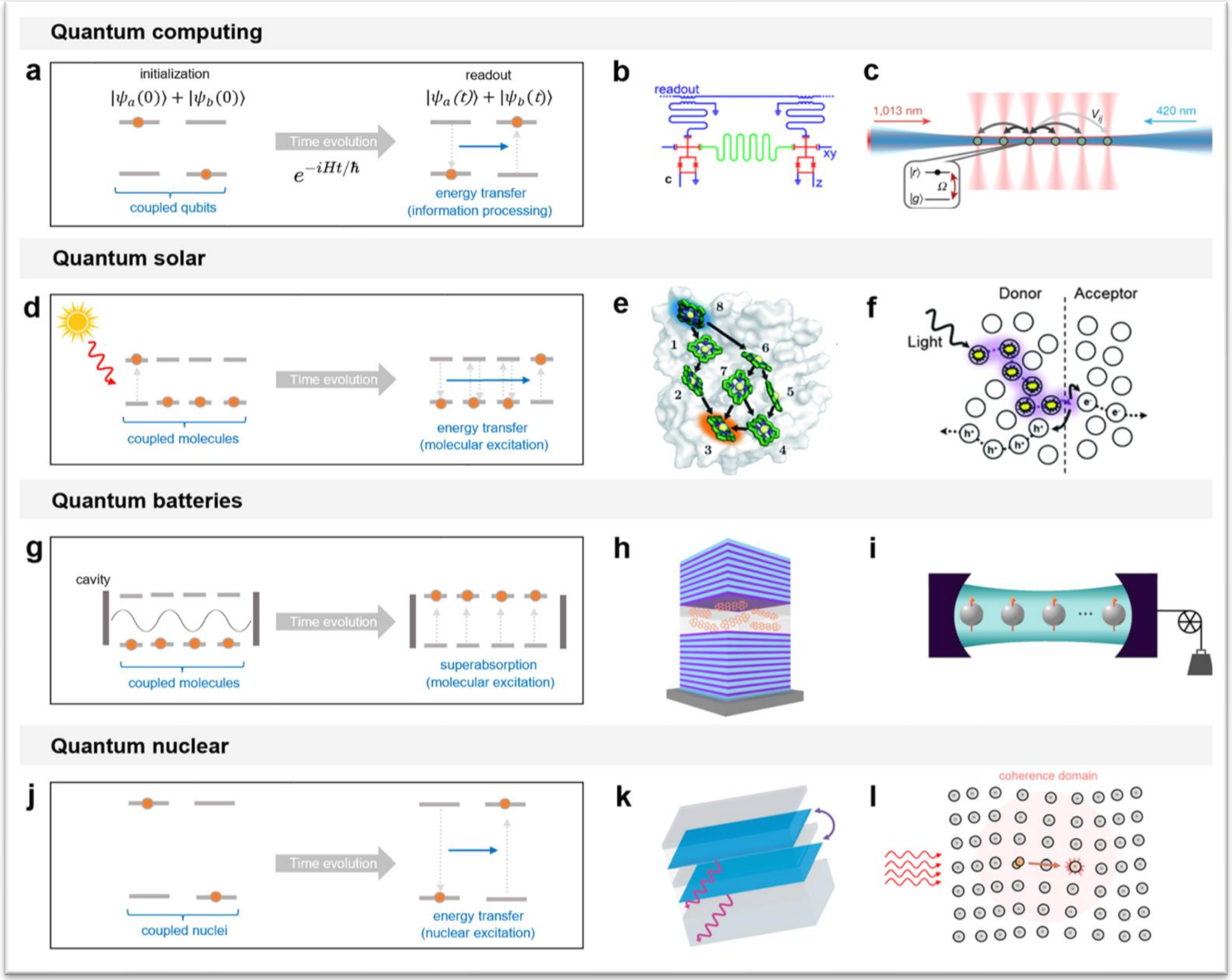


Quantum ratcheting

Vaquero-Stainer (2017), *Imperial College London*
Werren et al. (2023), *PRX Energy*

arpa·e CHANGING WHAT'S POSSIBLE

The Emergence of Quantum Energy Science



Metzler et al. 2022
https://arxiv.org/abs/2303.01632

CHANGING WHAT'S POSSIBLE

First conference on "Quantum Energy"

International Conference on *Quantum Energy*
4-6 December 2023
Pullman on the Park
MELBOURNE ▪ AUSTRALIA

86 days 17 hrs 9 mins 3 secs
left to the conference

Hosted by CSIRO

Home | Registration | Program | Sponsorship Information | Visit | Information

Breaking News | Late Breaking Posters Now Opened: Submit Now

See you at the MCG

ICQE 2023: Where quantum energy meets tomorrow

Australia's national science agency, CSIRO, is proud to present the International Conference
event to explore the role of quantum mechanics in addressing our global energy challenges

ICQE 2023 will bring together will bring together thought leaders from around the world to
of our global energy challenges and transform the energy landscape for the future.

It offers a cross-disciplinary program on the fundamental principles, and applied engineerin
conversion, storage and transport.

Australia's Chief Scientist, and renowned physicist, Dr Cathy Foley AO PSM will deliver the c
by six other esteemed keynote speakers including Prof Gerard Milburn, Dr Alexia Auffèves a
breaking work and latest insights.

ICQE 2023 promises a comprehensive line-up of speakers, an innovative program and first-
planning a packed agenda of science, food, arts, cafes and culture as your introduction to th

Don't miss out on this enlightening quantum event – reserve your spot today.

Dr James Q. Quach | PhD, PGradDip, BEng (Hons), BCS, BCom
Science Leader in Quantum Science and Technologies
Australia's national science agency, CSIRO

Key Dates

Call for abstracts
Closed

Registrations open
Open

Conference dates

SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

Superabsorption in an organic microcavity: Toward a quantum battery

James Q. Quach[1]*, Kirsty E. McGhee[2], Lucia Ganzer[3], Dominic M. Rouse[4], Brendon W. Lovett[4], Erik M. Gauger[5], Jonathan Keeling[4], Giulio Cerullo[3], David G. Lidzey[2], Tersilla Virgili[3]*

The rate at which matter emits or absorbs light can be modified by its environment, as markedly exemplified by the widely studied phenomenon of superradiance. The reverse process, superabsorption, is harder to demonstrate because of the challenges of probing ultrafast processes and has only been seen for small numbers of atoms. Its central idea—superextensive scaling of absorption, meaning larger systems absorb faster—is also the key idea underpinning quantum batteries. Here, we implement experimentally a paradigmatic model of a quantum battery, constructed of a microcavity enclosing a molecular dye. Ultrafast optical spectroscopy allows us to observe charging dynamics at femtosecond resolution to demonstrate superextensive charging rates and storage capacity, in agreement with our theoretical modeling. We find that decoherence plays an important role in stabilizing energy storage. Our work opens future opportunities for harnessing collective effects in light-matter coupling for nanoscale energy capture, storage, and transport technologies.

arpa·e
CHANGING WHAT'S POSSIBLE

Accelerating chemical reactions via quantum effects

“Scientists are intensely interested in what are known as ‘quantum-enhanced’ chemical reactions”

Phys.org 2023

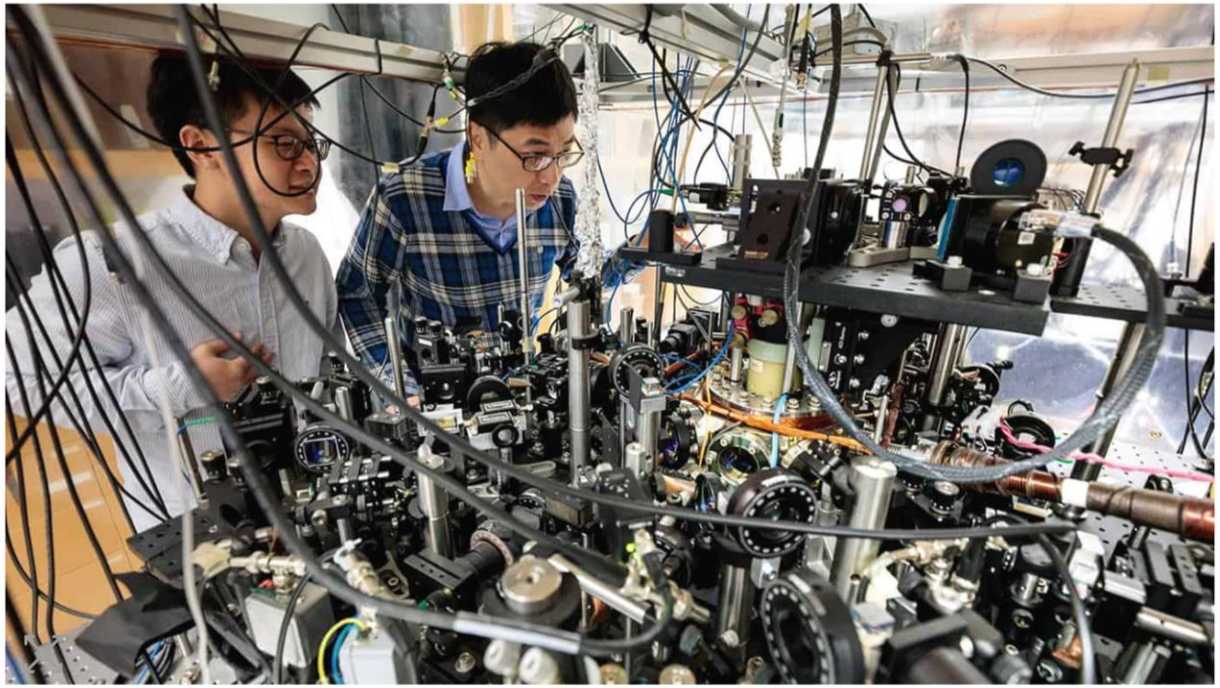
“molecules sharing a quantum state might produce accelerated chemical reactions if those molecules were 'coupled' together and reacting as one”

sciencealert 2023

CHEMICAL PROCESSES | RESEARCH UPDATE

Quantum superchemistry emerges in the laboratory

23 Aug 2023



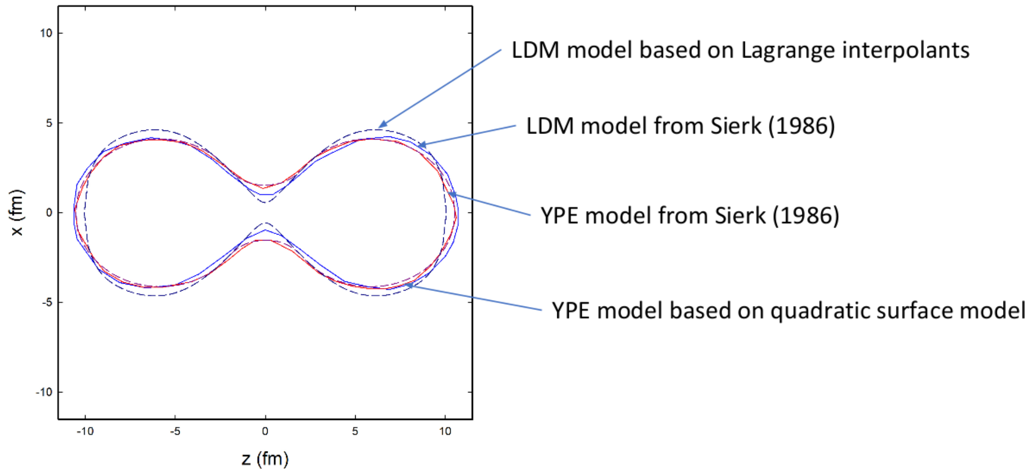
Atoms and molecules: Cheng Chin (r) and postdoctoral researcher Zhendong Zhang in the University of Chicago laboratory where they and colleagues observed the first evidence of quantum superchemistry. (Courtesy: John Zich/University of Chicago)

arpa·e
CHANGING WHAT'S POSSIBLE

Liquid drop models for determining nuclear excited states

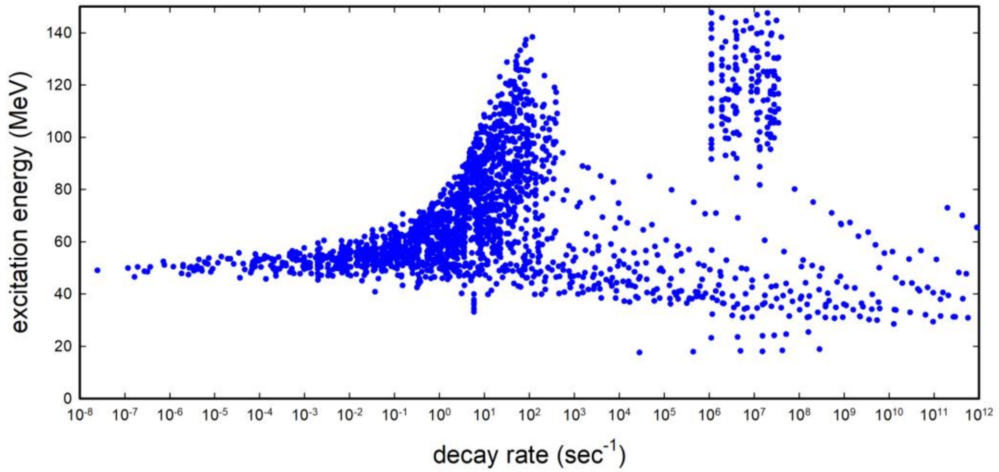
Pd-106 nuclear molecule (Vd-53 + Vd-53)

- Bohr-Wheeler model predicts a (not very stable) symmetric nuclear molecule for Pd-106 near 40.7 MeV



Nuclear molecule energy vs decay rate

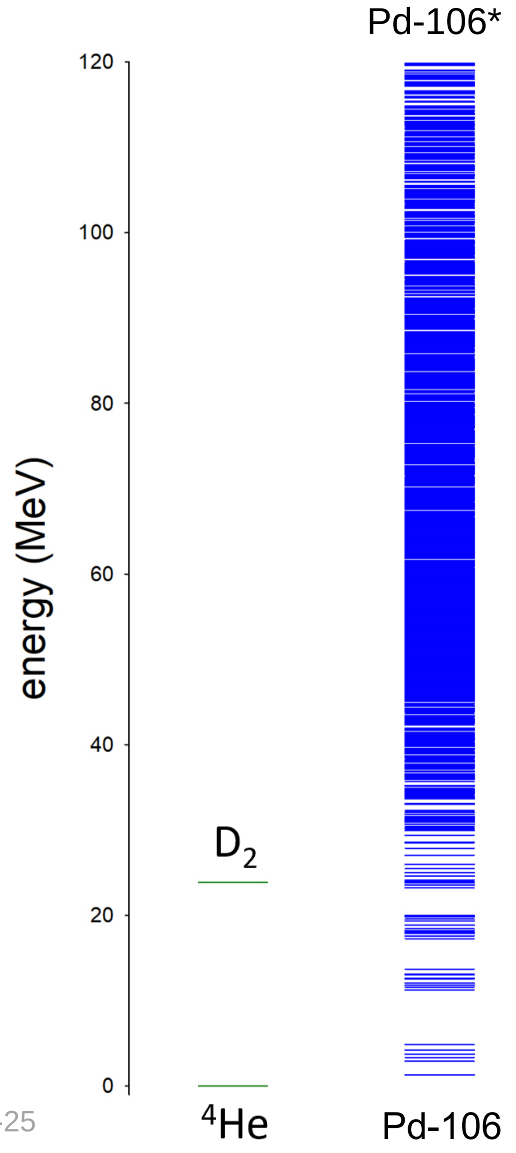
including tunneling and daughter decays



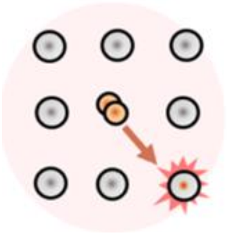
For all the stable Pd isotopes

Hagelstein 2023, ICCF-25

Long-lived excited states in Pd available for excitation transfer



Intermediate variables



Hamiltonian: $$H = \overbrace{\sum_j M_j c^2}^{nuclei} + \overbrace{\hbar\omega a^\dagger a}^{osc} + \overbrace{\sum_j (-\mu_j \cdot B)_+ + (-\mu_j \cdot B)_-}^{magn.\,interaction}$$

10^{12} D_2 molecules in PdD vacancies (U_e = 150 eV, fluctuations +/- 5pm) coupled to 10^6 Pd nuclei via magnon-nuclear coupling (coupling strength V = 100 neV)

QuTIP Python modeling of excitation transfer

jupyter nbviewer

JUPYTER FAQ

```
In [37]: bra_labels, ket_labels = make_braket_labels(nmm_list)
```

Now let's plot the results using a helper function `plot_prob` that pulls together plotting code that we used in the last tutorial.

```
In [38]: plot_prob(P, times, ket_labels)
         plt.title(f"2 TSS with {H_latex}  ($\Delta E \\approx 1.9328$, $\omega=1$, $U=0.1$)   (Fig 8)");
```

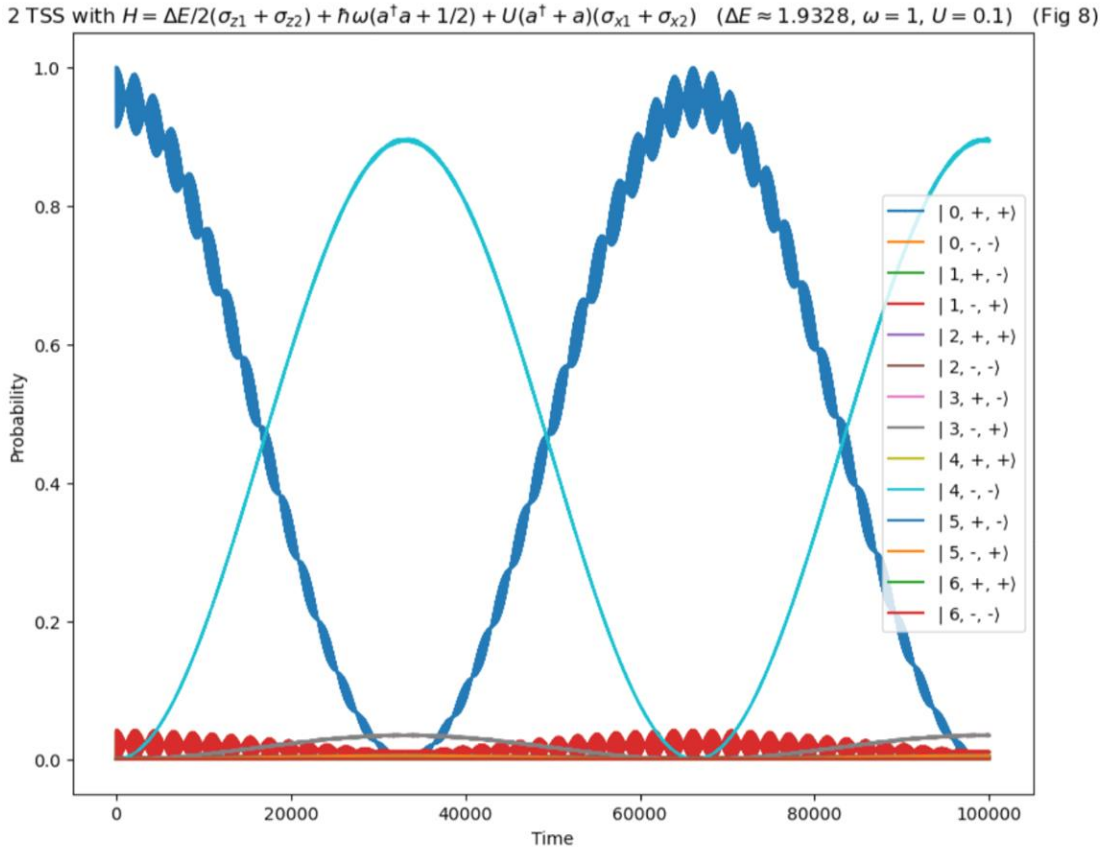
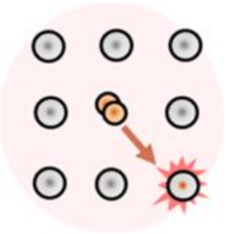


Fig 8 shows exactly what we expected, namely down conversion - both TSS transition from "+" to "-" each giving of 2 bosons in the process i.e. $|0,+,+\rangle \rightarrow |4,-,-\rangle$.

https://github.com/project-ida/two-state-quantum-systems/

arpa·e CHANGING WHAT'S POSSIBLE

Intermediate variables



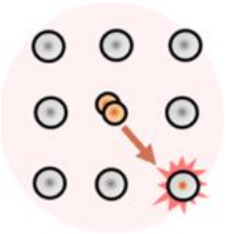
Hamiltonian: $$H = \overbrace{\sum_j M_j c^2}^{nuclei} + \overbrace{\hbar\omega a^\dagger a}^{osc} + \overbrace{\sum_j (-\mu_j \cdot B)_+ + (-\mu_j \cdot B)_-}^{magn.interaction}$$

10^{12} D_2 molecules in PdD vacancies (U_e = 150 eV, fluctuations +/- 5pm) coupled to 10^6 Pd nuclei via magnon-nuclear coupling (coupling strength V = 100 neV)

Dependent variable:

Transfer rate = fusion rate: $$\Gamma = \sqrt{N_{D_2}}\sqrt{N_{Pd\text{-}106}}\frac{[\frac{V}{\Delta E}\sqrt{\frac{vol_{nuc}}{vol_{mol}}}e^{-G}]\frac{V}{\Delta E}\Phi_{Pd\text{-}106}}{\hbar} = \frac{10^{-7}eV\,10^{-17}10^{-6}10^{-7}eV}{24 \times 10^6 eV}\,1\,\underbrace{\sqrt{10^{12}}\,\sqrt{10^6}}_{\text{Dicke enhancement}}\frac{1}{\hbar} = 10^{-18}s^{-1}$$

Intermediate variables



Hamiltonian:

$$H = \overbrace{\sum_j M_j c^2}^{nuclei} + \overbrace{\hbar\omega a^\dagger a}^{osc} + \overbrace{\sum_j (-\mu_j \cdot B)_+ + (-\mu_j \cdot B)_-}^{magn.interaction}$$

10^{12} D_2 molecules in PdD vacancies (U_e = 150 eV, fluctuations +/- 5pm) coupled to 10^6 Pd nuclei via magnon-nuclear coupling (coupling strength V = 100 neV)

Dependent variable:

Transfer rate = fusion rate:

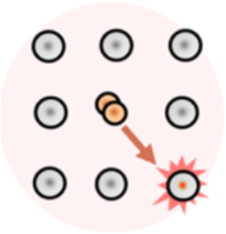
$$\Gamma = \sqrt{N_{D_2}}\sqrt{N_{Pd\text{-}106}}\frac{[\frac{V}{\Delta E}\sqrt{\frac{vol_{nuc}}{vol_{mol}}}e^{-G}]\frac{V}{\Delta E}\Phi_{Pd\text{-}106}}{\hbar} = \frac{10^{-7}eV\,10^{-17}10^{-6}10^{-7}eV}{24\times 10^6 eV}\,1\,\sqrt{10^{12}}\,\sqrt{10^6}\frac{1}{\hbar} = 10^{-18}s^{-1}$$

Dicke enhancement

Intermediate variables:

- # of nuclei coupled to oscillator
- Energy in oscillator mode
  - Excited plasmon & phonon modes
  - D diffusion rate
- DD proximity & screening potential
  - Lattice structure (vacancy content)
- Closeness of resonance between D_2 (23.8 MeV) and lattice nuclei

Intermediate variables



Hamiltonian:

$$H = \overbrace{\sum_j M_j c^2}^{nuclei} + \overbrace{\hbar\omega a^\dagger a}^{osc} + \overbrace{\sum_j (-\mu_j \cdot B)_+ + (-\mu_j \cdot B)_-}^{magn.\,interaction}$$

10^{12} D_2 molecules in PdD vacancies (U_e = 150 eV, fluctuations +/- 5pm) coupled to 10^6 Pd nuclei via magnon-nuclear coupling (coupling strength V = 100 neV)

Dependent variable: Transfer rate = fusion rate:

$$\Gamma = \sqrt{N_{D_2}}\sqrt{N_{Pd\text{-}106}}\frac{[\frac{V}{\Delta E}\sqrt{\frac{vol_{nuc}}{vol_{mol}}}e^{-G}]\frac{V}{\Delta E}\Phi_{Pd\text{-}106}}{\hbar} = \frac{10^{-7}eV\,10^{-17}10^{-6}10^{-7}eV}{24\times10^6 eV}\,1\,\underbrace{\sqrt{10^{12}}\,\sqrt{10^6}}_{\text{Dicke enhancement}}\frac{1}{\hbar} = 10^{-18}s^{-1}$$

Intermediate variables:

- # of nuclei coupled to oscillator
- Energy in oscillator mode
- DD proximity & screening potential
- Closeness of resonance between D_2 (23.8 MeV) and lattice nuclei
- Excited plasmon & phonon modes
- D diffusion rate
- Lattice structure (vacancy content)

Independent variables:

- Laser focal point size
- Laser intensity, wavelength, pulse length & freq.
- Temperature & pressure
- Microstructure of untreated sample
- Isotopic composition of untreated sample

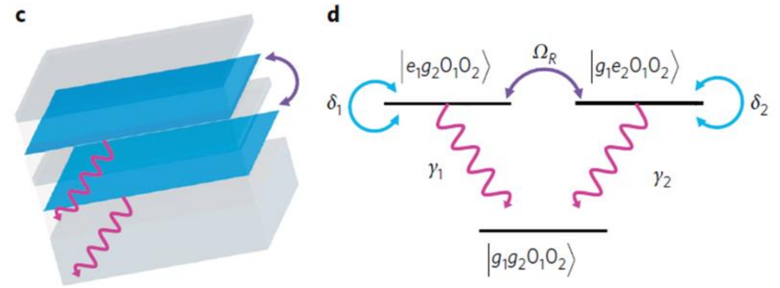
All the building blocks are there and accepted

ARTICLES
https://doi.org/10.1038/s41566-017-0013-3
nature photonics

Rabi oscillations of X-ray radiation between two nuclear ensembles

Johann Haber[1], Xiangjin Kong[2,3], Cornelius Strohm[1], Svenja Willing[1], Jakob Gollwitzer[1], Lars Bocklage[1], Rudolf Rüffer[4], Adriana Pálffy[2]* and Ralf Röhlsberger[1]*

The realization of the strong coupling regime between a single cavity mode and an electromagnetic resonance is a centrepiece of quantum optics. In this regime, the reversible exchange of a photon between the two components of the system leads to so-called Rabi oscillations. Strong coupling is used in the optical and infrared regimes, for instance, to produce non-classical states
Rabi oscillations of
bed by an effective
e Rabi oscillations
ctrum. Our results



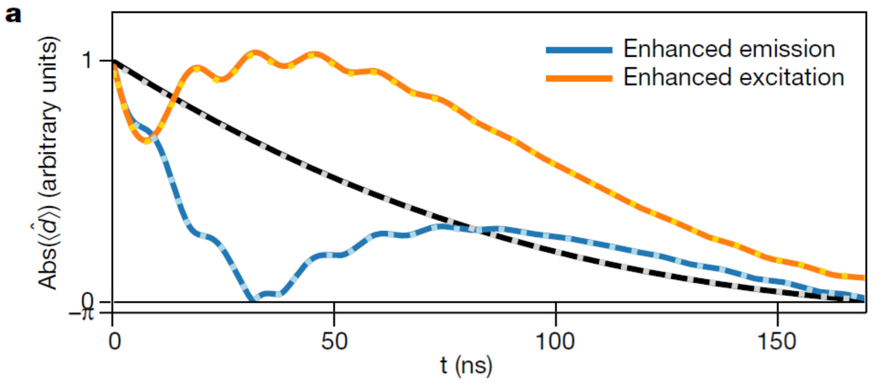
Article

Coherent X-ray–optical control of nuclear excitons

https://doi.org/10.1038/s41586-021-03276-x
Received: 22 October 2018
Accepted: 2 December 2020
Published online: 17 February 2021
Open access
Check for updates

Kilian P. Heeg[1], Andreas Kaldun[1], Cornelius Strohm[2], Christian Ott[1], Rajagopalan Subramanian[1], Dominik Lentrodt[1], Johann Haber[2], Hans-Christian Wille[2], Stephan Goerttler[1], Rudolf Rüffer[3], Christoph H. Keitel[1], Ralf Röhlsberger[2,4,5,6,7], Thomas Pfeifer[1] & Jörg Evers[1]✉

Coherent control of quantum dynamics is key to a multitude of fundamental studies and applications[1]. In the visible or longer-wavelength domains, near-resonant light fields have become the primary tool with which to control electron dynamics[2]. Recently, coherent control in the extreme-ultraviolet range was demonstrated[3], with a few-attosecond temporal resolution of the phase control. At hard-X-ray energies (above 5–10 kiloelectronvolts), Mössbauer nuclei feature narrow nuclear resonances due to their recoilless absorption and emission of light, and spectroscopy of these resonances is widely used to study the magnetic, structural and dynamical properties of matter[4,5]. It



All the building blocks are there and accepted

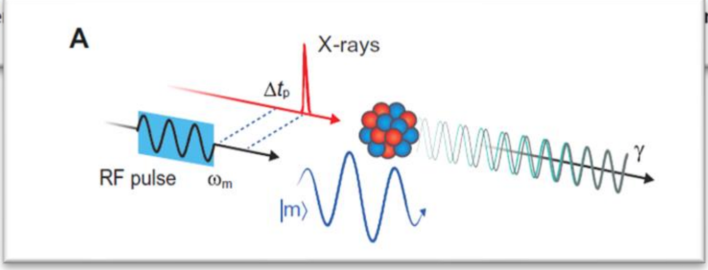
SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

Coherent control of collective nuclear quantum states via transient magnons

Lars Bocklage[1,2]*, Jakob Gollwitzer[1], Cornelius Strohm[1], Christian F. Adolff[1,2], Kai Schlage[1], Ilya Sergeev[1], Olaf Leupold[1], Hans-Christian Wille[1], Guido Meier[3,2], Ralf Röhlsberger[1,2,4,5,6]

Ultrafast and precise control of quantum systems at x-ray energies involves photons with oscillation periods below 1 as. Coherent dynamic control of quantum systems at these energies is one of the major challenges in hard x-ray quantum optics. Here, we demonstrate that the phase of a quantum system embedded in a solid can be coherently controlled via a quasi-particle with subattosecond accuracy. In particular, we tune the quantum phase of a collectively excited nuclear state via transient magnons with a precision of 1 zs and a timing stability below 50 ys. These small temporal shifts are monitored interferometrically via quantum beats between different hyperfine-split levels. The experiment demonstrates zeptosecond interferometry and shows that transient quasi-particles e… …nvironments.

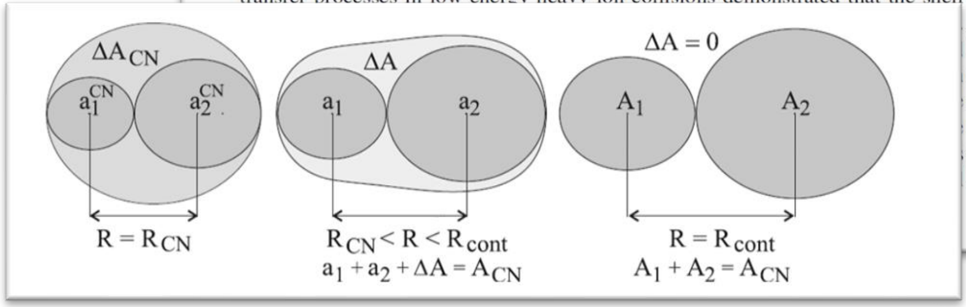


Chapter 7
Giant Nuclear Systems of Molecular Type

Valery Zagrebaev and Walter Greiner

7.1 Introduction

Cluster structure is very often set off against the shell structure of light and medium nuclei. However the appearance of clusters themselves (compact pieces of nuclear matter) is conditioned just by the shell effects. In light nuclei these clusters are mainly alpha-particles. In heavy nuclear systems tightly packed nuclei (such as ^{132}Sn or ^{208}Pb) may lead to energetically favorable two (and even three) center configurations. These cluster configurations play an important role both in the structure of heavy nuclear systems and in the low-energy nuclear dynamics. The asymmetric nuclear fission (see, for example, Ref. [1]), the heavy-ion radioactivity [2, 3], the shape isomeric states of heavy nuclei [4] and the true ternary fission of superheavy nuclei (see below) are the manifestations of such kind of clusterization. Our studies of fusion–fission reactions and multi-nucleon transfer processes in low-energy heavy ion collisions demonstrated that the shell



arpa·e
CHANGING WHAT'S POSSIBLE

All the building blocks are there and accepted

nature physics
LETTERS
https://doi.org/10.1038/s41567-017-0001-z

Superradiance of an ensemble of nuclei excited by a free electron laser

Aleksandr I. Chumakov[1,2]*, Alfred Q. R. Baron[3]*, Ilya Sergueev[4], Cornelius Strohm[4], Olaf Leupold[4], Yuri Shvyd'ko[5], Gennadi V. Smirnov[2], Rudolf Rüffer[1], Yuichi Inubushi[6], Makina Yabashi[3], Kensuke Tono[6], Togo Kudo[3] and Tetsuya Ishikawa[3]

In 1954 Dicke predicted the accelerated initial decay of multiple atomic excitations[1], laying the foundation for the concept of superradiance. Further studies[2–4] suggested that emission of the total energy was similarly accelerated, provided that the system reaches the inversion threshold. Superradiant emission of the total energy has been confirmed by numerous studies[4–12], yet the acceleration of the initial decay has not been experimentally demonstrated. Here we use resonant diffraction of X-rays from the Mössbauer transition[13] of ^{57}Fe nuclei to investigate superradiant decay, photon by photon, along the entire chain of the de-excitation cascade of up to 68 simultaneous coherent nuclear excitations created by a pulse of an X-ray free-electron laser. We find agreement with Dicke's theory[1] for the accelerated initial decay as the number of excitations is increased. We also find that our results are in agreement with a simple statistical model, providing a necessary baseline for discussing further properties of superradiance, within and beyond the low-excitation regime.

Even when $N \ll n_a$, this is a very large N-fold acceleration. Therefore, the acceleration of the initial decay predicted by Dicke can be studied even in the low-excitation regime.

We studied the accelerated initial decay of multiple coherent nuclear excitations created by an X-ray pulse of the SPring-8 Angstrom Compact free electron LAser (SACLA)[14], the only source that can presently provide temporally and spatially coherent pulses of many photons within the bandwidth of the convenient 14.4 keV nuclear transition of ^{57}Fe. For X-rays, the small-system limit is fundamentally excluded because the wavelength is similar to interatomic distances. However, one can create a phased excitation of an extended system. The ideal 'X-ray lattice'[10] is offered by atomic periodicity, and the 'seeded coherence'[12] is provided in nuclear resonance diffraction conditions[15]. Similar to the 'collective dipole' of atoms coupled to the light field in an infrared optical cavity[10–12], the 'compound' excited state[16,17] of an ensemble of nuclei under diffraction[15] or forward-scattering[18,19] conditions leads to enhancement of emission and strong 'speed-up' of the collective response[15–23]. In

New Journal of Physics
The open-access journal for physics

Symmetry-enhanced supertransfer of delocalized quantum states

Seth Lloyd[1,2,4] and Masoud Mohseni[2,3]

[1] Department of Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA
[2] Center for Extreme Quantum Information Theory, Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[3] Center for Excitonics, Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
E-mail: slloyd@mit.edu

New Journal of Physics **12** (2010) 075020 (10pp)
Received 26 February 2010
Published 23 July 2010
Online at http://www.njp.org/
doi:10.1088/1367-2630/12/7/075020

Abstract. Coherent hopping of excitation relies on quantum coherence over physically extended states. In this work, we consider simple models to examine the effect of symmetries of delocalized multi-excitation states on the dynamical timescales, including hopping rates, radiative decay and environmental interactions. While the decoherence (pure dephasing) rate of an extended state over N sites is comparable to that of a non-extended state, superradiance leads to a factor of N enhancement in decay and absorption rates. In addition to superradiance, we illustrate how the multi-excitonic states exhibit 'supertransfer' in the far-field regime—hopping from a symmetrized state over N sites to a symmetrized state over M sites at a rate proportional to MN. We argue that such symmetries could play an operational role in physical systems based on the competition between symmetry-enhanced interactions and localized

arpa·e
CHANGING WHAT'S POSSIBLE