Brief Overview on Facilities for Photonuclear Reactions in Europe

TECHNISCHE UNIVERSITÄT DARMSTADT

EL EM EN TS

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Review

Photonuclear reactions—From basic research to applications

Check for updates

A. Zilges [a,*], D.L. Balabanski [b], J. Isaak [c], N. Pietralla [c]

2022

brand-new review article

the scientific and methodological progress achieved in the field of photonuclear reactions. We restrict ourselves to the reactions of atomic nuclei with real photons in the energy range between the energy scales of atomic and nucleonic structure, i.e. between about 0.1 and 100 MeV. The wavelengths of photons of the discussed energies are in the

Nuclear Photonics

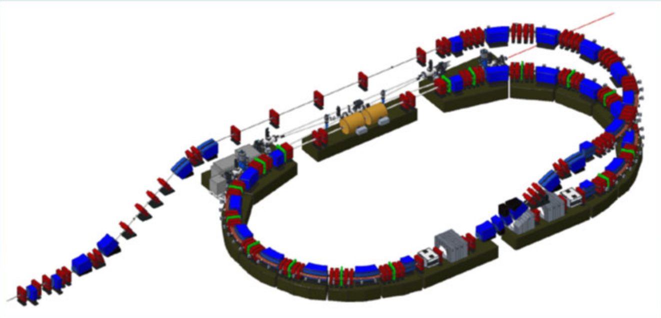
Topics covered in recent Review

- Formalism of photonuclear reactions
  - Nuclear Resonance Fluorescence
  - Photoabsorption
  - Photodissociation
  - Photofission
- Photon sources and instrumentation
- Examples for scientific research
- Examples for applications

- 583 reference citations covered
- Data on 163 different nuclides
  - ranging from ^{2}H to ^{240}Pu
  - in years 2000 – 2020
  - mainly from AIST, HIγS, HZDR, MIT, NewSubaru, S-DALINAC

- Bremsstrahlung and Laser-Compton Backscattering

- Facilities in Europe
  - γELBE @ HZDR
  - S-DALINAC
    - DHIPS
    - Tagger
  - Under construction: ELI-NP



Outline

Facilities for Photonuclear Reactions in Europe

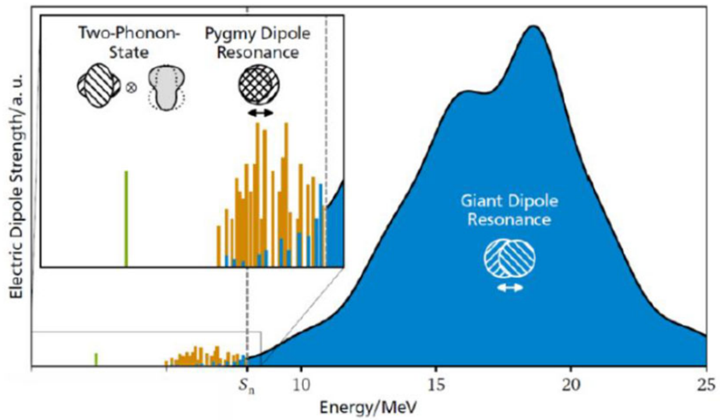
Complementarity of LCB and Bremsstrahlung

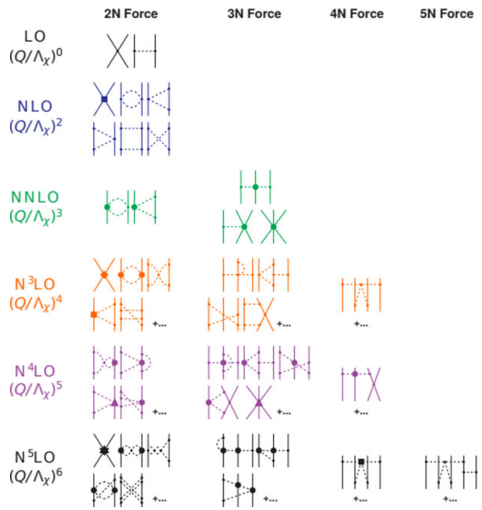
Example: DHIPS @ S-DALINAC

- Photonuclear strength distribution
  - Shell-effect of pygmy dipole resonance in Cr isotopes
- Precision measurements with RSA
  - The „first“ γ-decay in nuclei
  - Test of chiral-Effective Field Theory

Future Plans

Summary





Bremsstrahlung vs. Laser-Compton

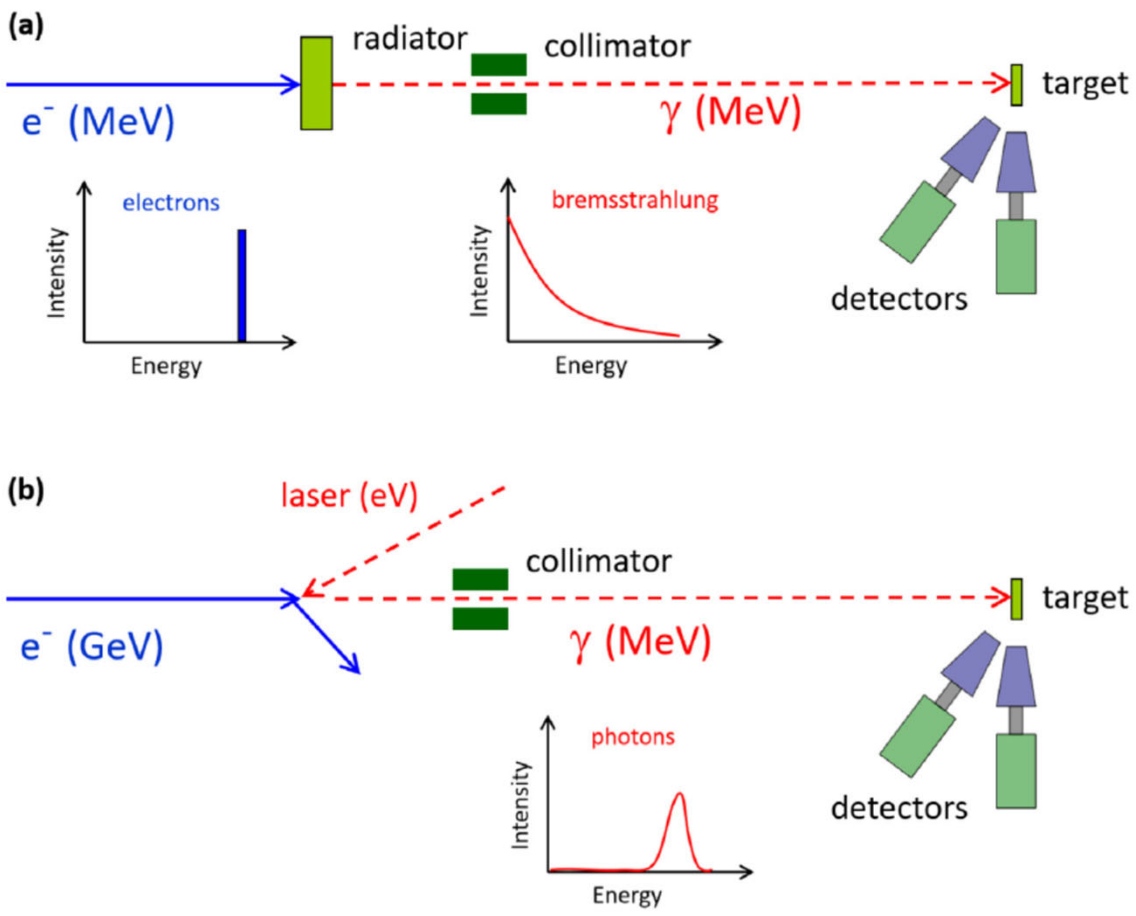


Fig. 26. Principle of generating a photon beam by (a) bremsstrahlung or by (b) laser Compton backscattering.

Bremsstrahlung

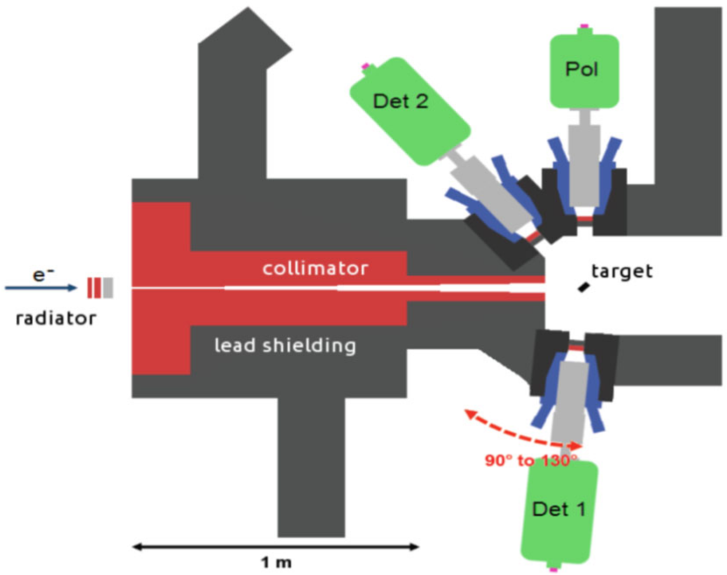
- easy-to-calibrate flux
- precision cross-sections

LCB

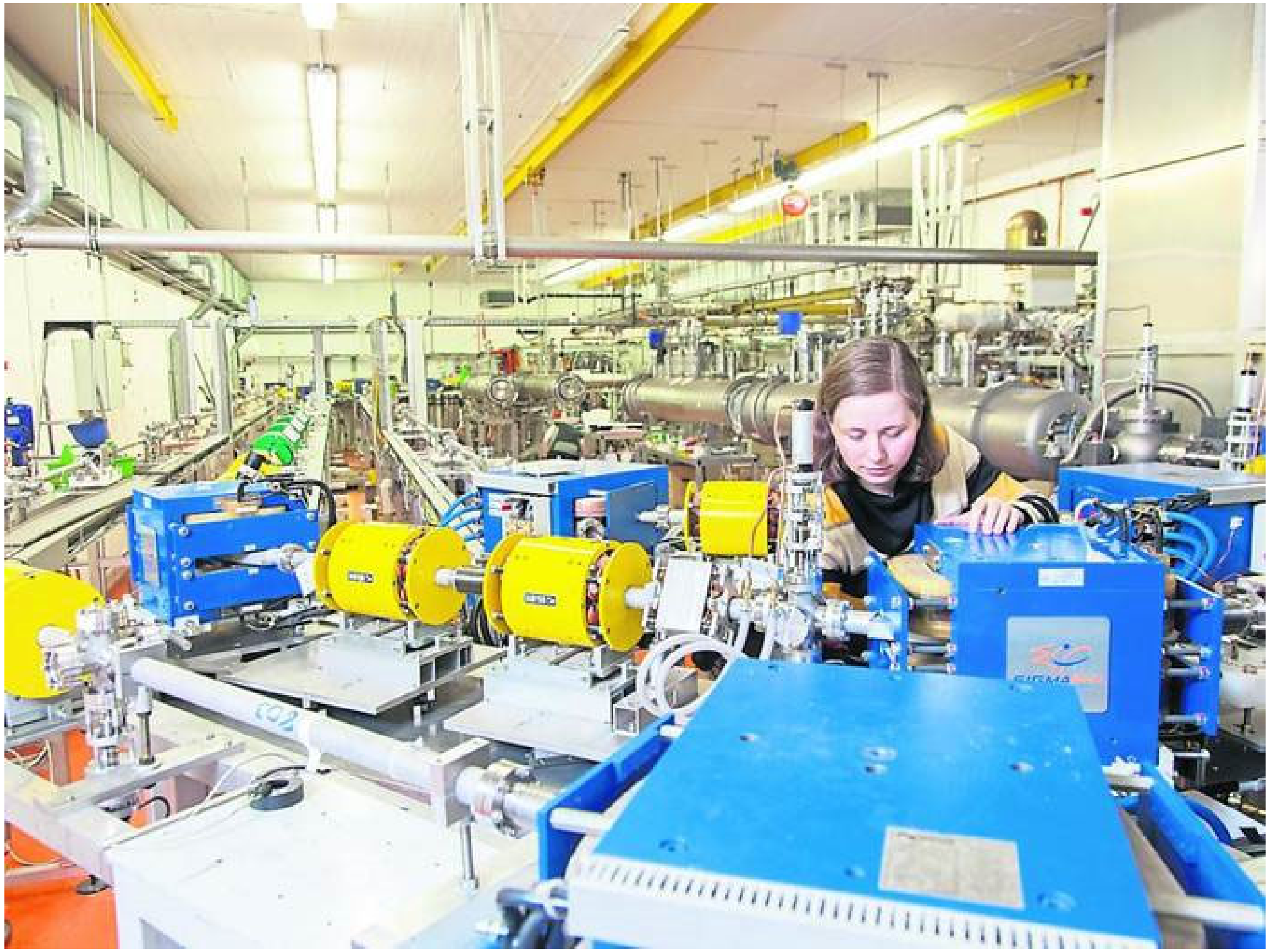
- higher sensitivity
- parity information

Bremsstrahlung Facilities in Europe

	γELBE/HZDR	S-DALINAC/TUD
E_{max}	13 MeV	10 MeV
$I_{max}(e^-)$	1000 μA	10 μA
Radiator material:	Nb ($Z = 41$)	Cu ($Z = 29$)
Radiator thickness:	10-100 μm	14000 μm
Photon flux:	10^2 γ/(eV cm^2 s)	10^3 γ/(eV cm^2 s)



S-DALINAC @ TU Darmstadt



N. Pietralla, "*Laboratory Portrait*“, Nucl. Phys. News **28**, 4 (2018).

→ **2014-2016 upgrade to a thrice-recirculating LINAC and**

→ **a super-conducting energy-recovery LINAC (ERL)**

M. Arnold et al., Phys. Rev. Acc. Beams **23**, 020101 (2020).

→ **First performant multi-turn SRF-ERL Aug. 2021**

S-DALINAC @ TU Darmstadt

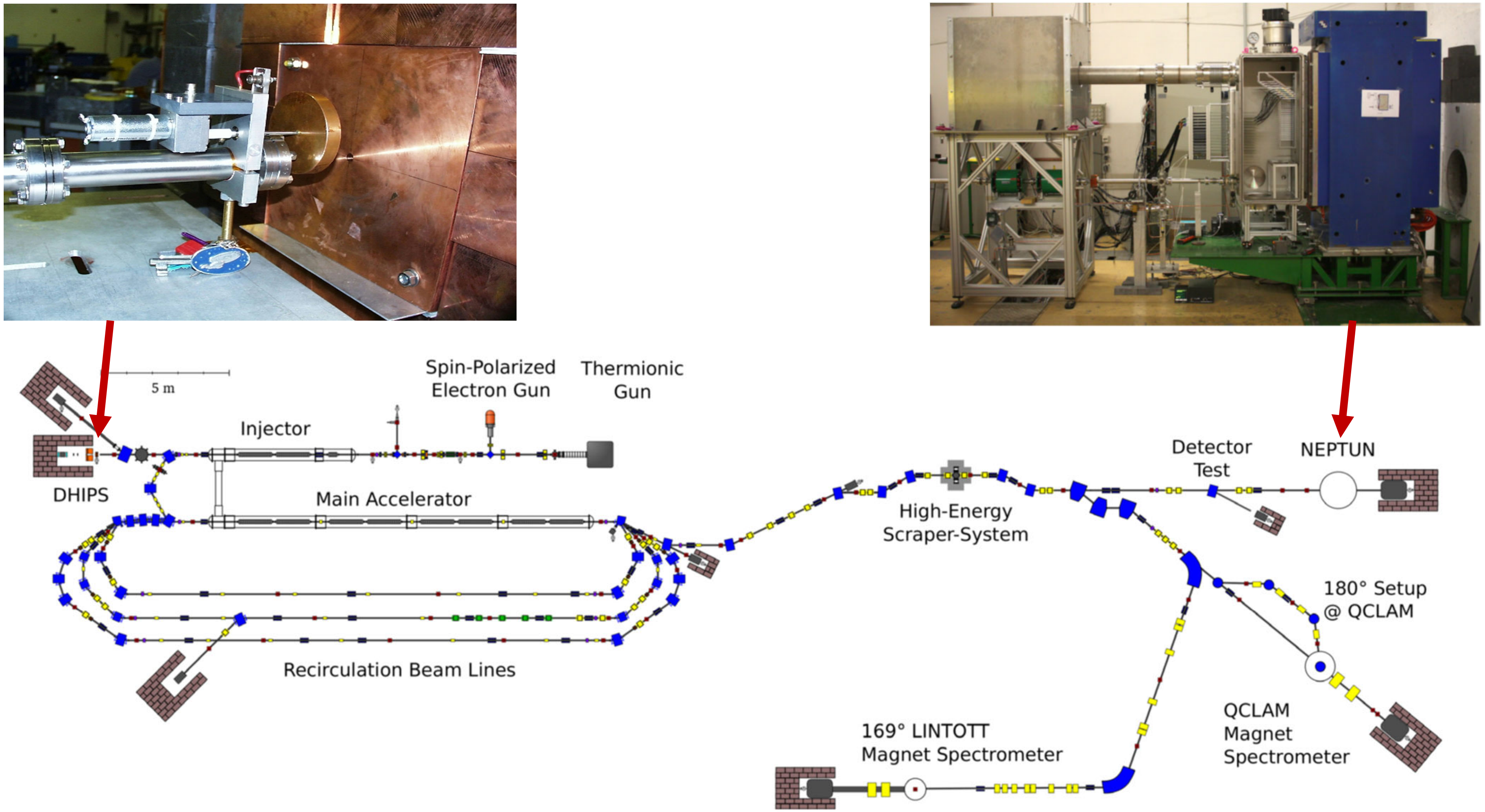


Figure 1: Floorplan of the S-DALINAC with its experimental setups.

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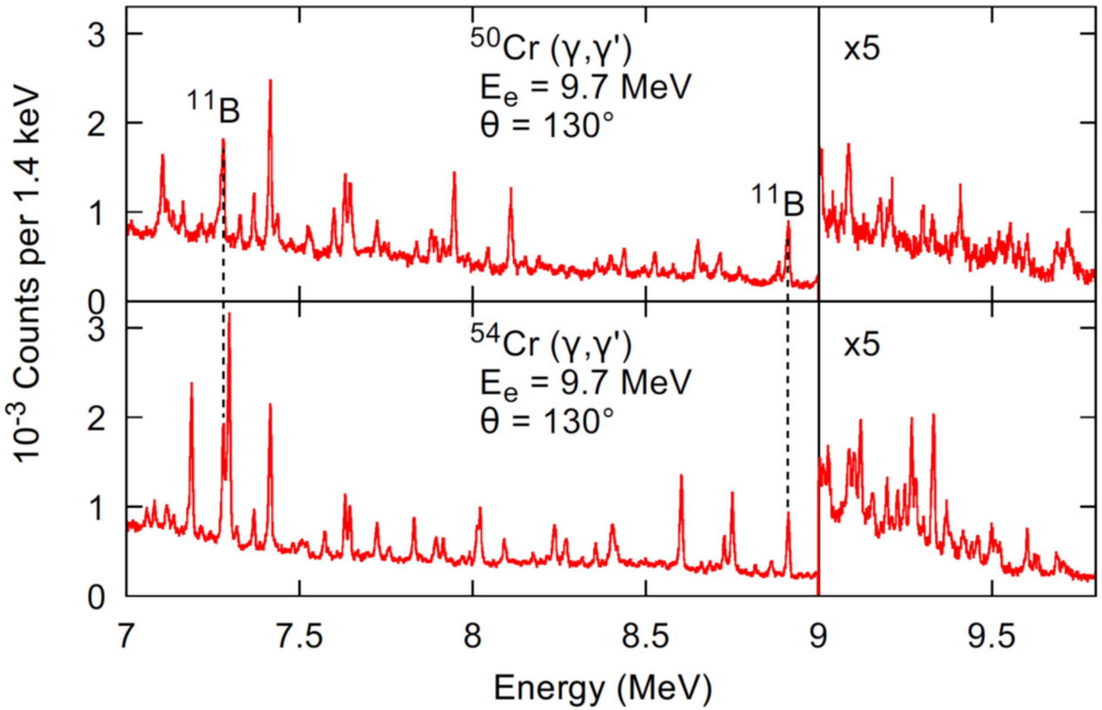
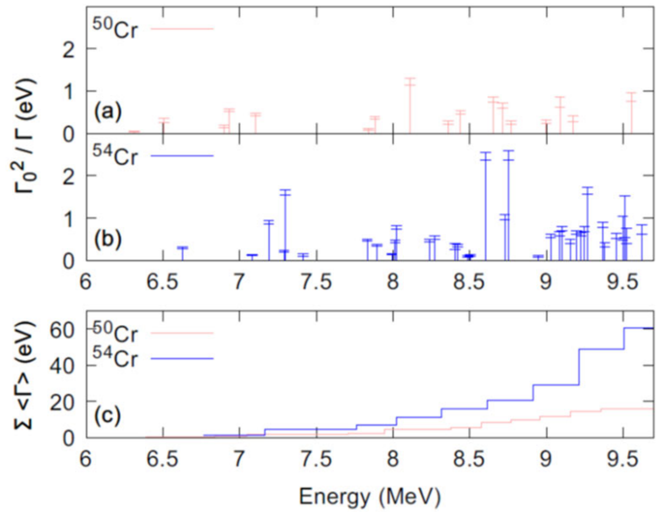
Strength Distributions

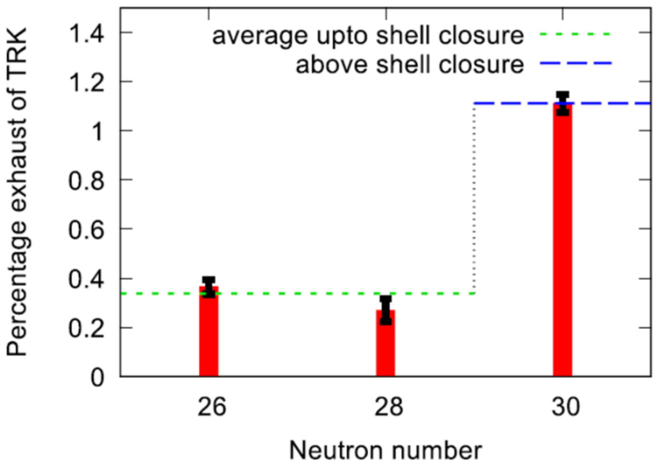
Nuclear Photonics

Total Photonuclear Cross Sections

N=28 cross-shell effect in Cr-isotopes





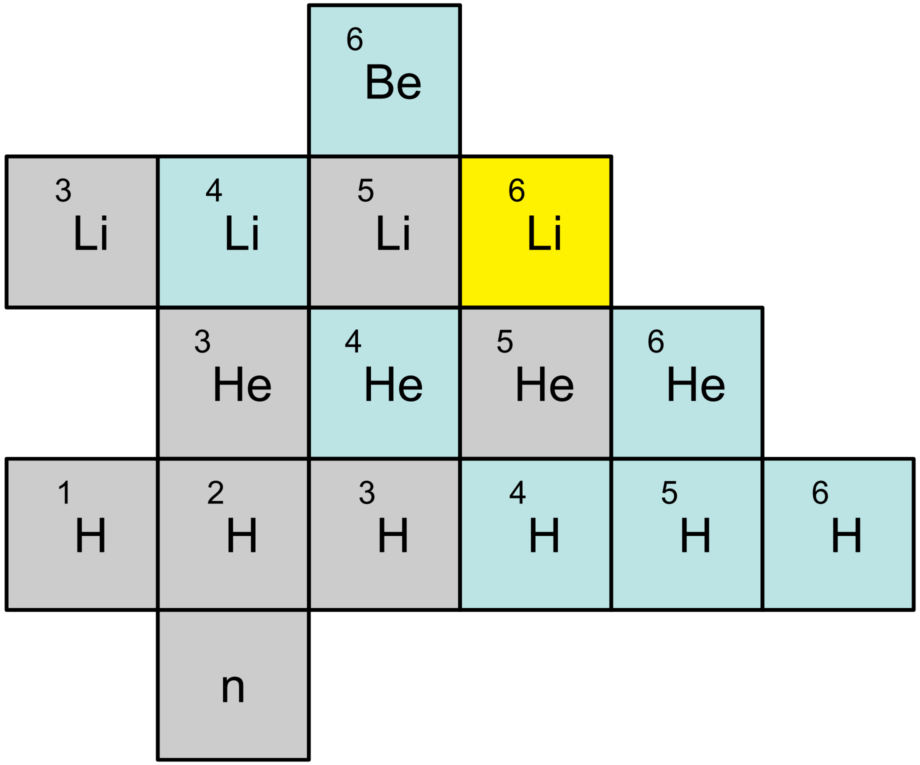


P. C. Ries et al., Phys. Rev. C 100, 021301(R) (2019).

Relative Nuclear Self-Absorption

Testing Theory for Consistent EM Transitions

Predominant decay modes of excited states of known A ≤ 6 nuclei

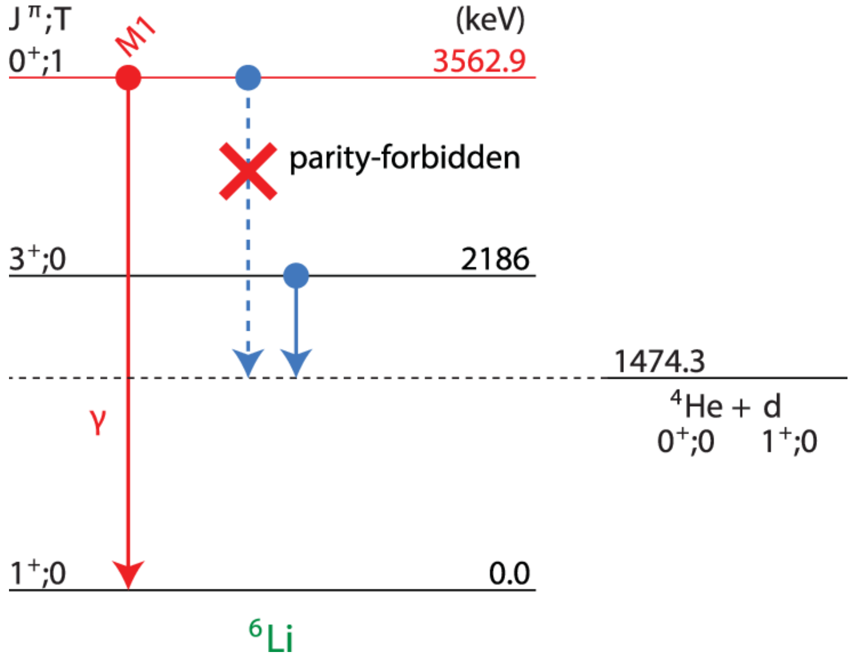


no bound excited state
particle emission
particle + γ emission

- ^{6}Li(3.562 MeV) is the lightest system that decays predominantly via EM interaction
- B(M1; $0^{+} \rightarrow 1^{+}$) one of the strongest known M1 transitions
- Ideal testing ground for ab-initio nuclear theory

Decay data from: https://www.nndc.bnl.gov/ (03/25/2019)

The "Simplest" γ-Ray Transition in Nuclei



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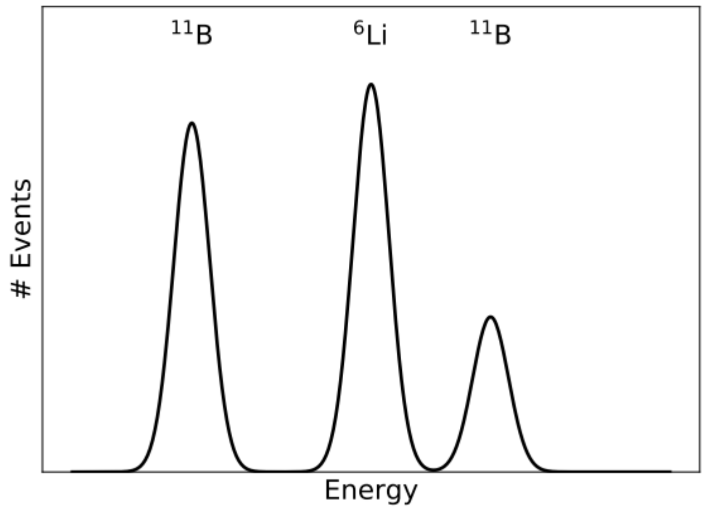
Nuclear Resonance Fluorescence

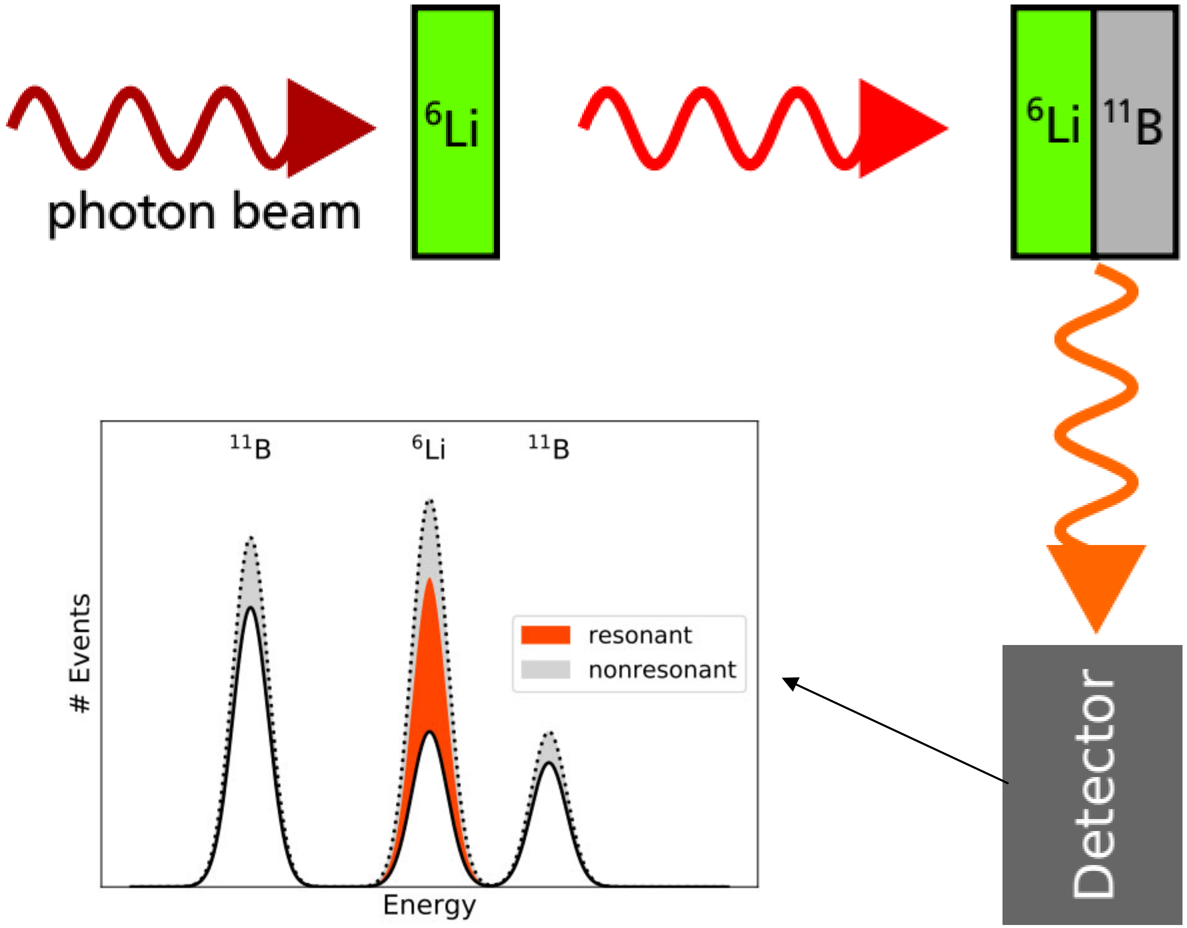


- Nuclear resonance fluorescence (NRF)
- Measurement at the photon point
- → no extrapolation
- Proportionality of cross section to level width / B(M1) (in this case)

$$I \propto \Gamma \propto \frac{h}{2\pi} / \tau \propto B(\mathrm{M1})$$

→ Measurement relative to calibration standard

Relative Self-Absorption



- Relative self-absorption (RSA) based on NRF

N. Pietralla *et al.*, Phys. Rev. C **51**, 1021 (1995)

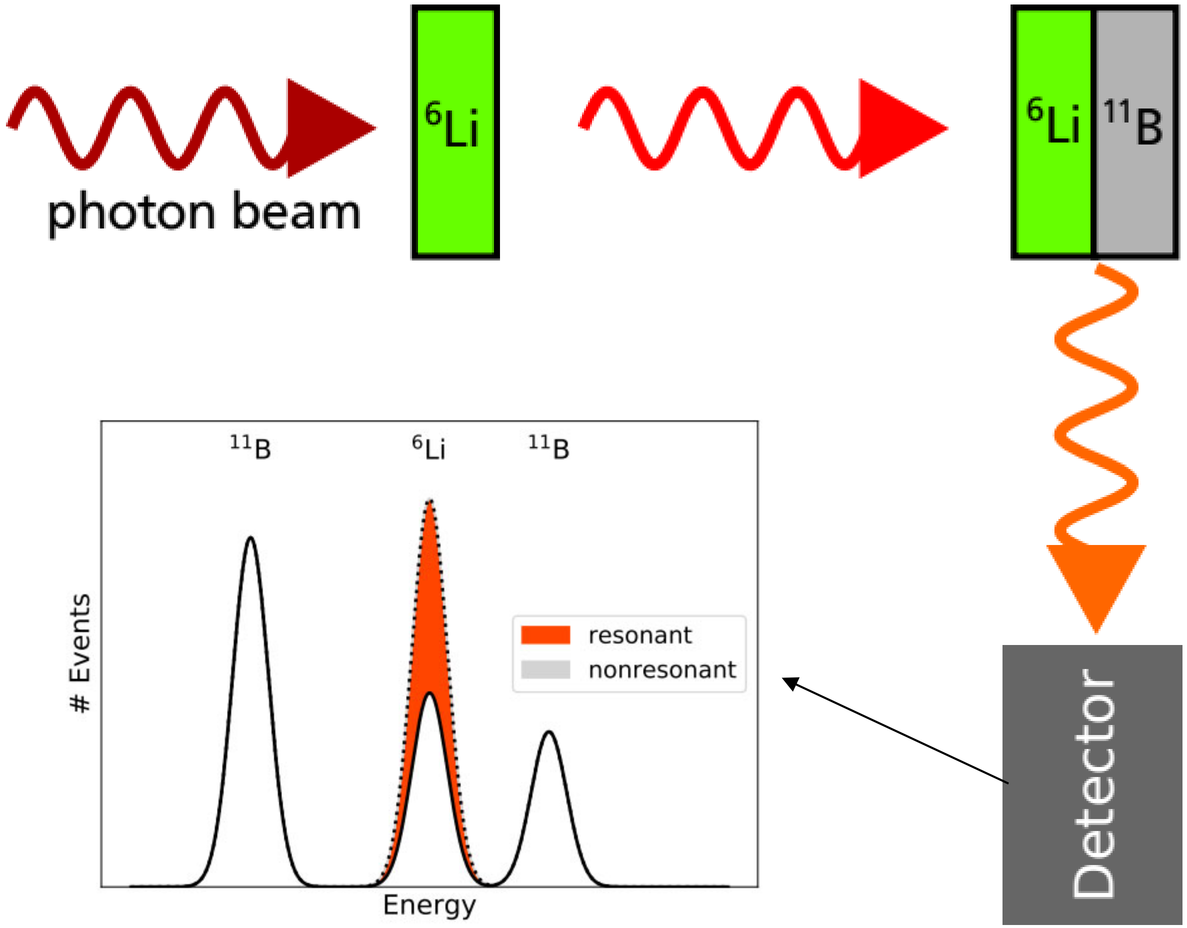
C. Romig, Doctoral Thesis, TU Darmstadt (2015)

U. Friman-Gayer et al. PRL 126, 102501 (2021)

- Reduction of count rate depends on level width
- and atomic absorption

$$R\left(\Gamma_{0^+\rightarrow 1^+}\right) = \frac{N_{NRF} - N_{RSA}}{N_{NRF}}$$

Relative Self-Absorption



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- Reduction of count rate depends on level width
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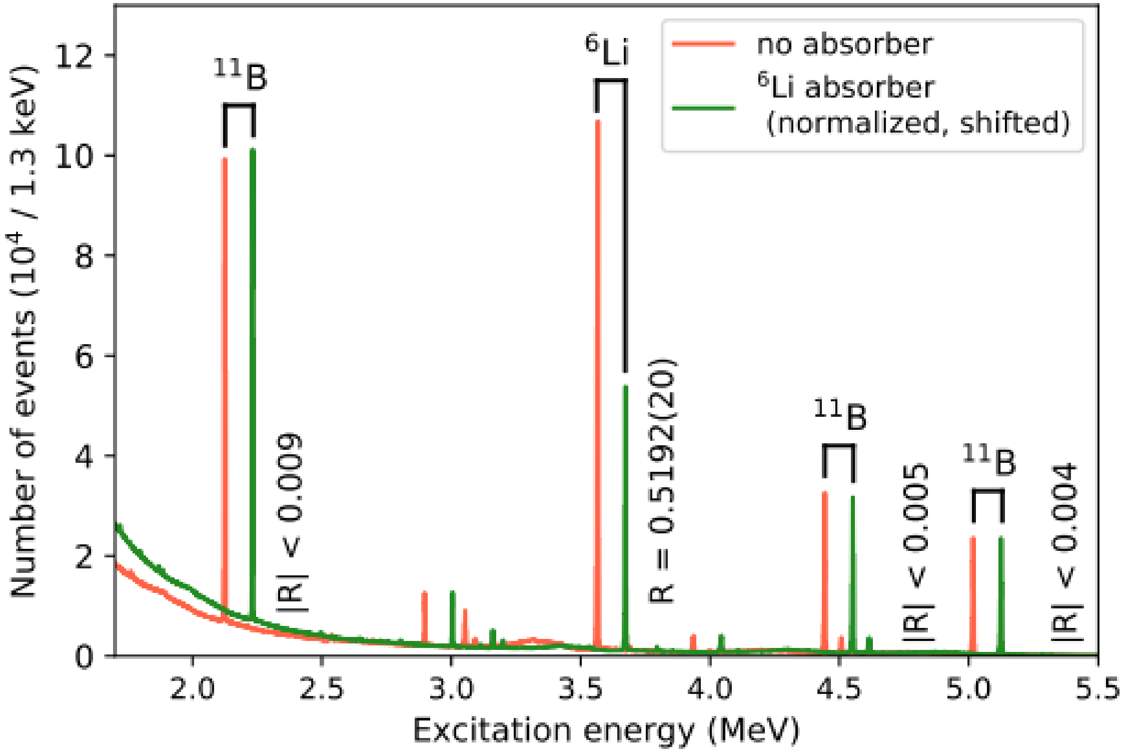
$$R\left(\Gamma_{0^+\rightarrow 1^+}\right) = \frac{N_{NRF} - N_{RSA}}{N_{NRF}}$$

- ‘Monitor target’ to correct for atomic absorption

Spectrum



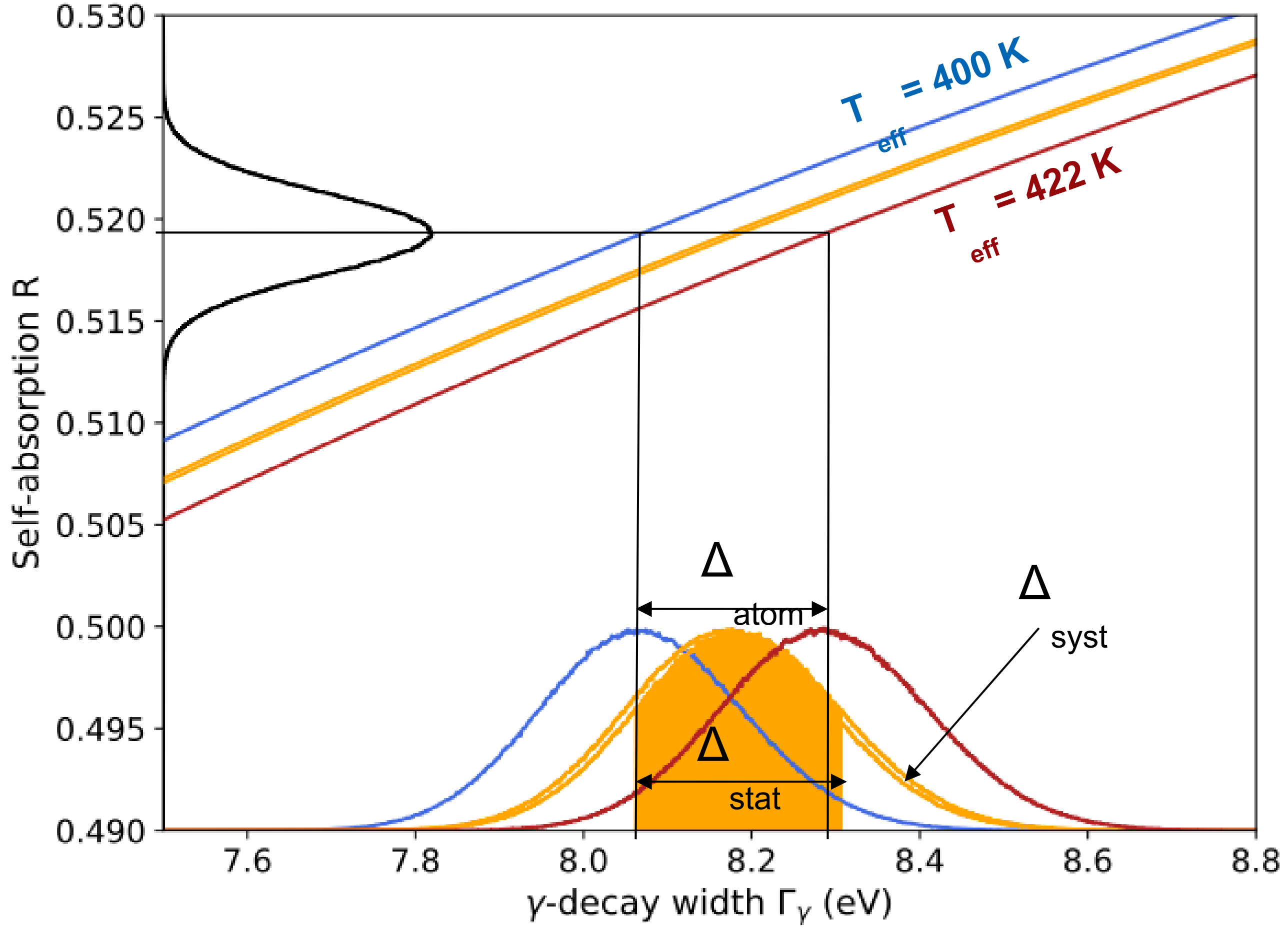
- Normalization of atomic scattering to ^{11}B monitor target

- Measuring times:
- 122h (NRF)
- 189h (RSA)

$$R\left(\Gamma_{0^+\to 1^+}\right) = \frac{N_{NRF} - N_{RSA}}{N_{NRF}}$$
$$= 0.5192(20)$$

→ Relative statistical **uncertainty of 0.4%**!

Uncertainty Budget



B(M1) = 15.61

Δ stat statistics

+0.23 – 0.21

Δ atom atomic theory

+0.19 – 0.21

Δ syst target dimensions

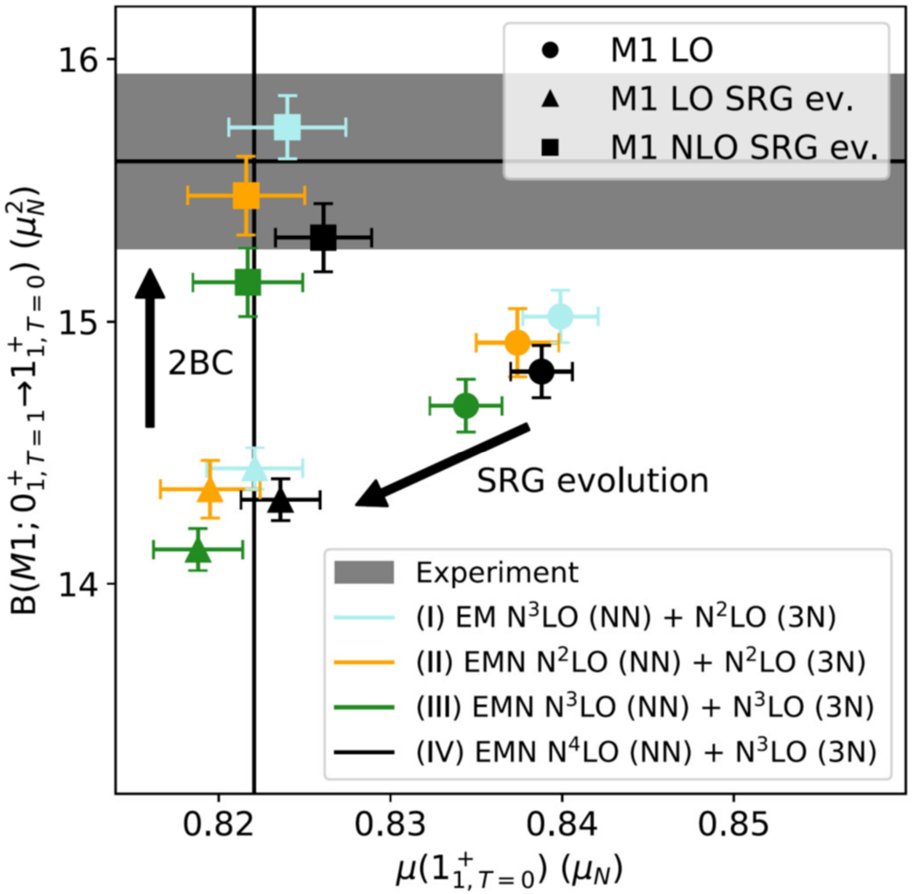
+-0.04

Δ num numerical evaluation

+- << 0.01

= 15.61 +- 0.30
(100% +- 1.9%)

Comparison with theory



- χEFT calculations of $B(M1;1^+\to0^+)$ and $\mu(1^+)$ in the no-core shell model
- SRG-evolved chiral NN+3N interactions up to N4LO+N3LO
  D.R. Entem, R. Machleidt, Y. Nosyk, PRC **96** (2017)
- Evolved M1 operator at NLO

→ First complete chiral calculation of these observables

U.Friman-Gayer et al.
Role of Chiral Two-Body Currents in 6Li Magnetic Properties in Light of a New Precision Measurement with the Relative Self-Absorption Technique
Phys. Rev. Lett. **126**, 102501 (2021)

High experimental precision crucial to test state-of-the-art theory!

Future Plans

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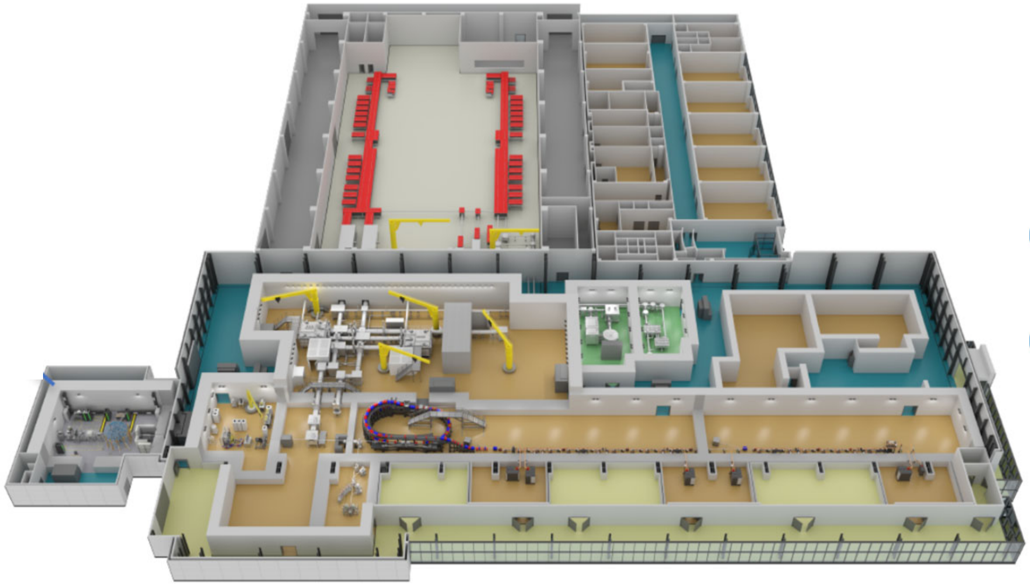
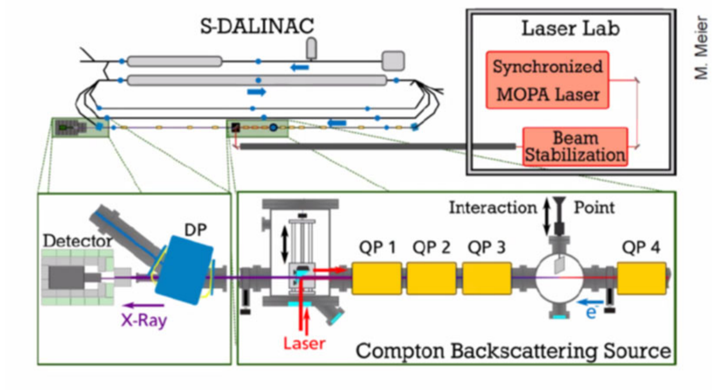
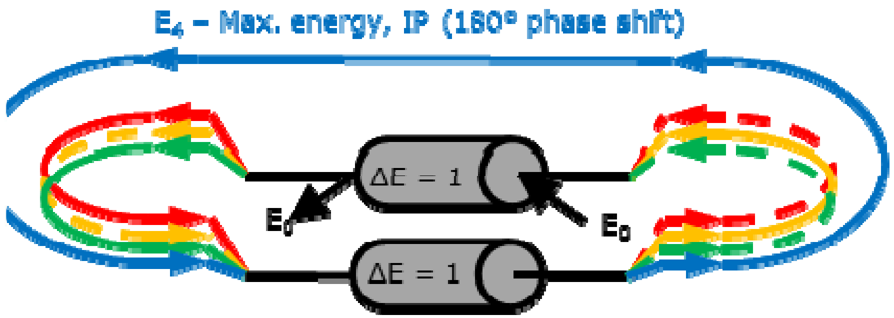
VEGA @ ELI-NP

1 – 20 MeV, <1% bandwidth
5 x 10^3 γ/(s eV)



Funded, completion in 2023





DICE
Darmstadt individually-recirculating compact ERL

Design study

Nuclear Photonics

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