FRIEDRICH-ALEXANDER
UNIVERSITÄT
ERLANGEN-NÜRNBERG

NATURWISSENSCHAFTLICHE
FAKULTÄT

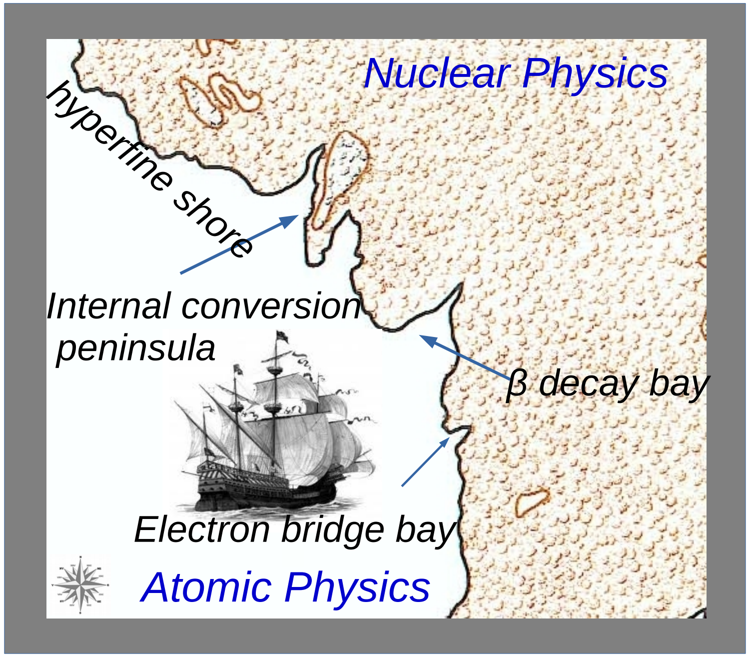
Interaction of atomic and nuclear degrees of freedom

Adriana Pálffy

Friedrich Alexander University of Erlangen-Nürnberg
Max Planck Institute for Nuclear Physics, Heidelberg

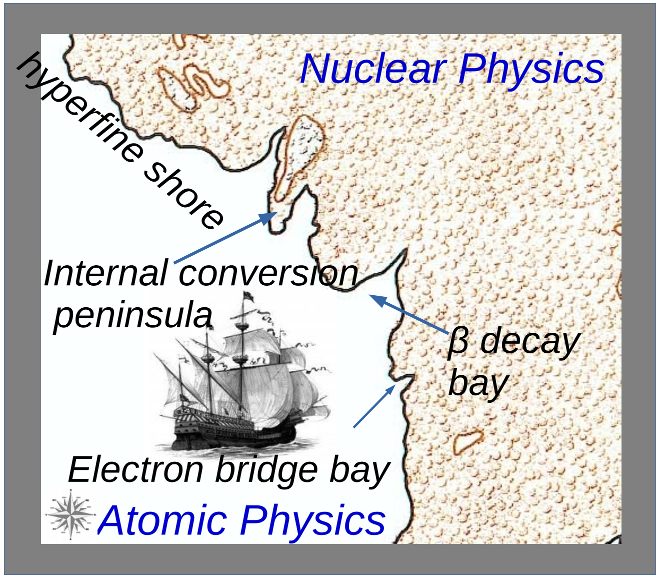
Physics Opportunities with the Gamma Factory
3 December 2020

The interface of atomic and nuclear physics



- Exploring nuclear physics properties via atomic physics experiments
- Nuclear processes directly involving electrons

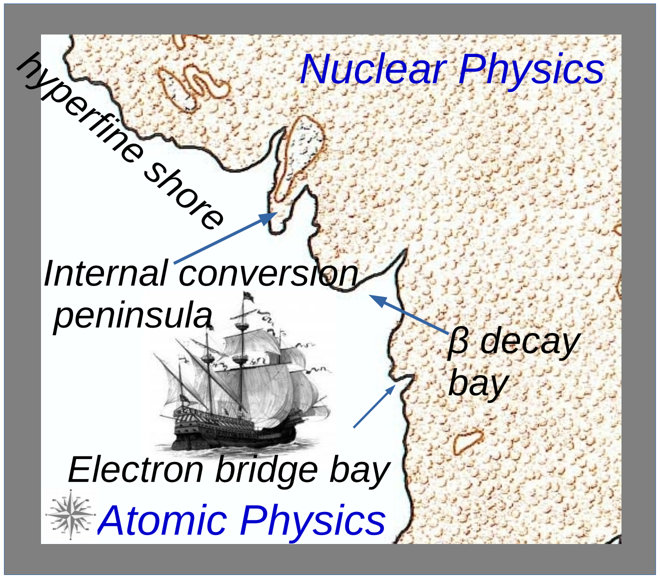
The interface of atomic and nuclear physics



- Exploring nuclear physics properties via atomic physics experiments

- Hyperfine structure (Andrey's talk today) – high-precision laser spectroscopy
- Muonic atoms
- Isotope shifts and nuclear charge radii (laser spectroscopy, dielectronic recombination)

The interface of atomic and nuclear physics



- Nuclear processes directly involving electrons

- Electron capture (EC) $$p + e_b \rightarrow n + \nu_e$$

- Bound beta decay $$n \rightarrow p + e_b + \tilde{\nu}_e$$

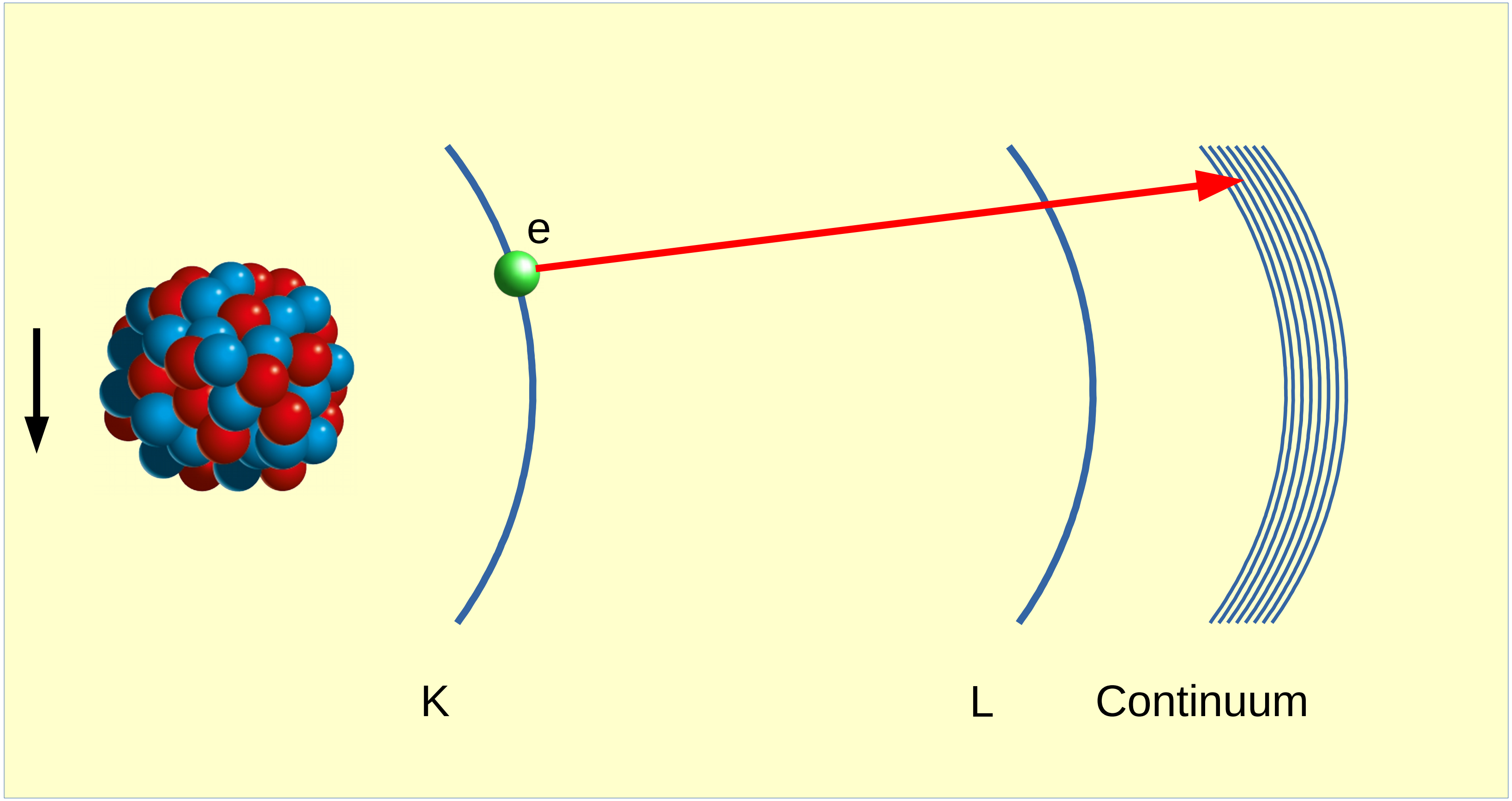
VOLUME 77, NUMBER 26 PHYSICAL REVIEW LETTERS 23 DECEMBER 1996

Observation of Bound-State β^- Decay of Fully Ionized ^{187}Re: ^{187}Re-^{187}Os Cosmochronometry

F. Bosch,[1] T. Faestermann,[2] J. Friese,[2] F. Heine,[2] P. Kienle,[2] E. Wefers,[2] K. Zeitelhack,[2] K. Beckert,[1] B. Franzke,[1] O. Klepper,[1] C. Kozhuharov,[1] G. Menzel,[1] R. Moshammer,[1] F. Nolden,[1] H. Reich,[1] B. Schlitt,[1] M. Steck,[1] T. Stöhlker,[1] T. Winkler,[1] and K. Takahashi[2,3]

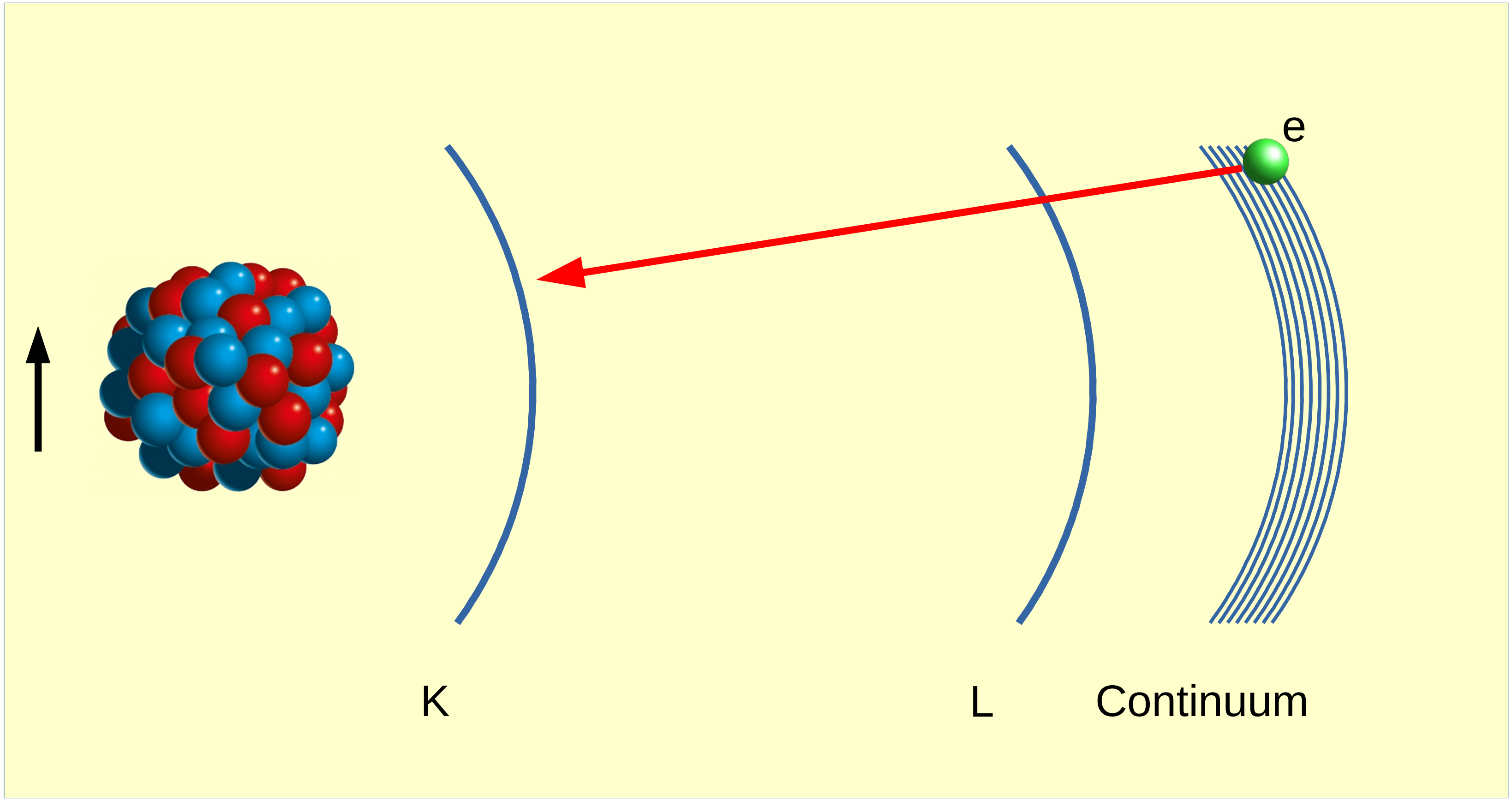
Internal conversion and NEEC

Internal conversion



Internal conversion and NEEC

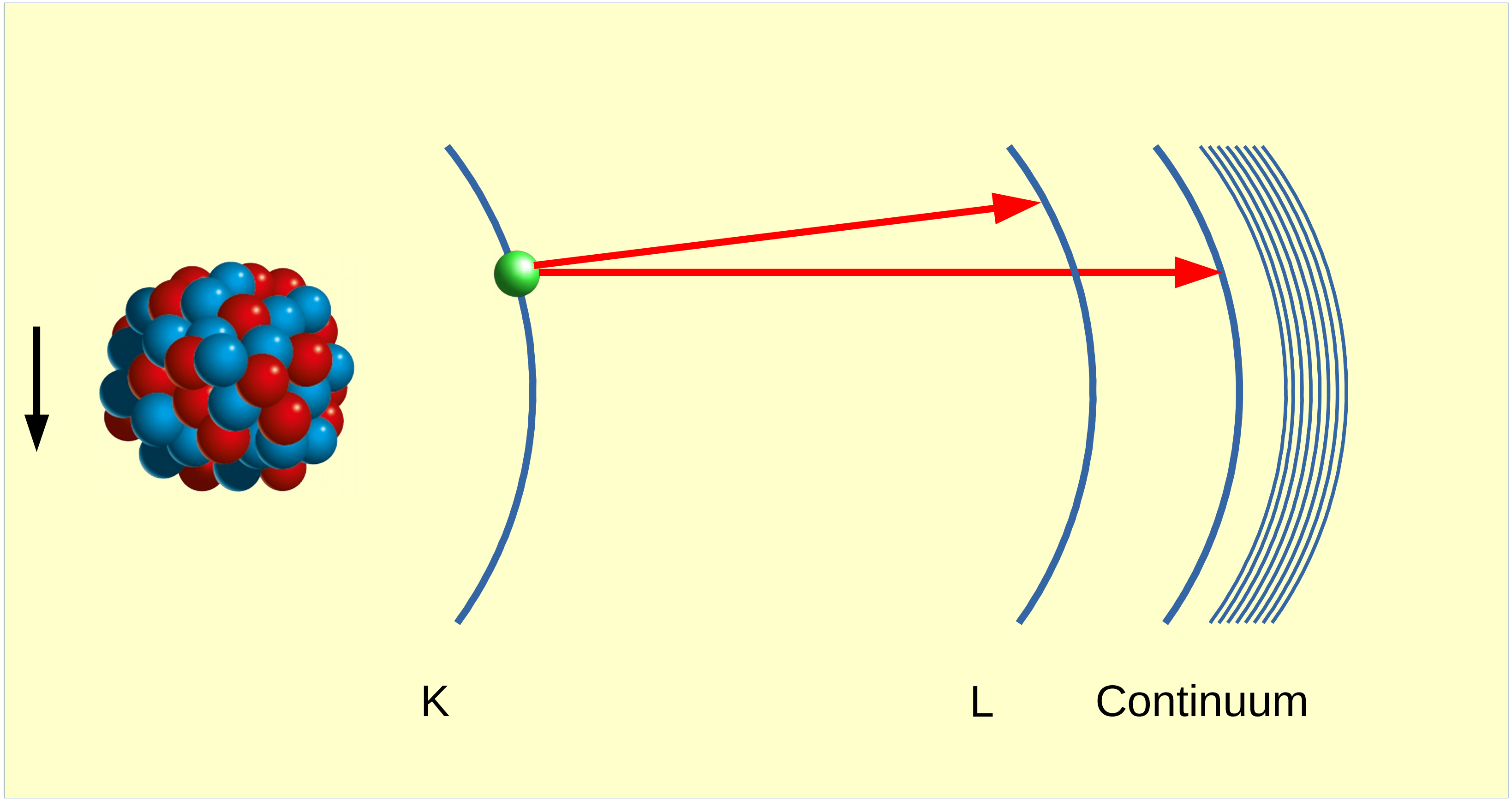
Internal conversion + inverse process nuclear excitation by electron capture



Chronologically, IC - 1924, NEEC proposed – 1976, observed (?) 2018

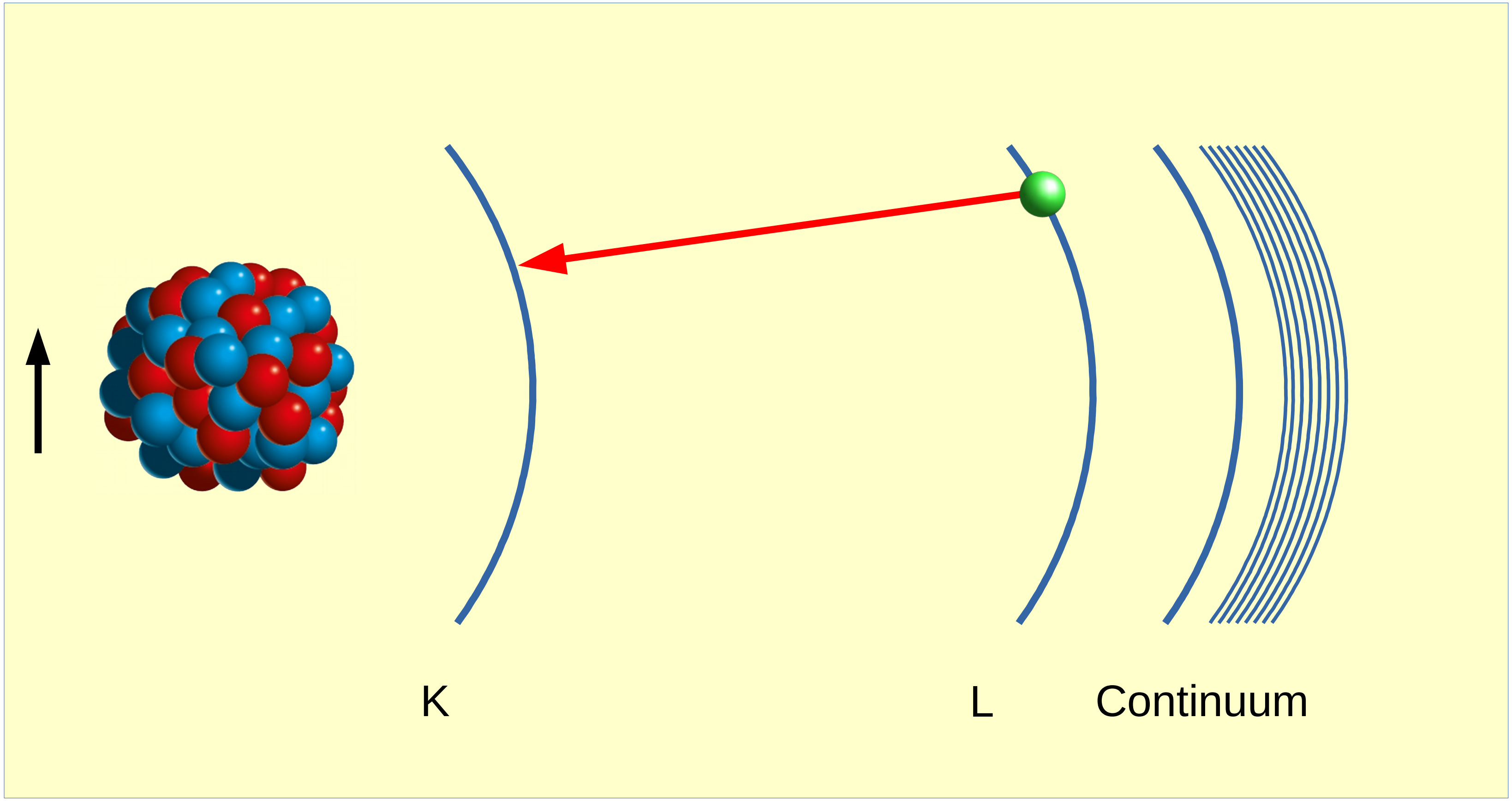
Bound internal conversion and NEET

Bound internal conversion



Bound internal conversion and NEET

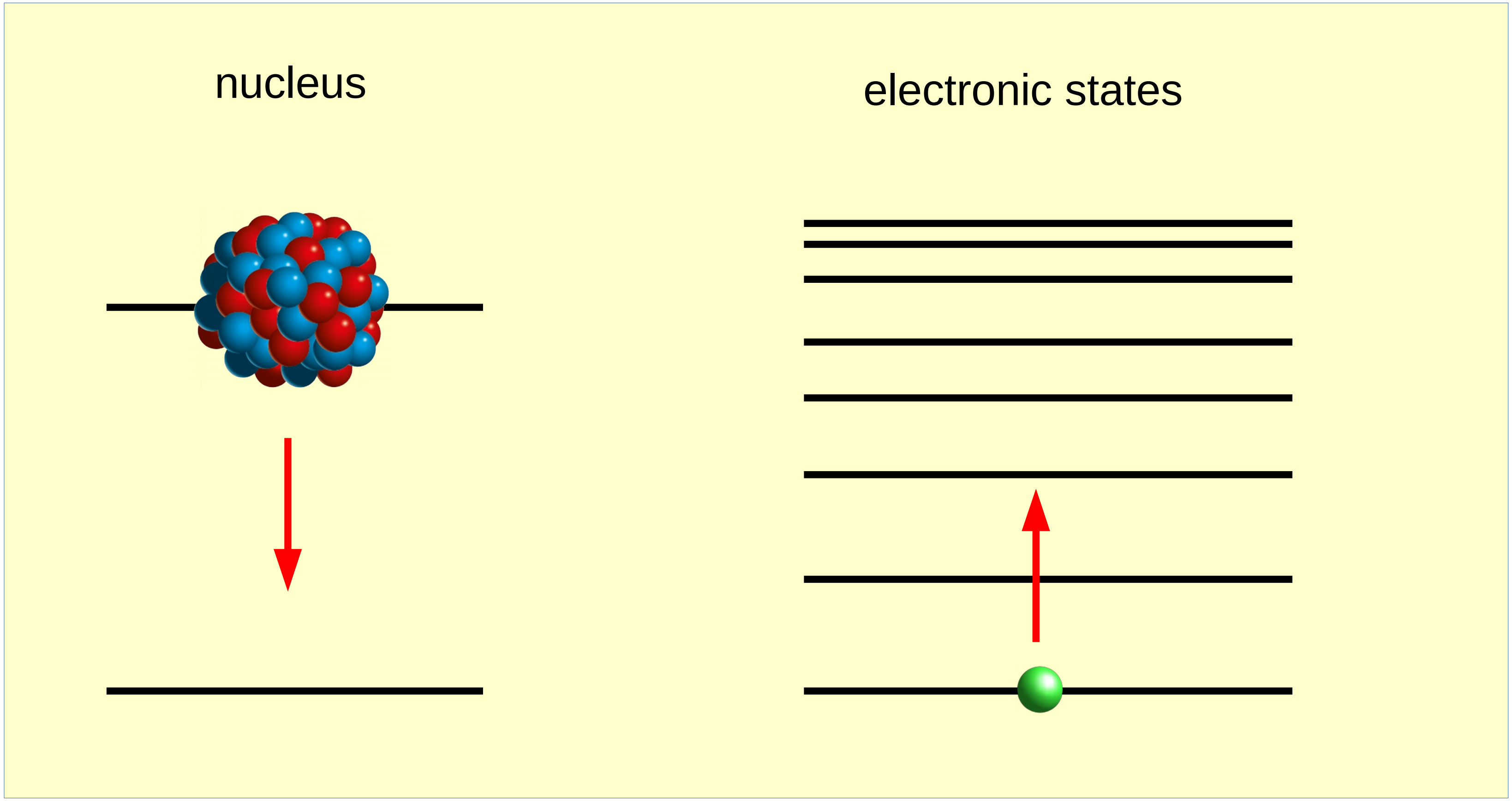
Bound internal conversion + inverse process nuclear excitation by electron transition



Difficult to find in nature such perfect matches of atomic and nuclear transition energies!

Electronic bridge

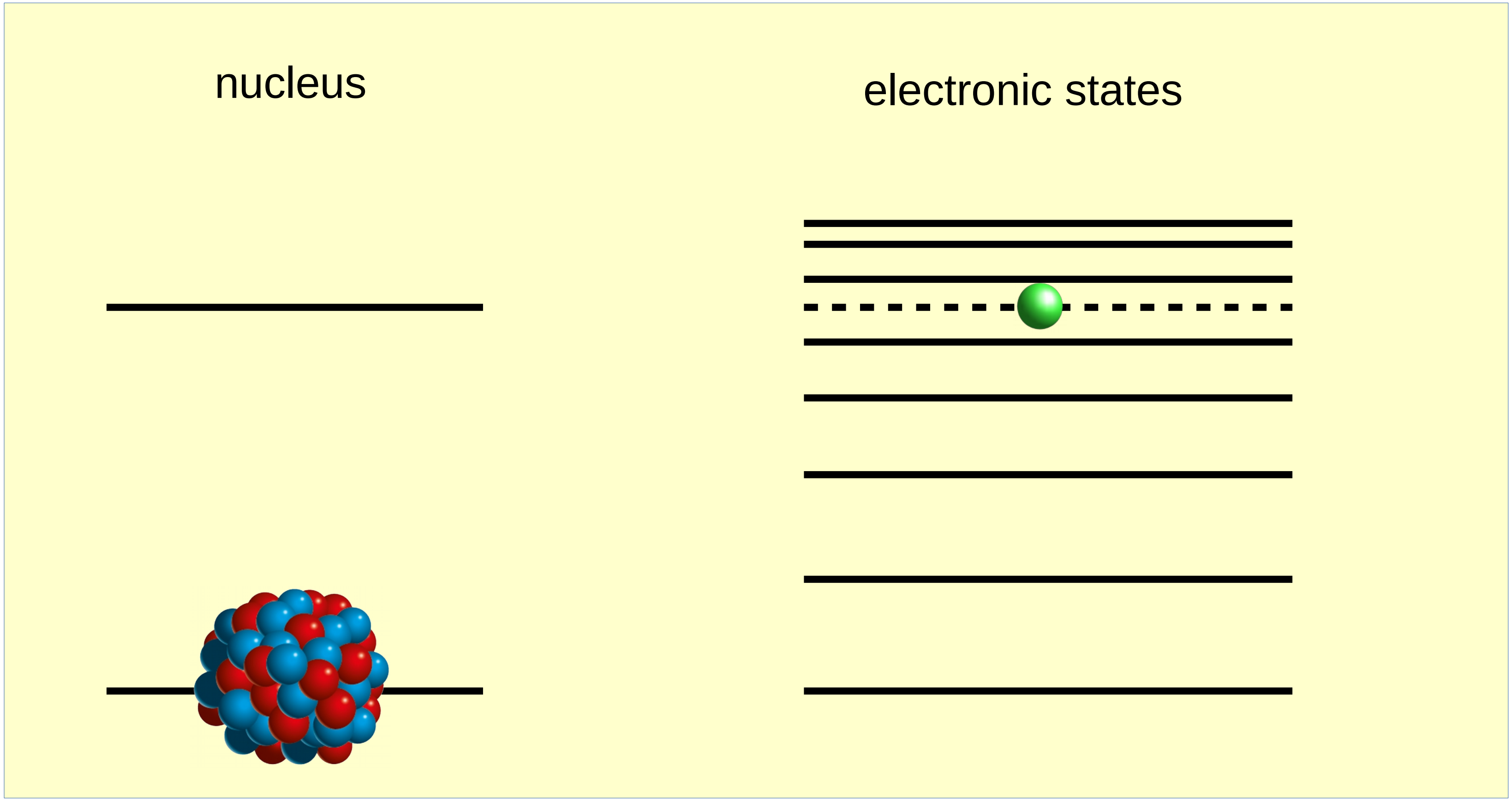
Electronic bridge – nuclear decay: both IC and BIC are forbidden



There is no electronic state at right energy - virtual state!

Electronic bridge

Electronic bridge – nuclear decay: both IC and BIC are forbidden



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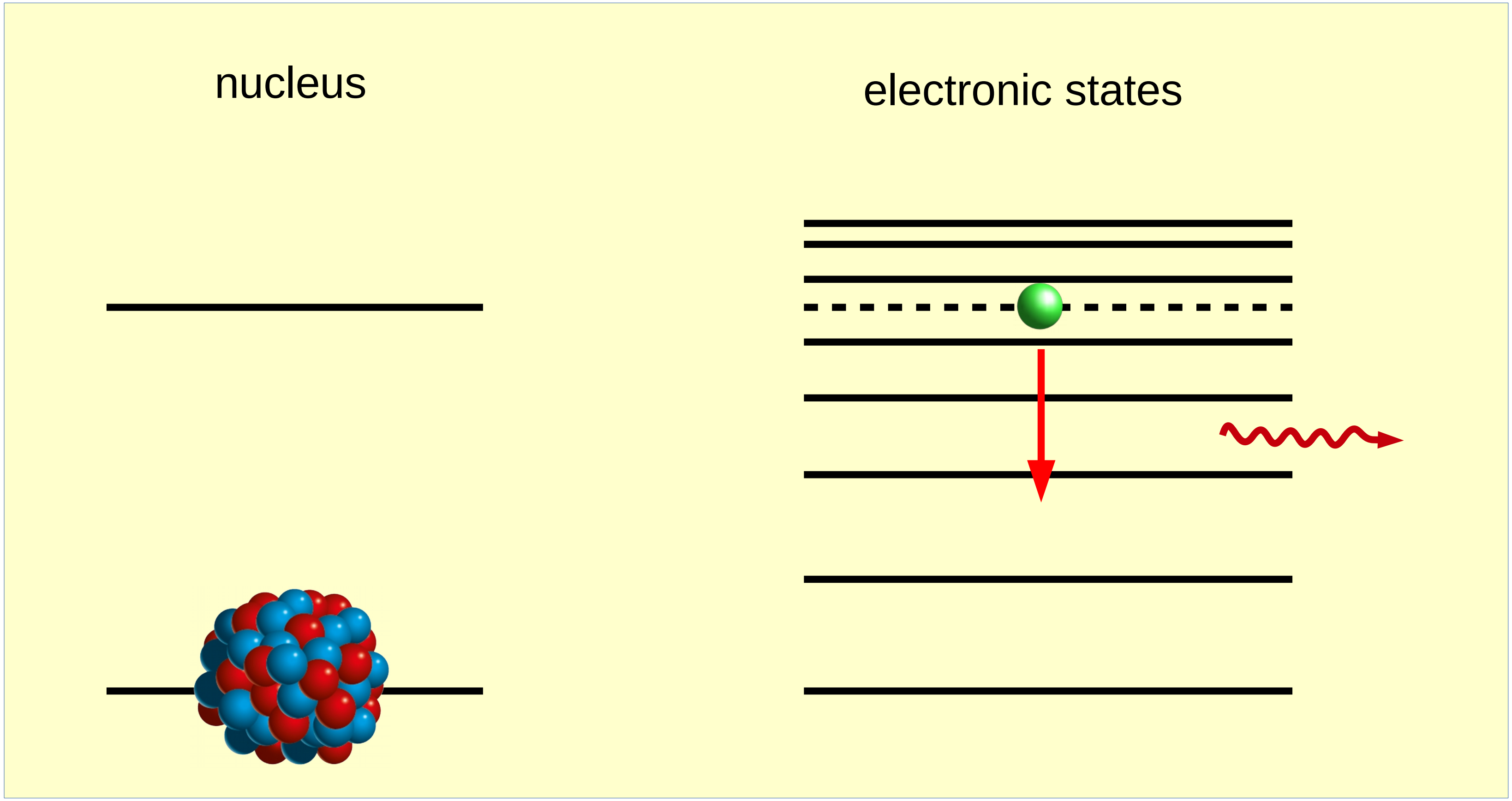
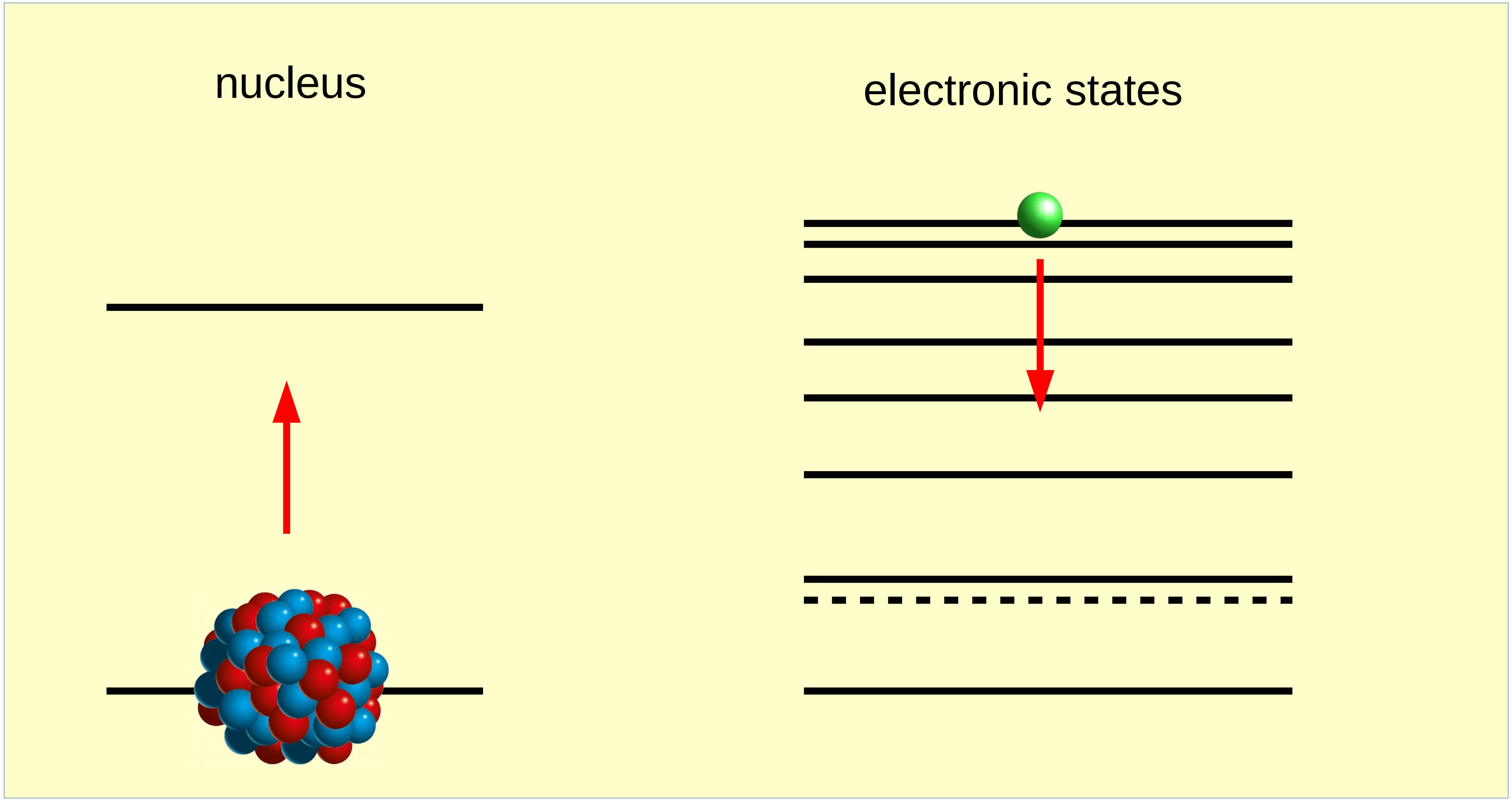


Virtual state decays to a real state by emitting a photon.

Electronic bridge

Electronic bridge – as nuclear excitation mechanism (same name)



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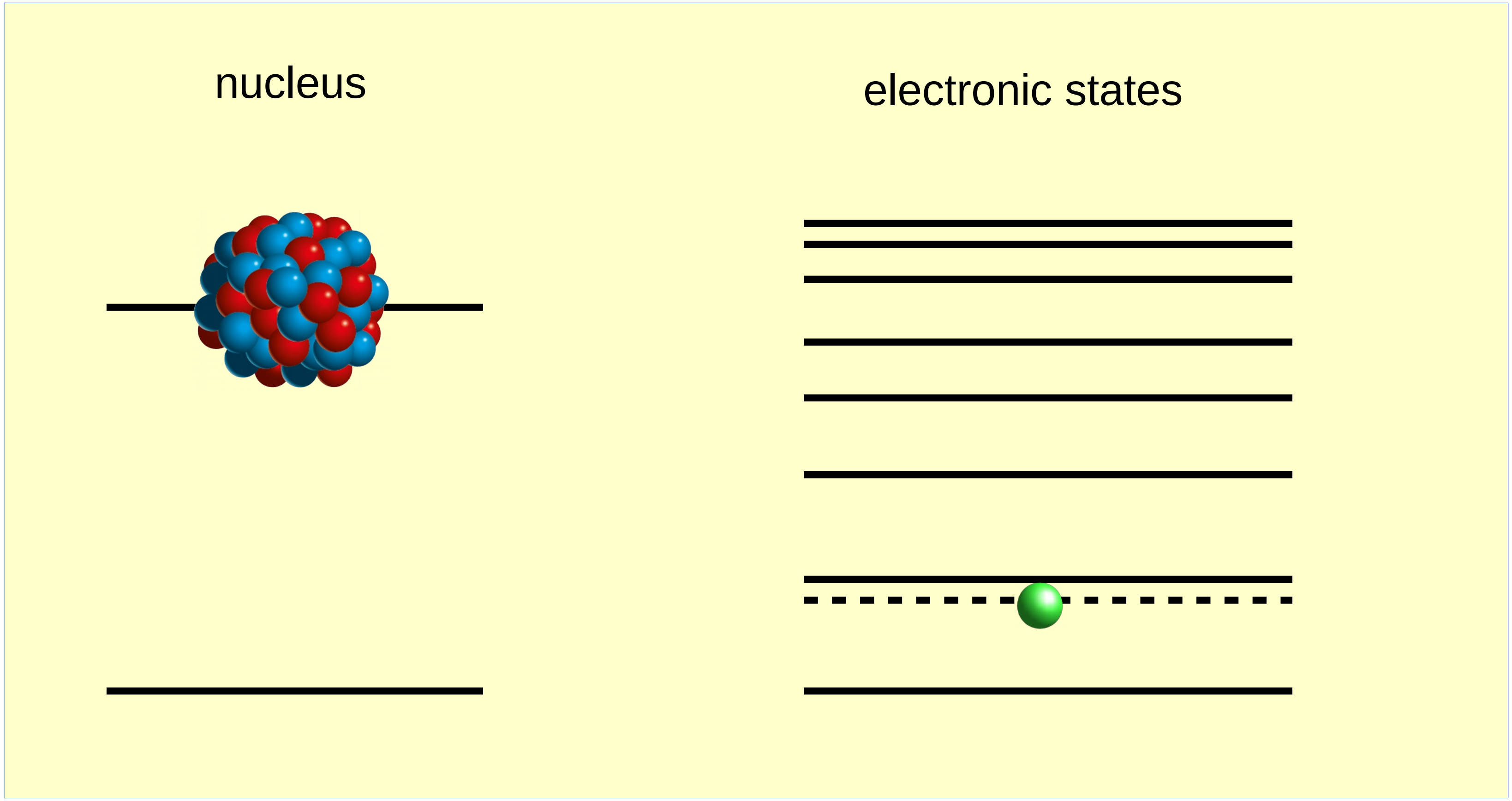

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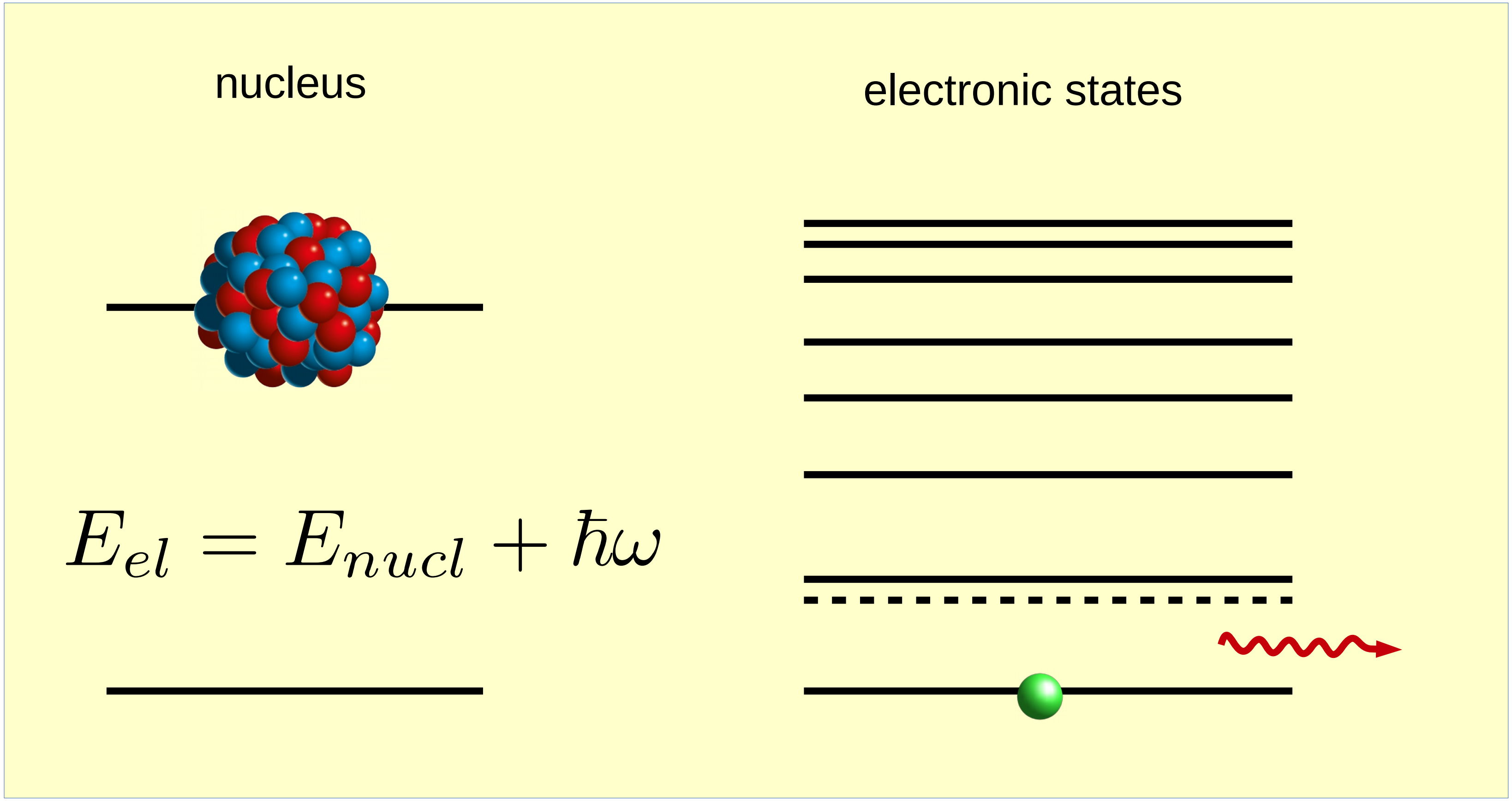
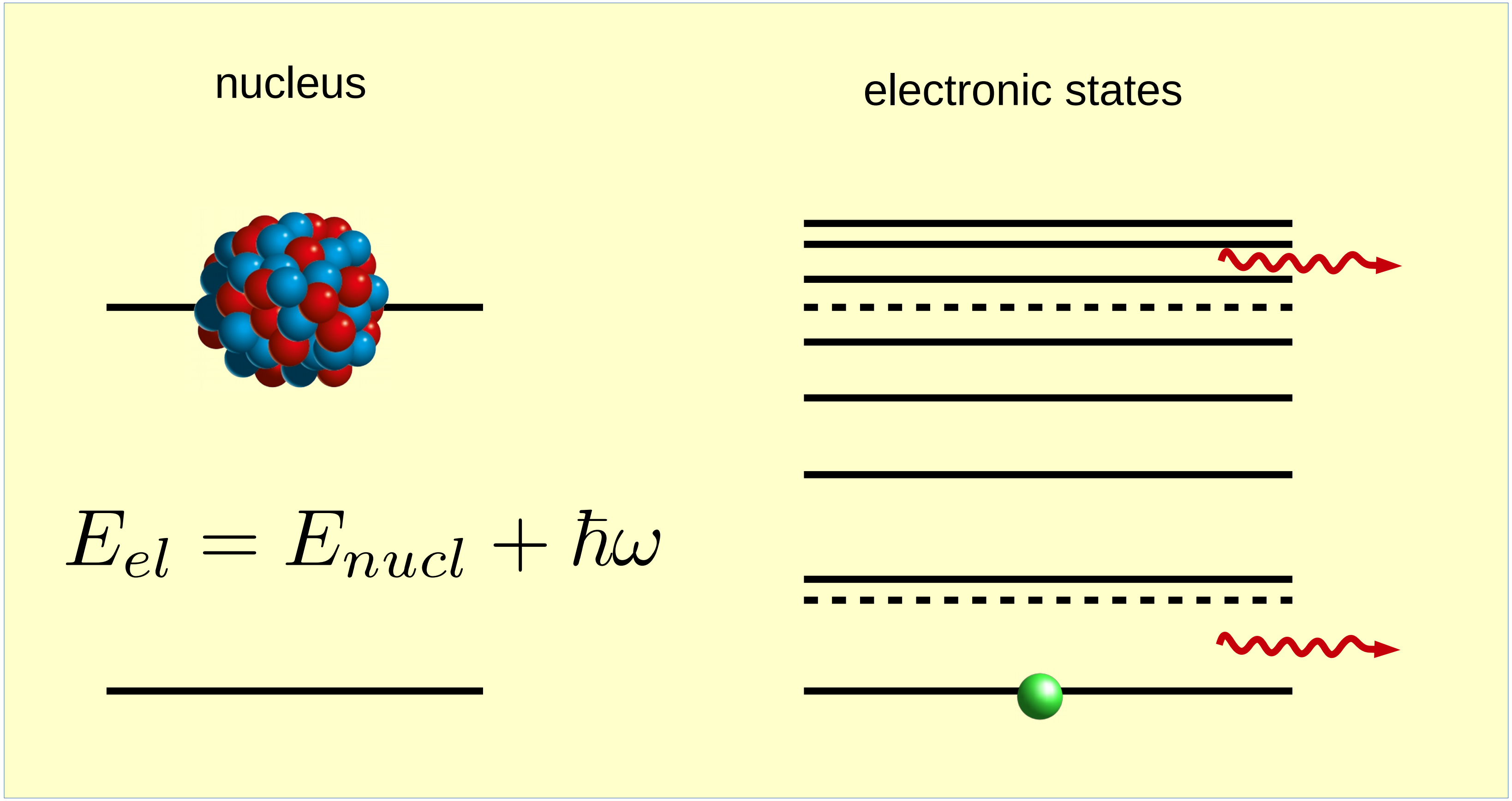


$$E_{el} = E_{nucl} + \hbar\omega$$

There is no electronic state at right energy - virtual states!

Electronic bridge

Electronic bridge – as nuclear excitation mechanism (same name)

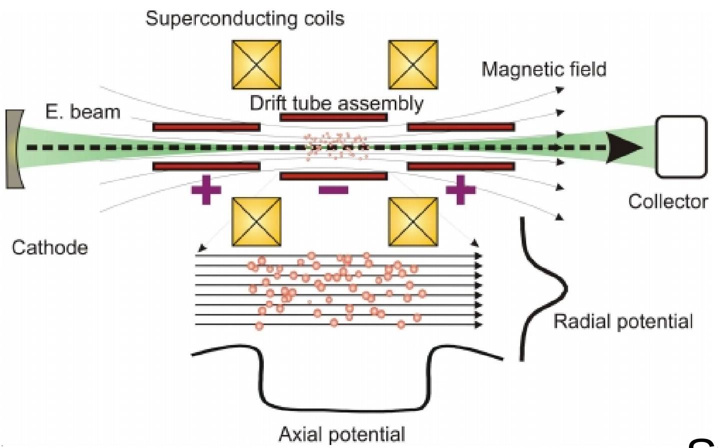


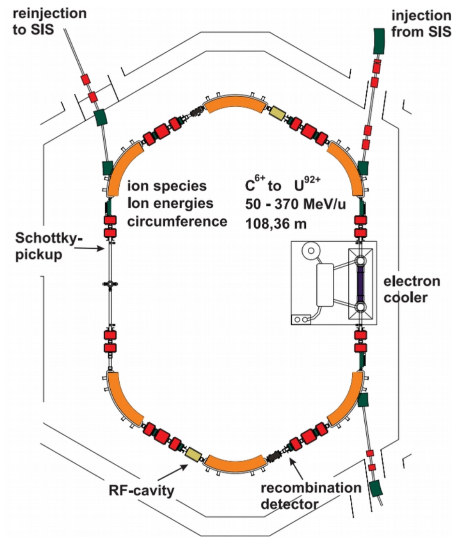
Two pathways: photon + nuclear excitation or nuclear excitation + photon

(Highly) charged ions

Andrey's "partially stripped ions"

Nuclear excitation processes require atomic shell vacancies or even highly charged ions



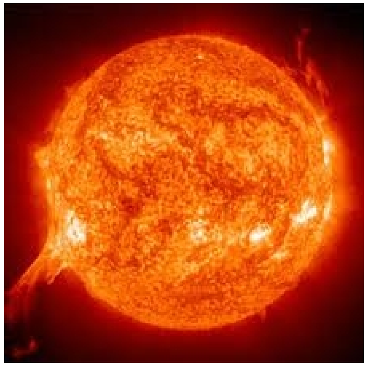


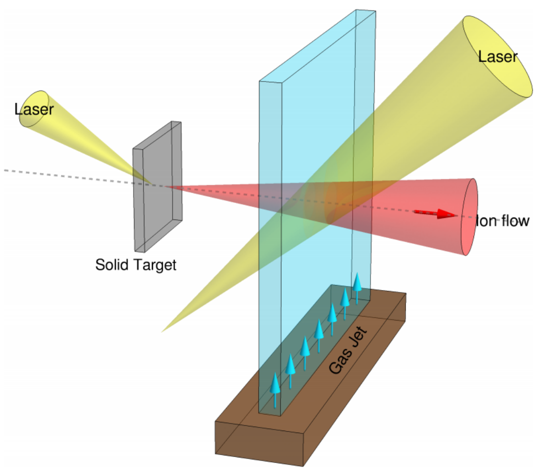
Storage rings

EBIT

Plasmas

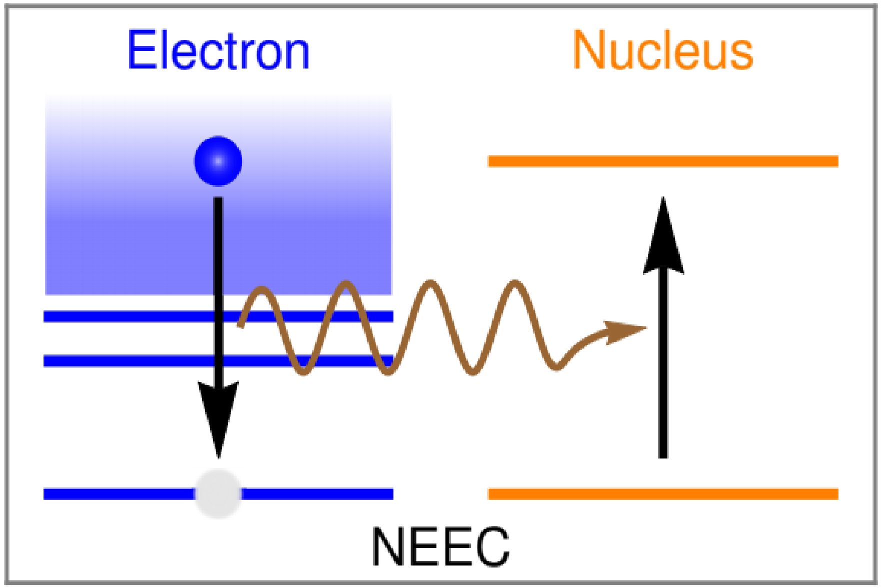
Nuclear reactions





NEEC

- Proposed theoretically by Goldanskii & Namiot Phys. Lett. 62B (1976)
- First experimental observation claimed in 2018 – C. J. Chiara *et al.*, Nature 554, 216



Study of:

population mechanisms of excited nuclear levels

atomic vacancy effects on nuclear lifetime

switch off IC decay channel

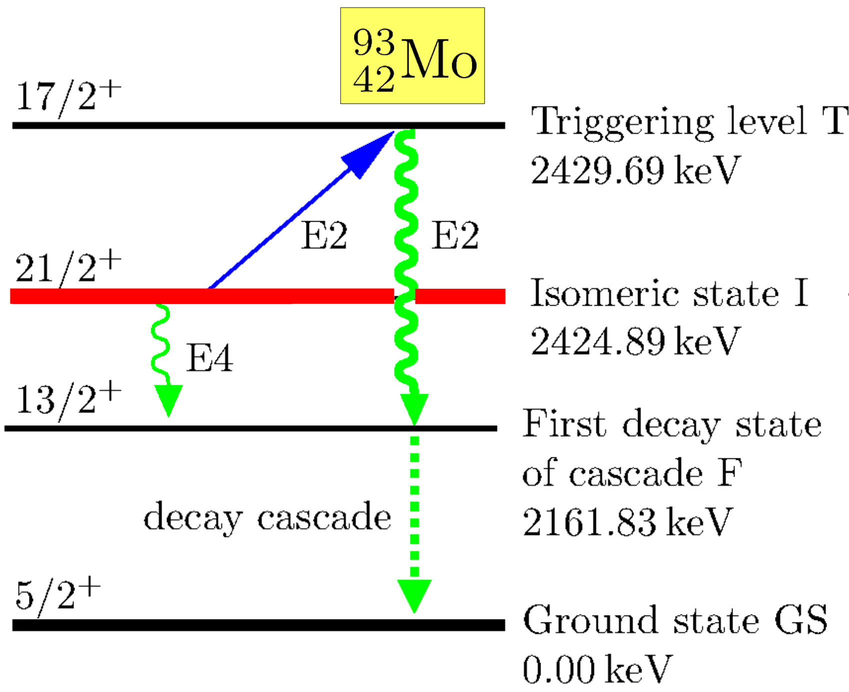
Relevant for:

dense astrophysical plasmas

depleting of isomers

Y. Litvinov's talk yesterday

Depletion of isomers



Nuclear isomers – metastable states
that store energy over long periods of time

$\tau \simeq 7$ hours

population or depletion of the isomer

NEEC 100 times more efficient than photons!

First claim of NEEC experimental observation
C. J. Chiara *et al.*, Nature 554, 216 (2018)

Energy/Mass ratio
(kWh/kg)

0.7

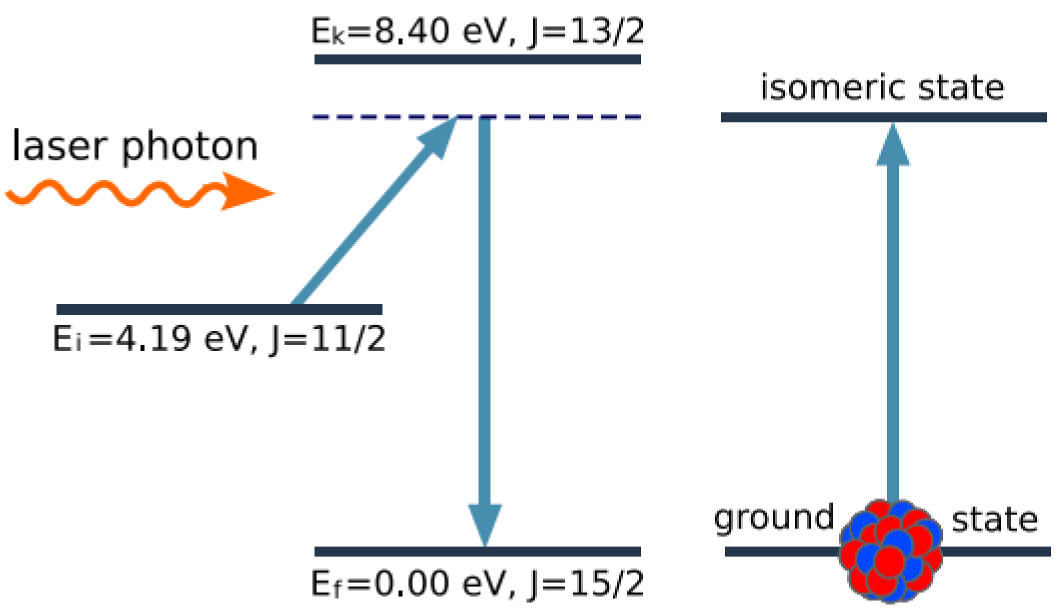
Molybdenum

660 000

NUCLEAR ENERGY
STORAGE

Example of EB in $^{229}Th^{35+}$

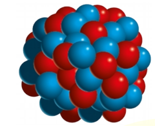
Use external laser (UV) photon to drive EB



In principle, similar schemes could work for higher x-ray or gamma-ray frequencies.

Particular case of Thorium: we don’t have good access to VUV photons, exploit EB.

Summarizing
Where can GF enter the picture?



- Nuclear coupling to atomic shells only for low-energy nuclear transitions < 100 - 200 keV.

  Y. Litvinov: "*Nuclear structure is not aiming at the highest GF energies!*"

  The higher the nuclear excitation, the less the atomic shell matters.

- For low-lying nuclear transitions ~ 10 keV, atomic coupling dominates photoexcitation

  Any concrete examples where we'd like to exploit this? Isomer depletion?

- EB is appealing for ^{229}Th, but for higher photon energies direct photoexcitation most efficient

  Nuclear photoexcitation with GF photons could work great without involving atomic shells.

Brainstorming

- GF photons (primary beam and laser excitation) for atomic shell excitation
  + atomic coupling to the nucleus   Hyperfine coupling – talk by Andrey

- GF photons (primary beam and laser excitation) for nuclear excitation
  + atomic shell controls nuclear decay   Any cases of interest?

- Use GF as primary beam of highly charged ions for NEEC?
  NEEC would require electron target; use GF photons for driving atomic shell?

- Use GF secondary photon beam for nuclear excitation
  + atomic shell controls nuclear decay   Requires highly charged ions as target