Nucleosynthesis in neutron star mergers

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Course on Neutron Star Physics

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Helmholtz Forschungsakademie Hessen für FAIR

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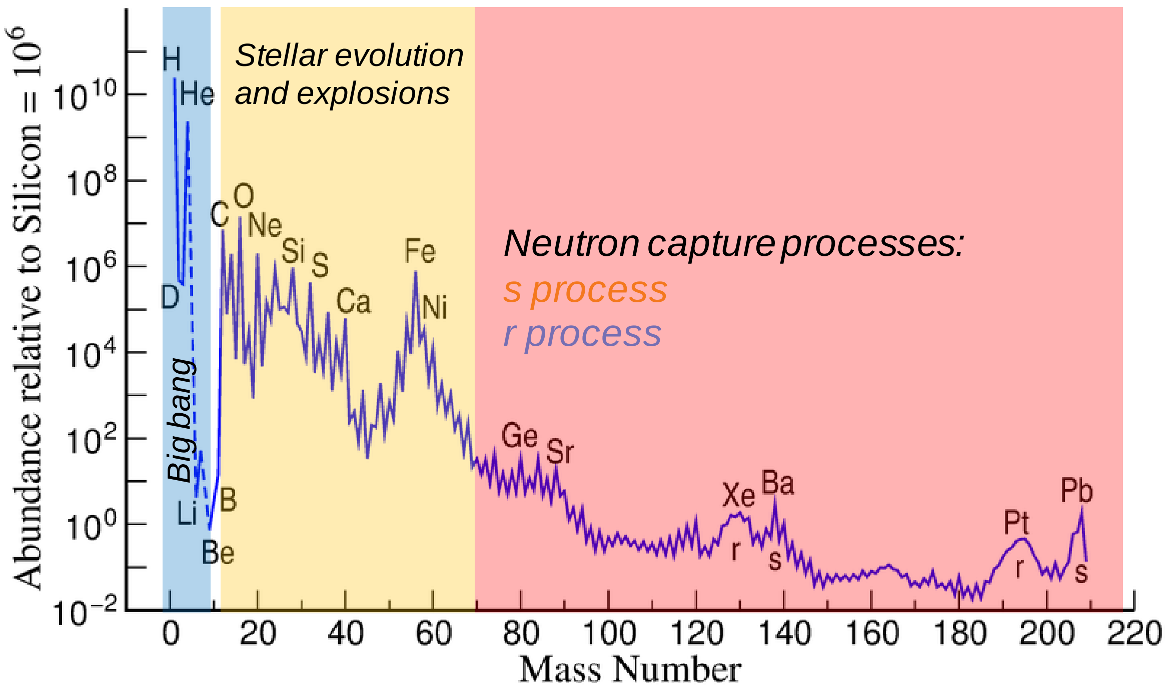
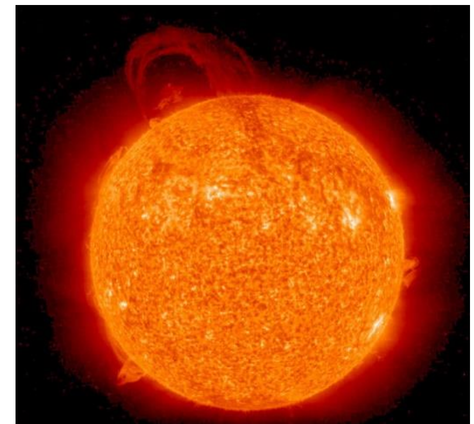
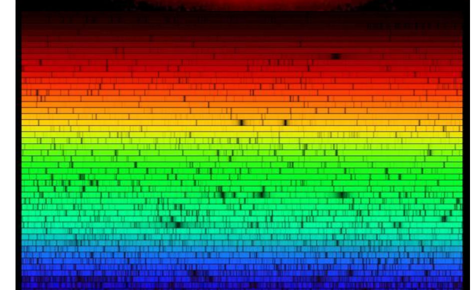
Solar system abundances

Solar photosphere and meteorites:
chemical signature of gas cloud where the Sun formed



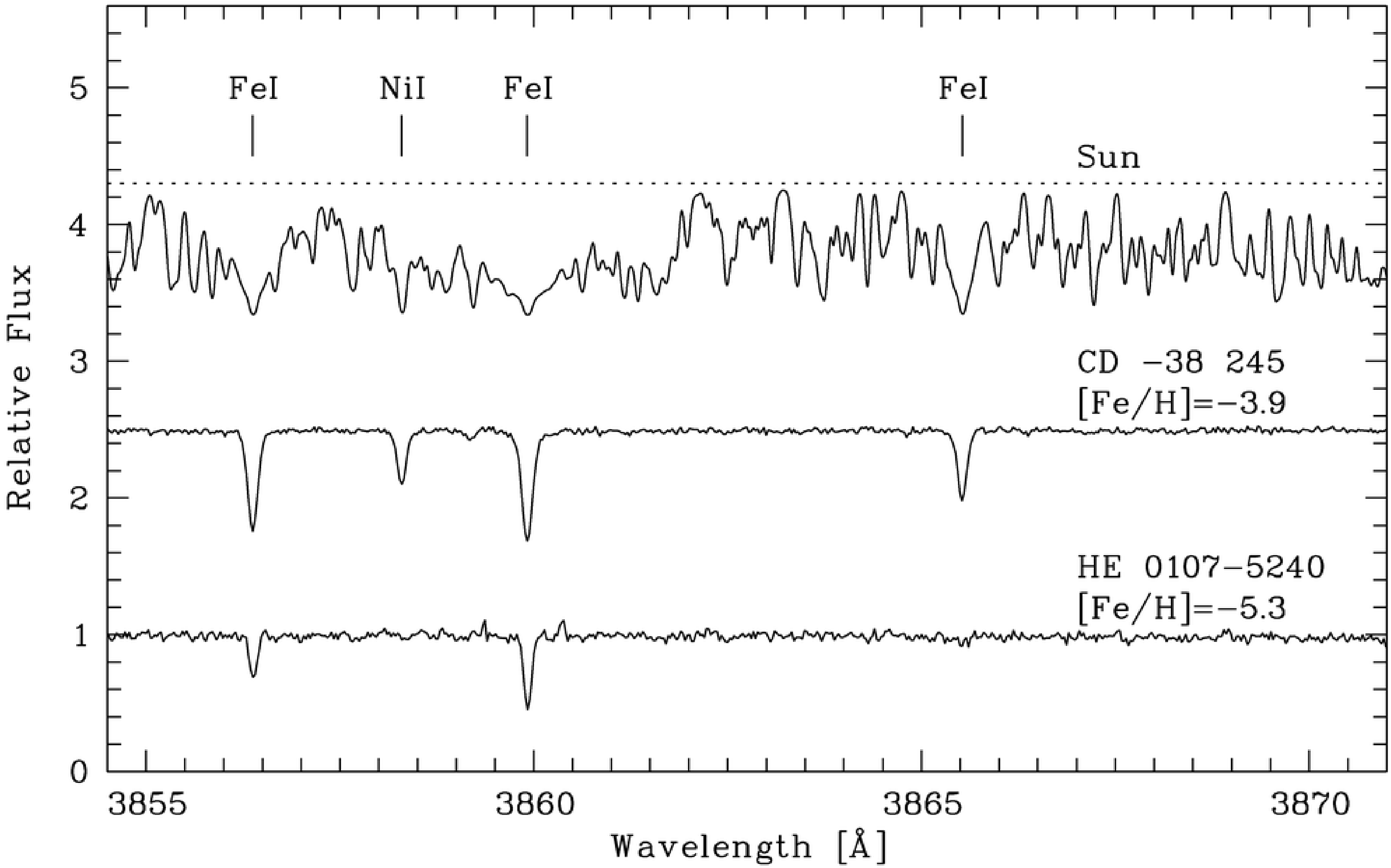




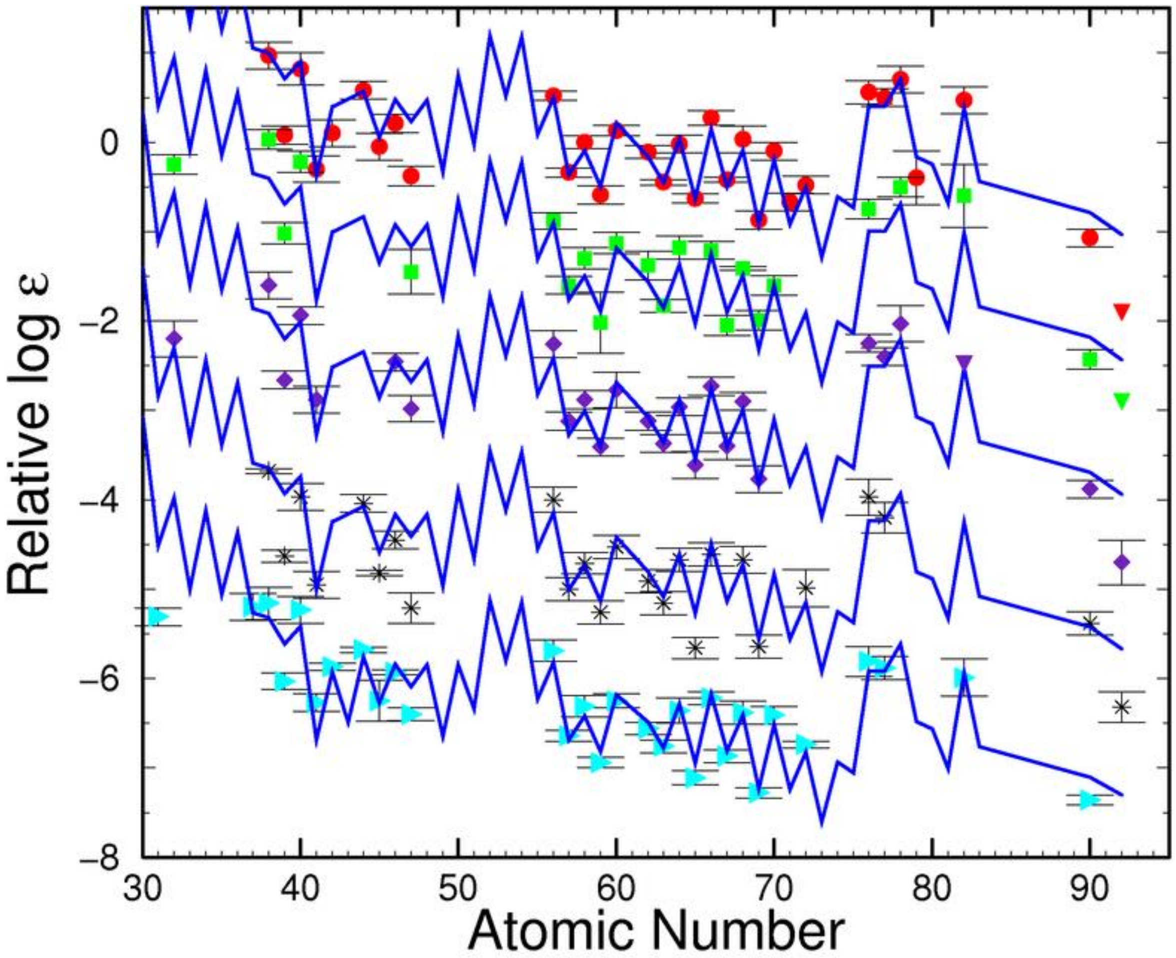
Signatures of nuclear structure and nuclear stability
Contributions of different nucleosynthesis processes

Observing other stars

. Age of a star is correlated with the content of Iron.



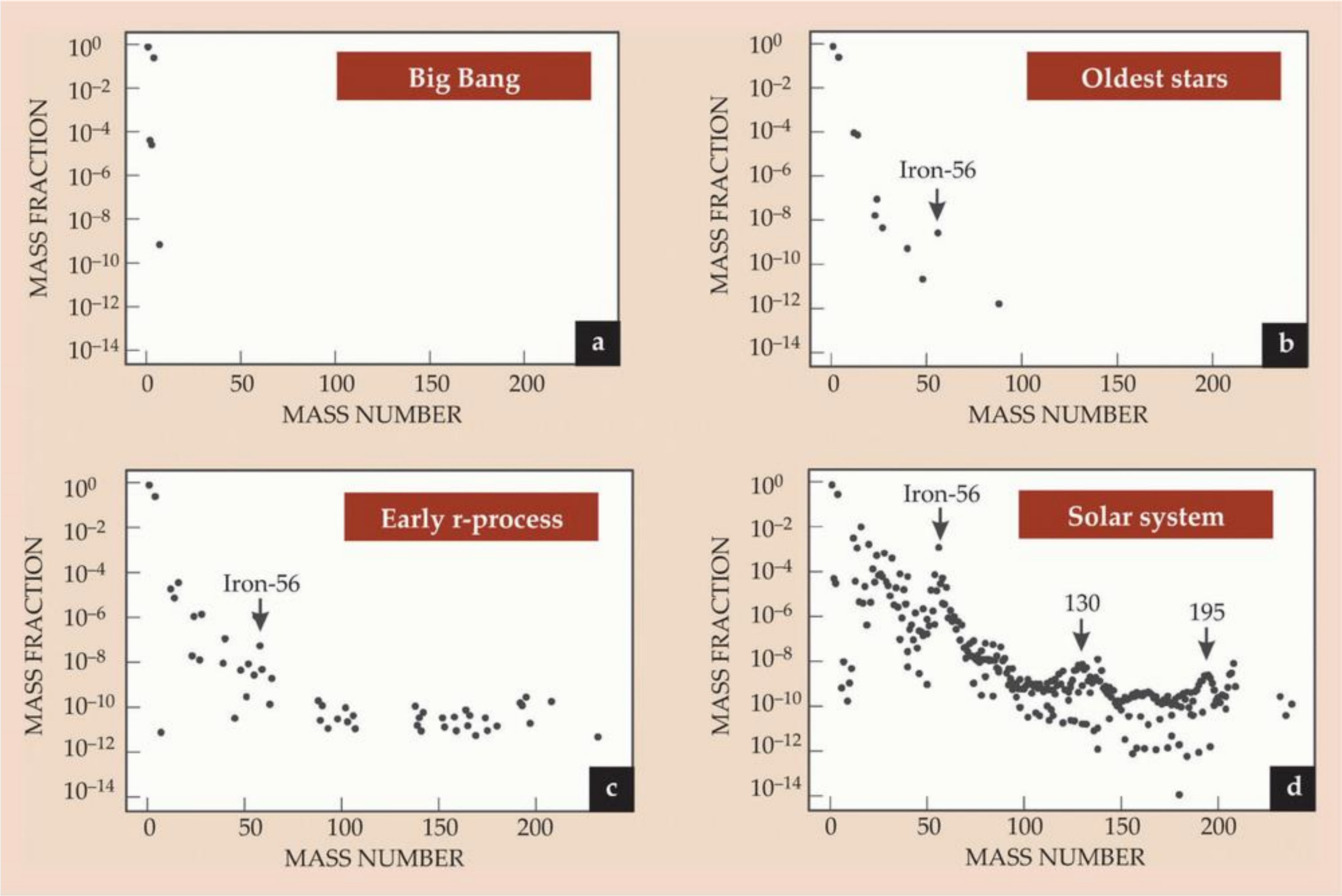
Metal-poor stars observations



- Observations indicate that r process operates from early Galactic history in rare (high yield) events

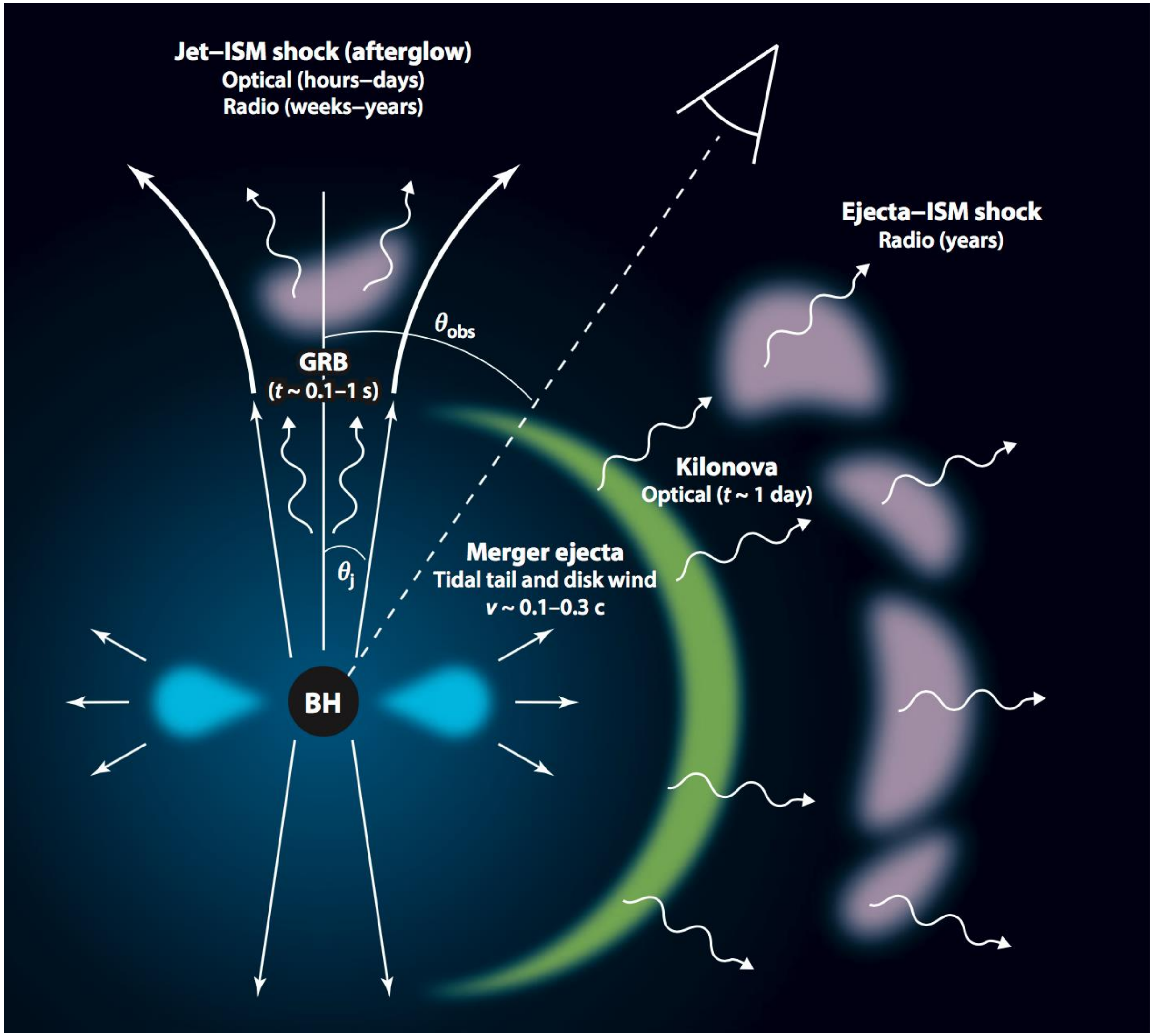
Composition evolves with time

Composition depends on the time the star formed



Kilonova: signature of the r-process

Line of view GW170817



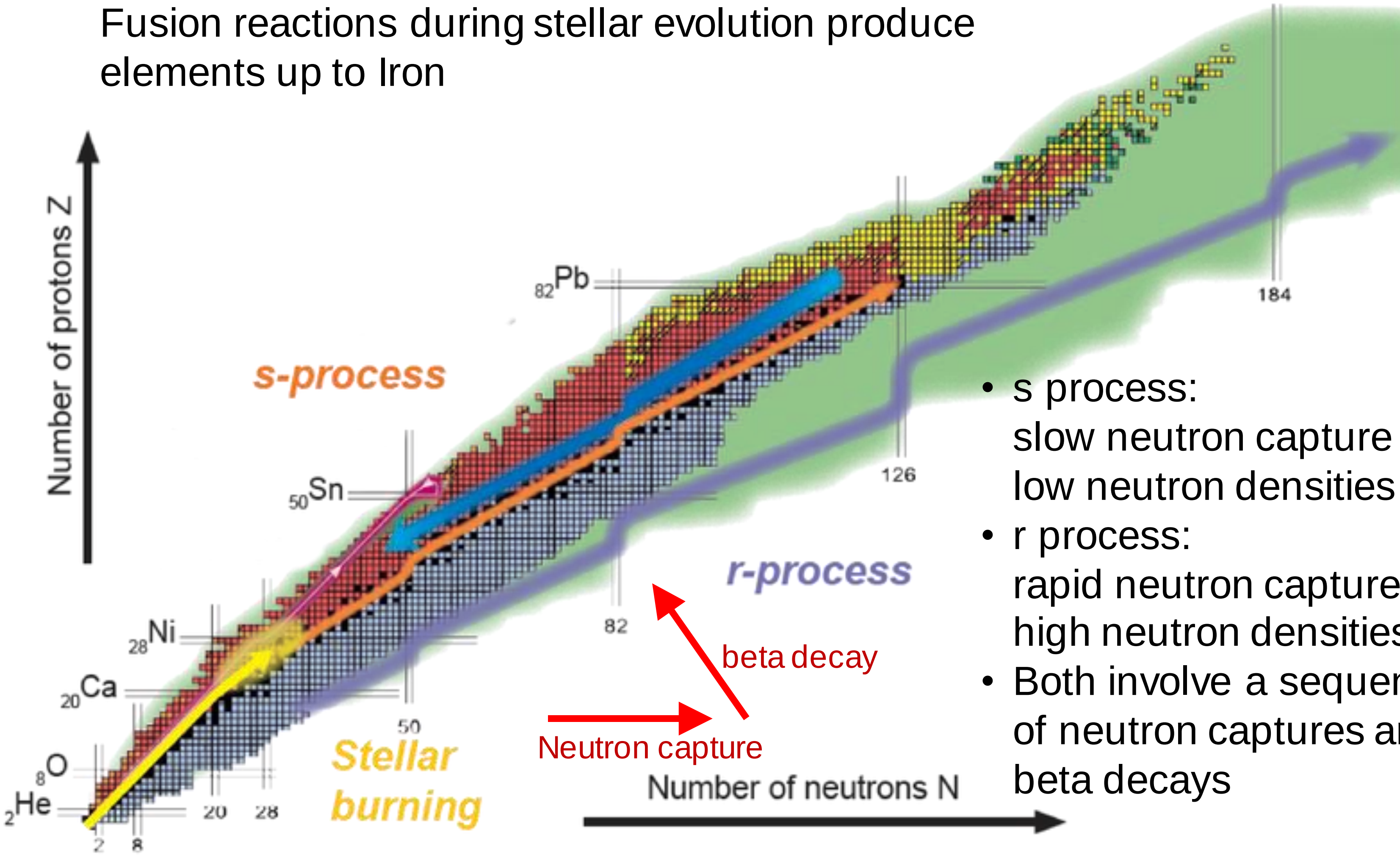
Metzger & Berger 2012

Kilonova: An electromagnetic transient due to long term radioactive decay of r-process nuclei

- Electromagnetic counterpart to Gravitational Waves
- Diagnostics physical processes at work during merger
- Direct probe of the formation r-process nuclei

Nucleosynthesis processes

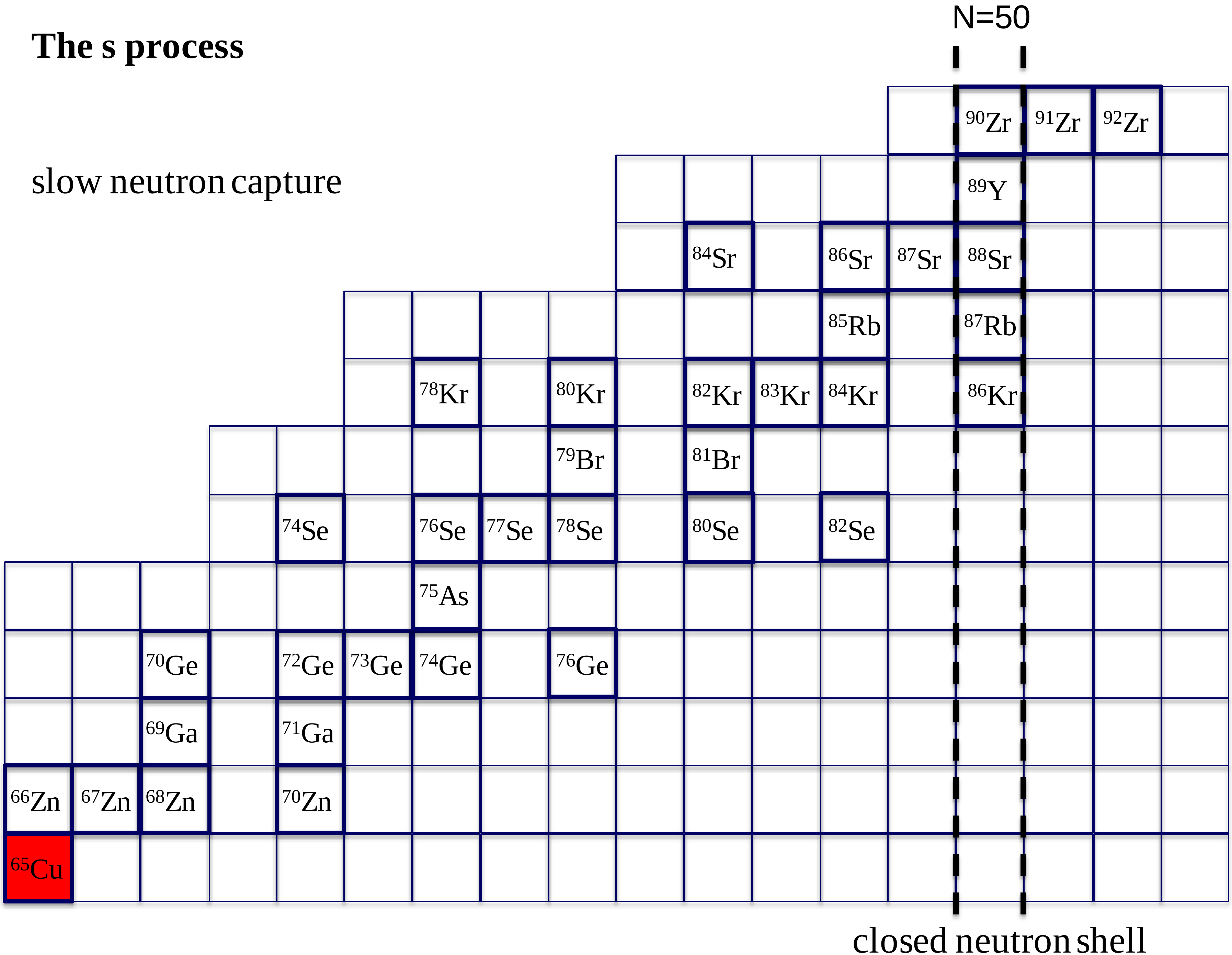
Fusion reactions during stellar evolution produce elements up to Iron



- s process:
  slow neutron capture
  low neutron densities
- r process:
  rapid neutron capture
  high neutron densities
- Both involve a sequence of neutron captures and beta decays

The s process

slow neutron capture



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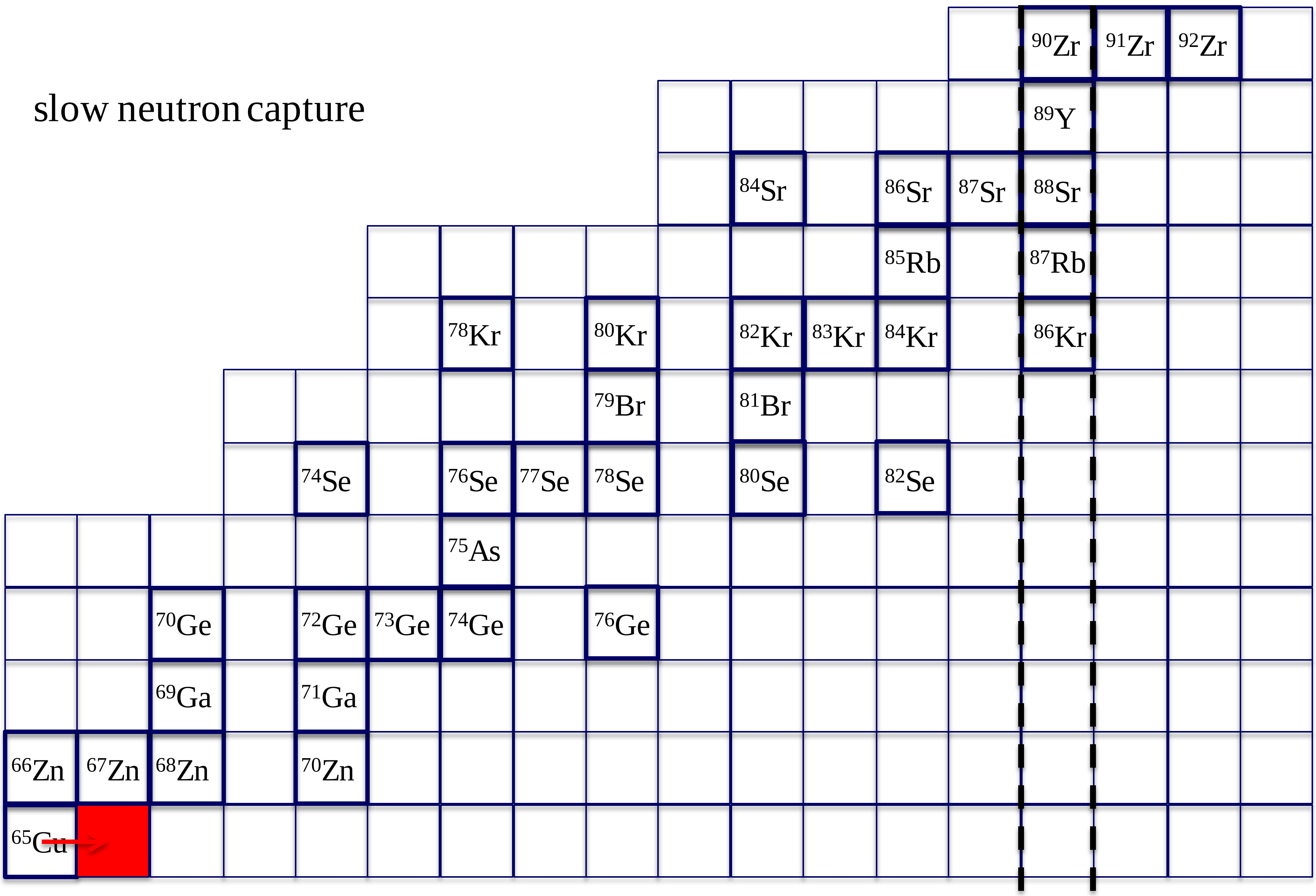

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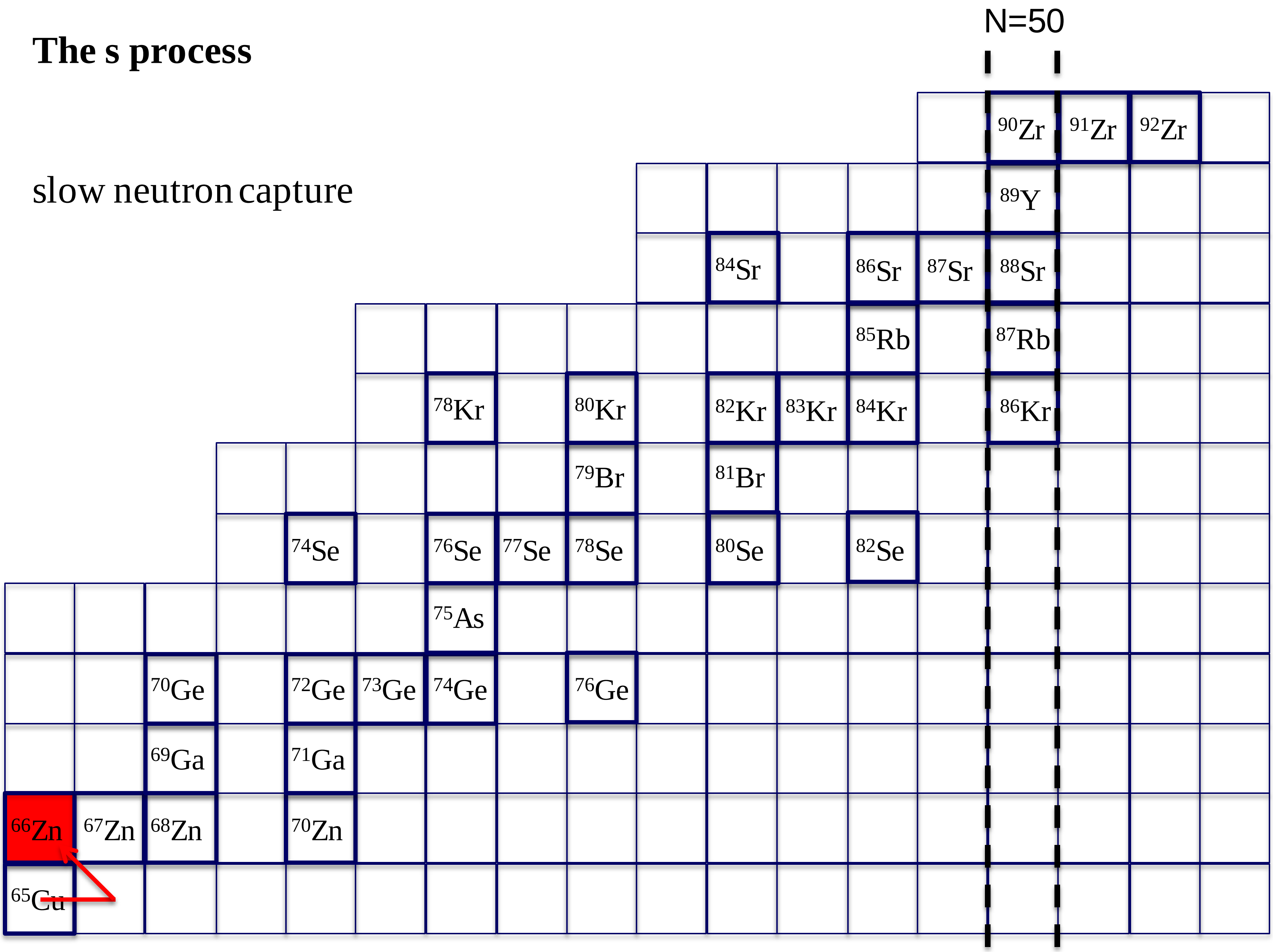

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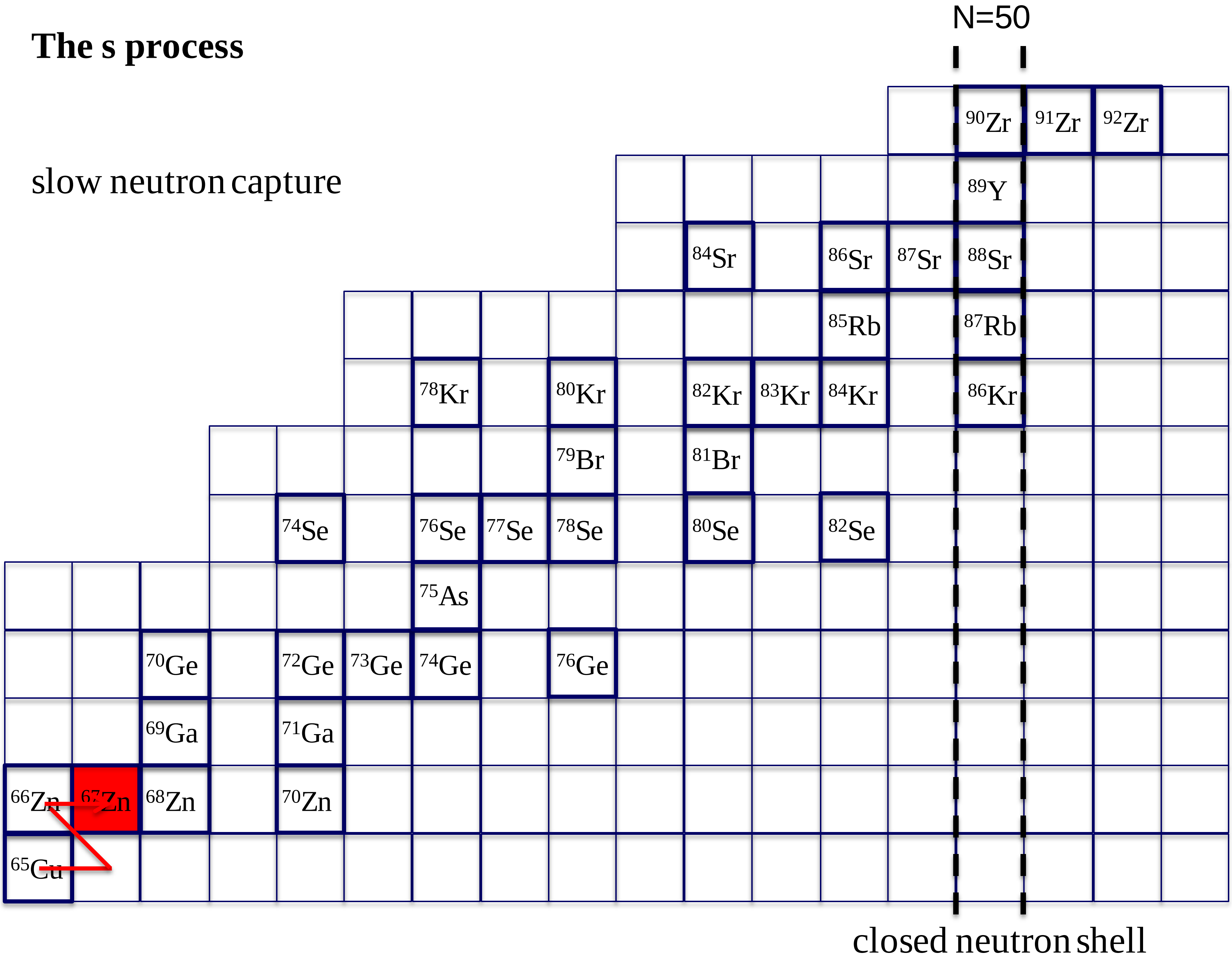

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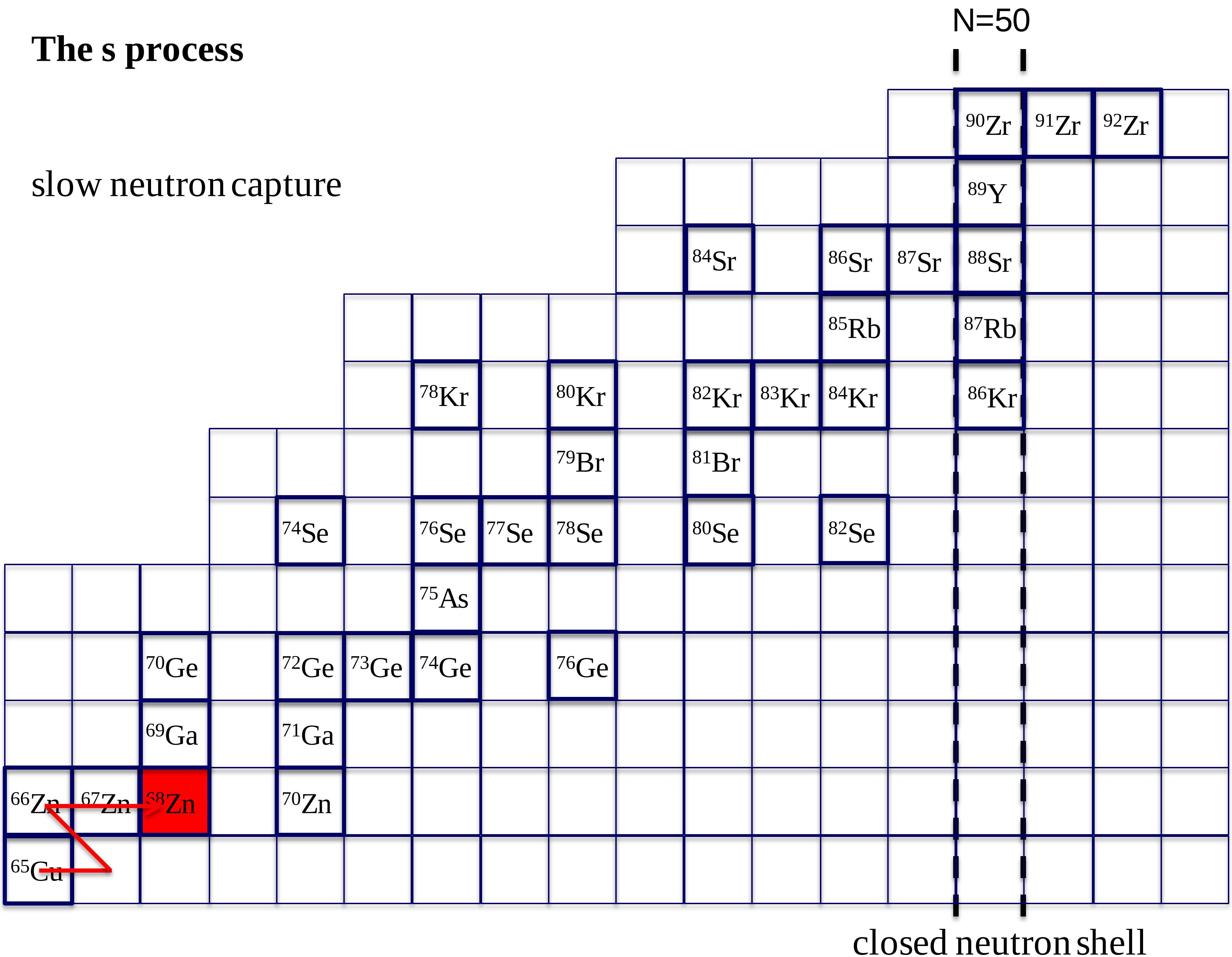

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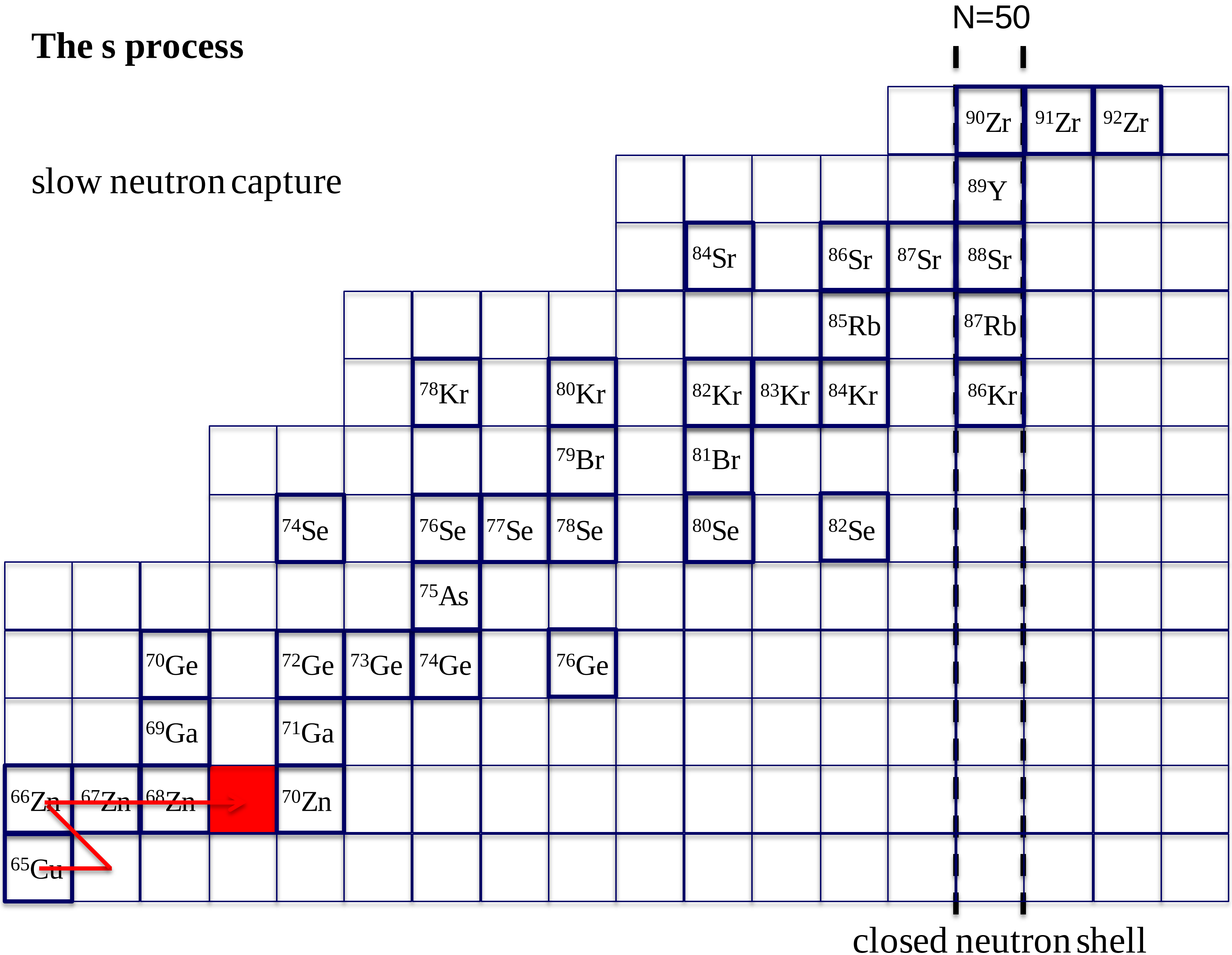

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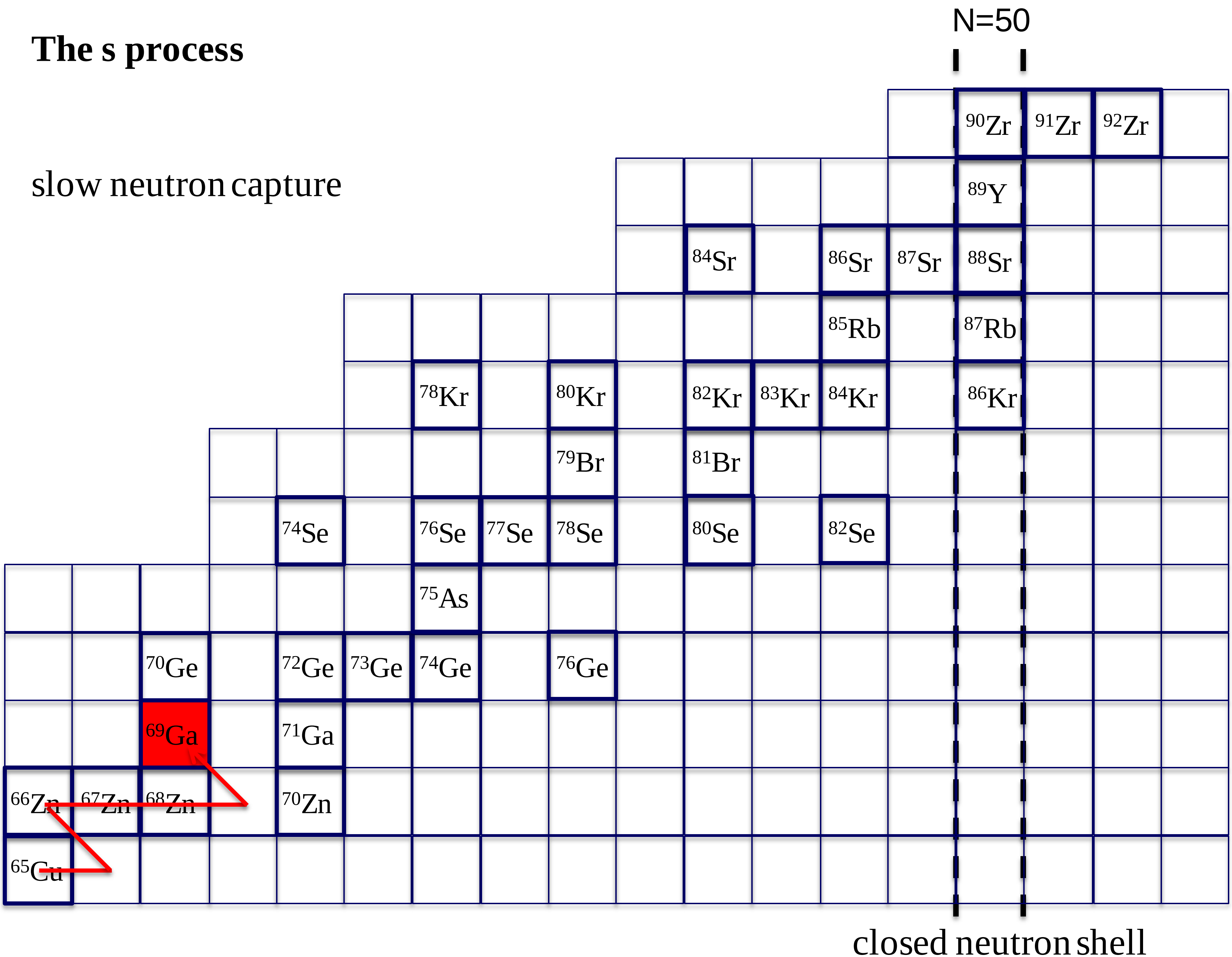

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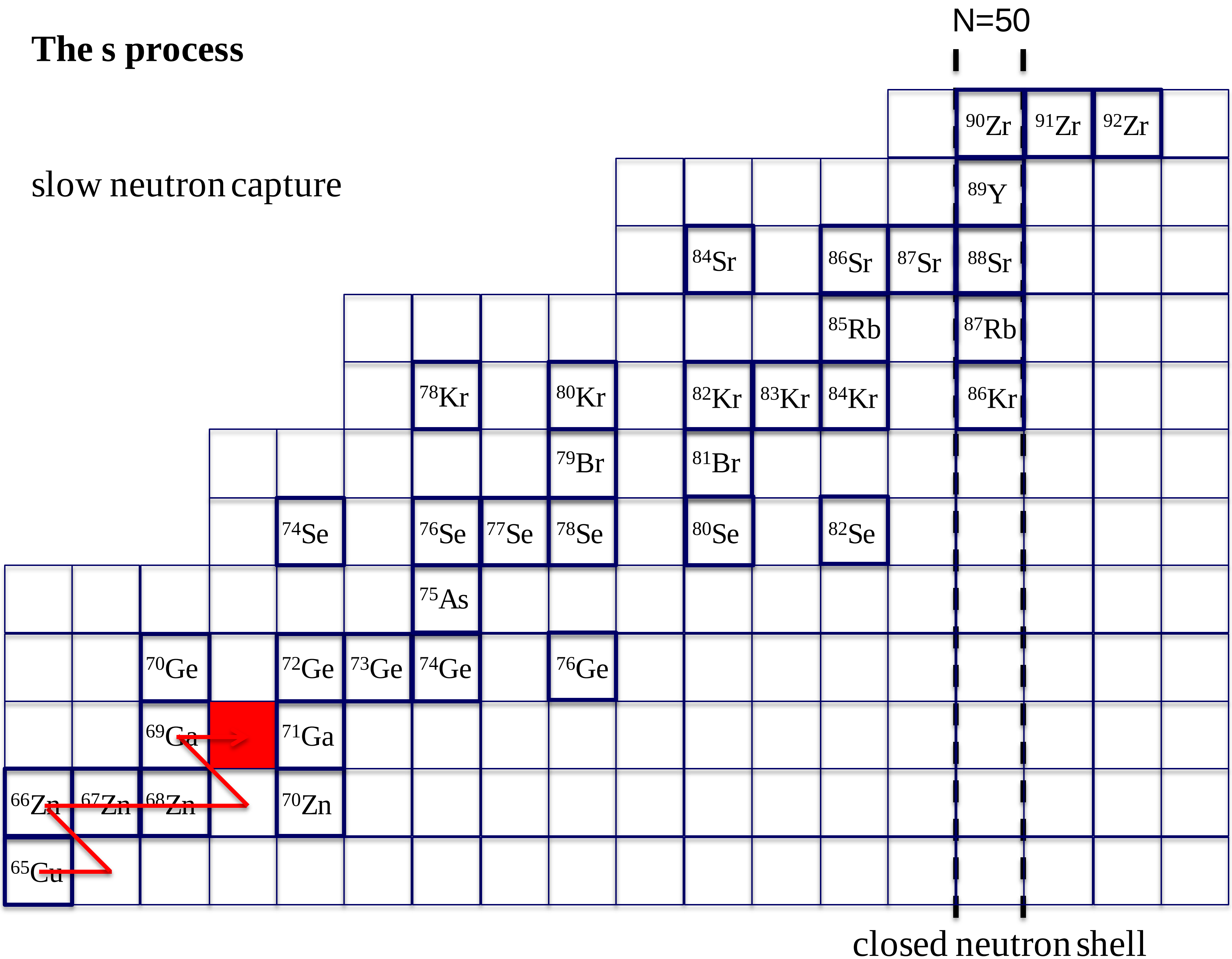

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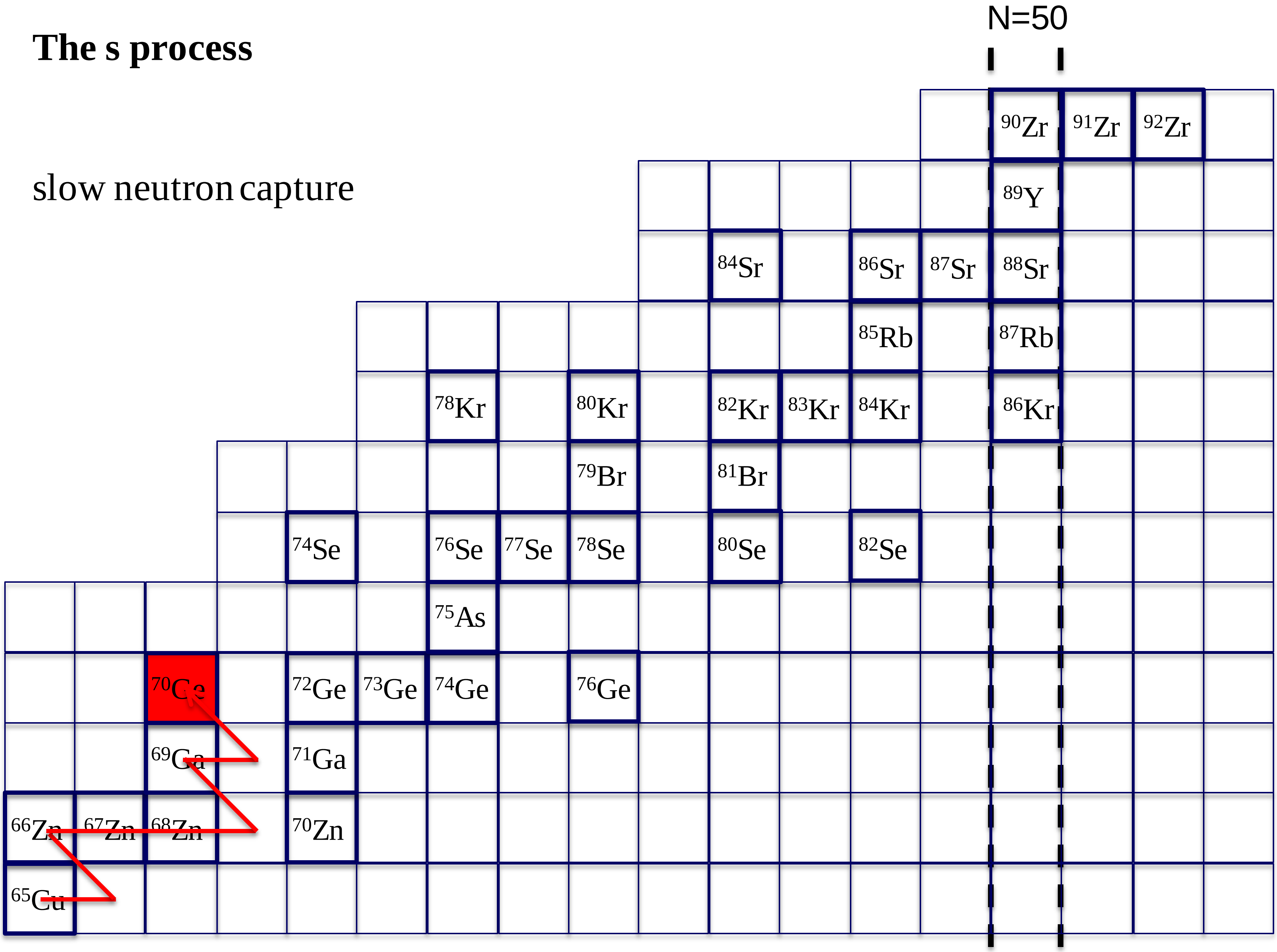

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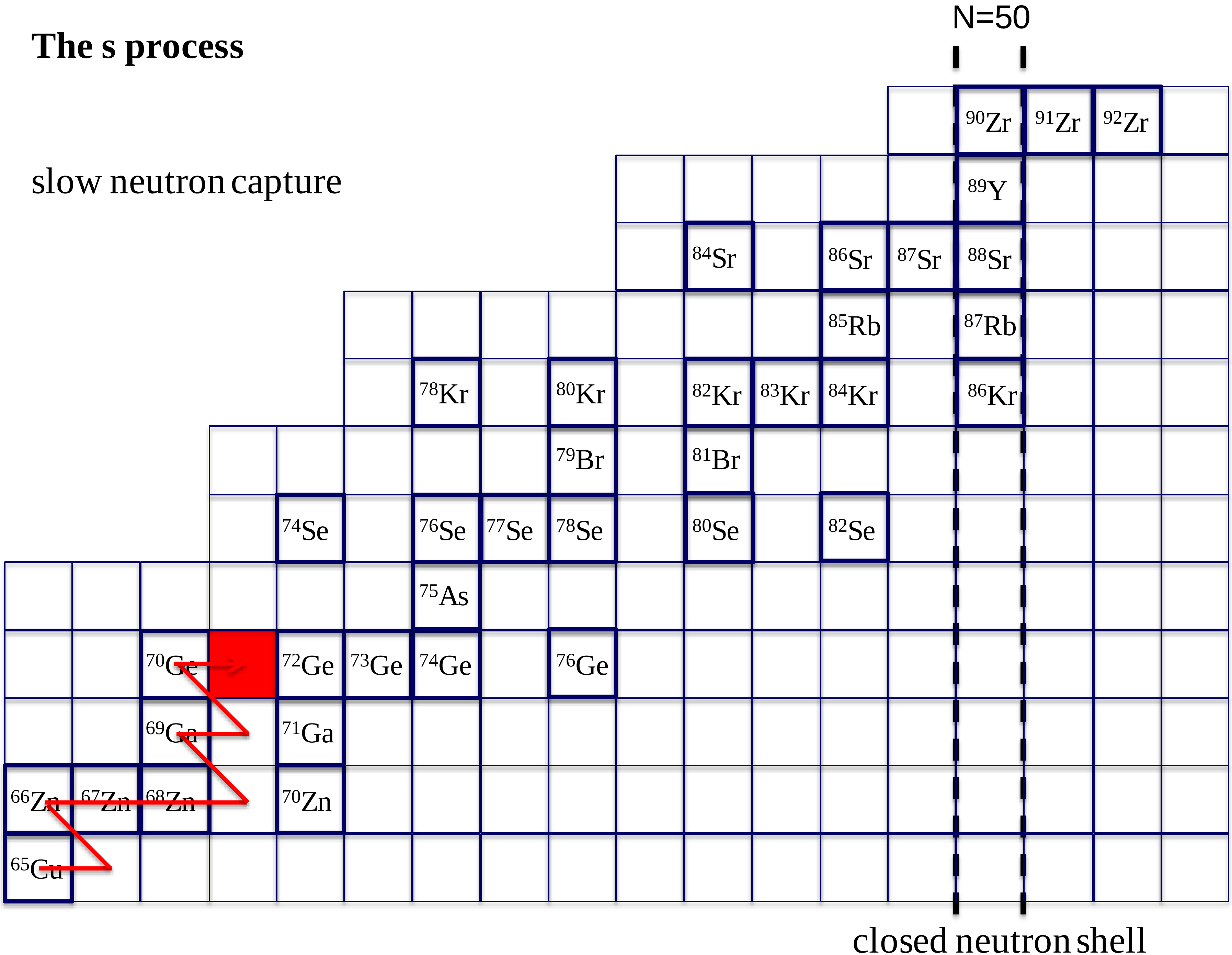

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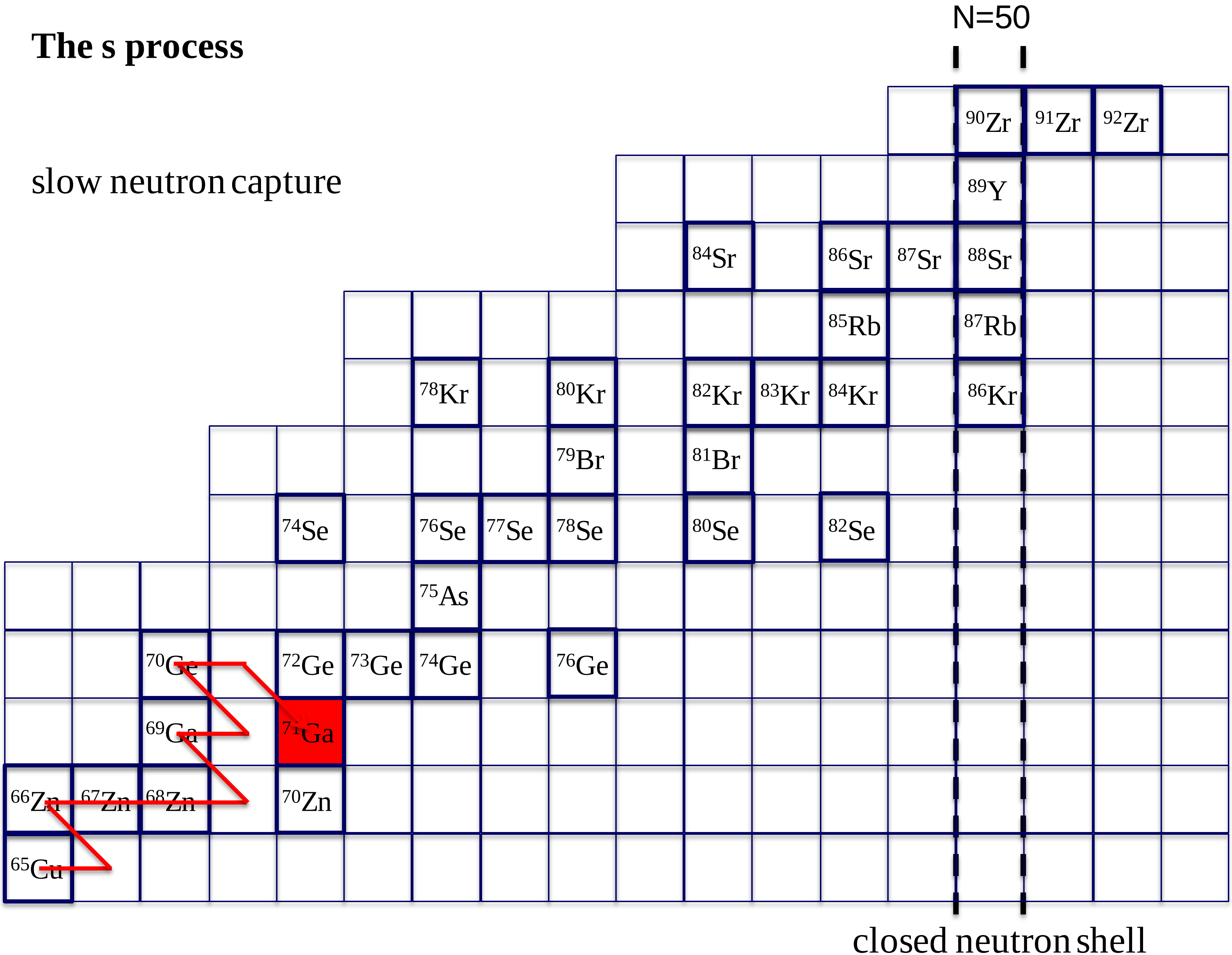

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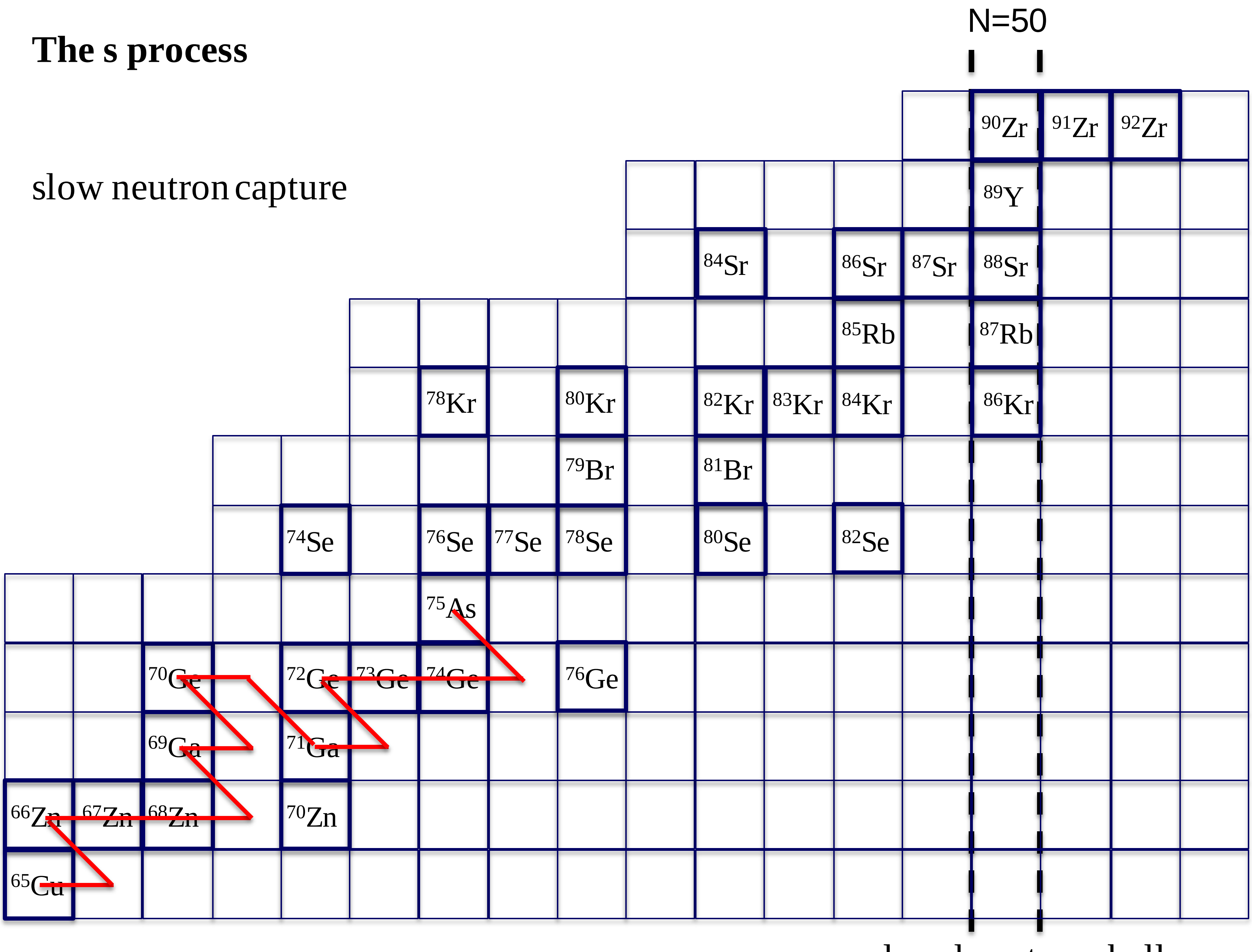

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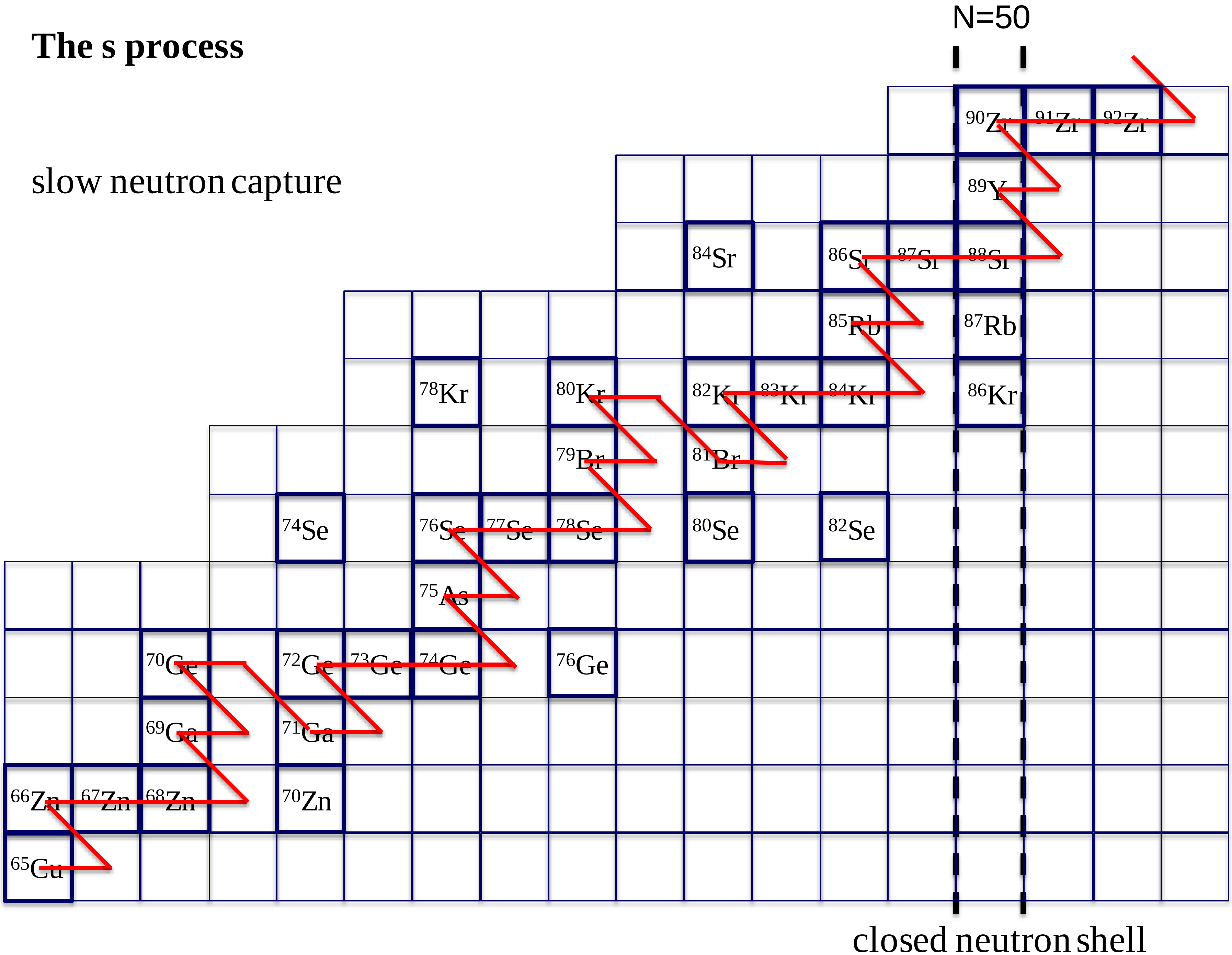

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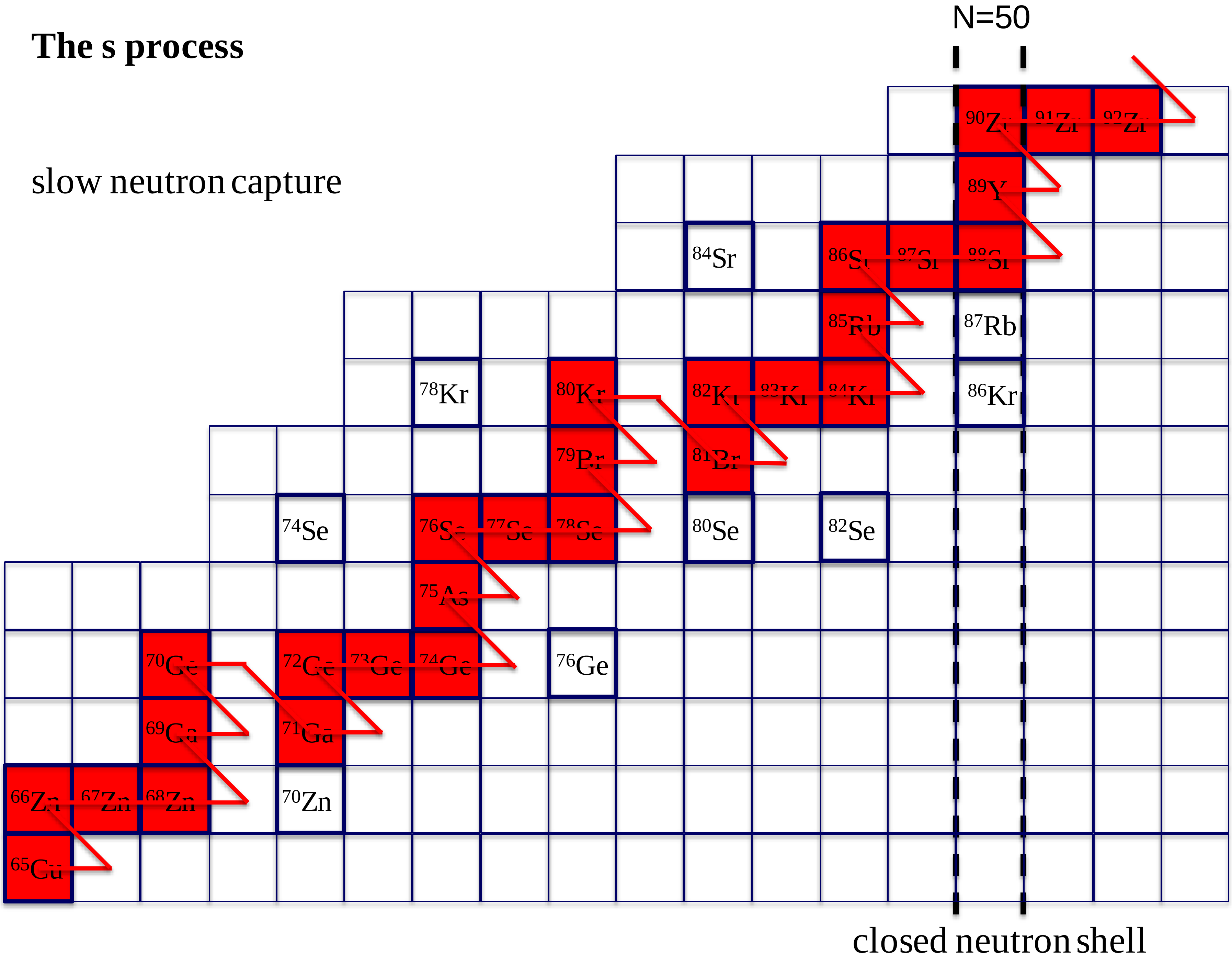
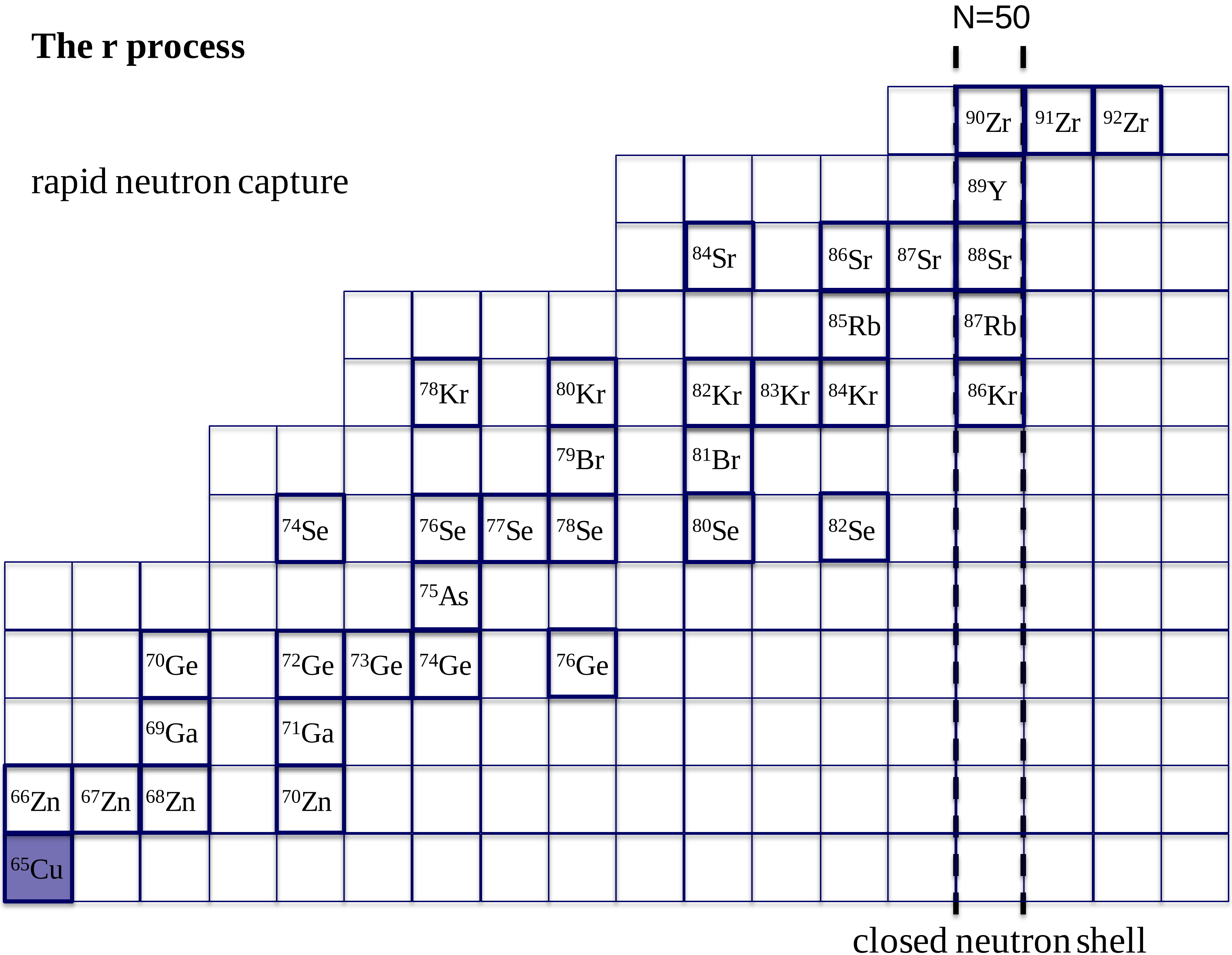


The r process

rapid neutron capture



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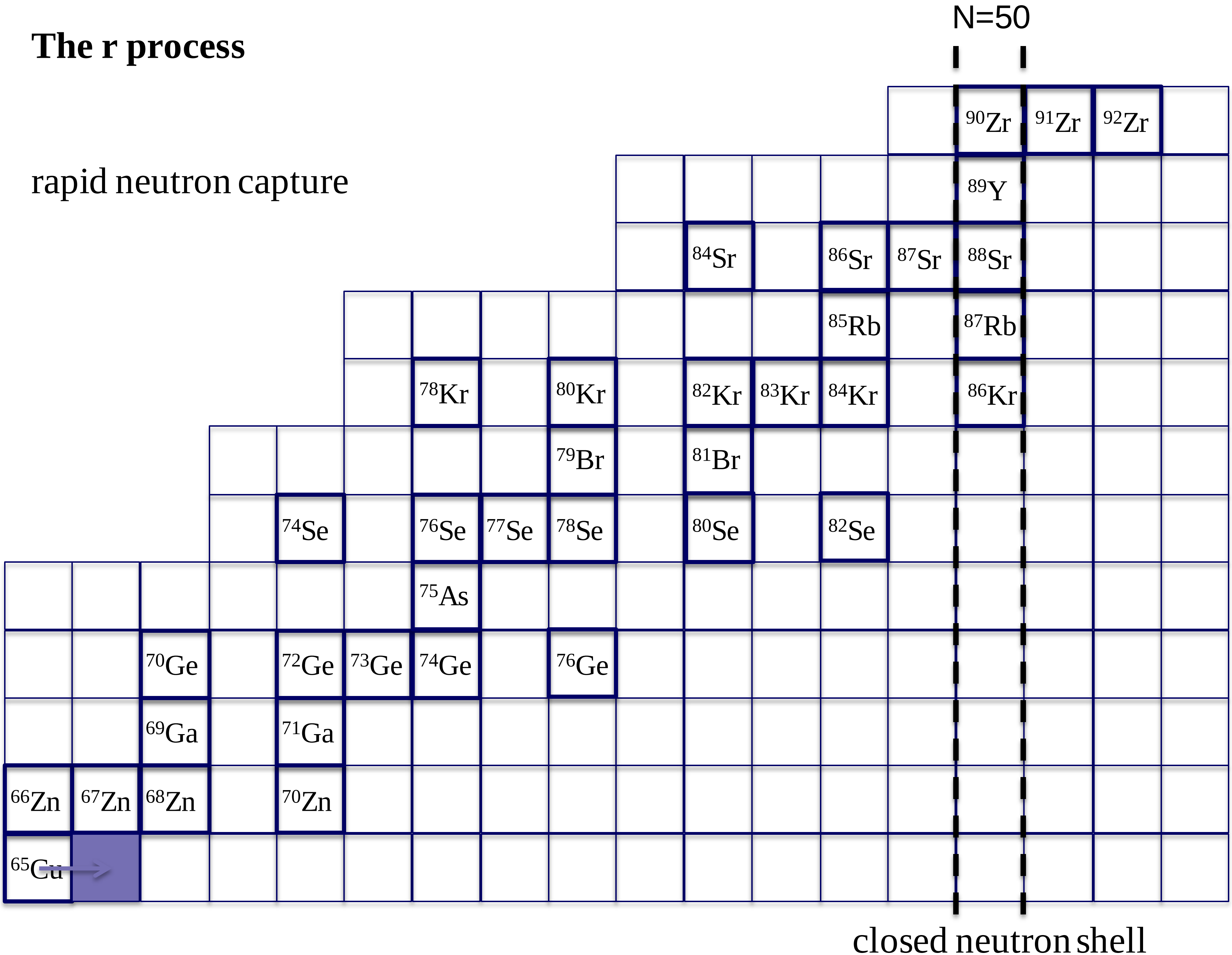

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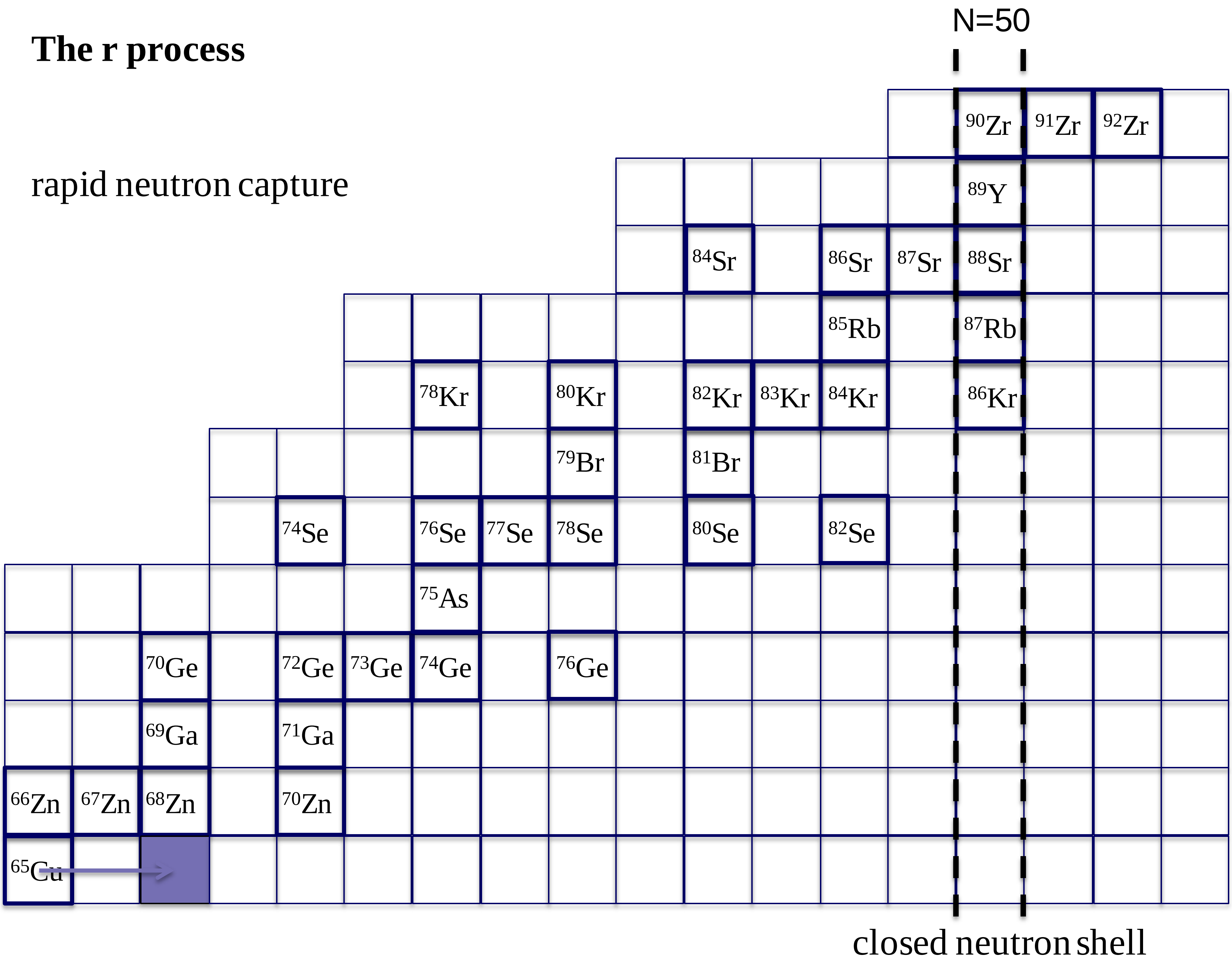

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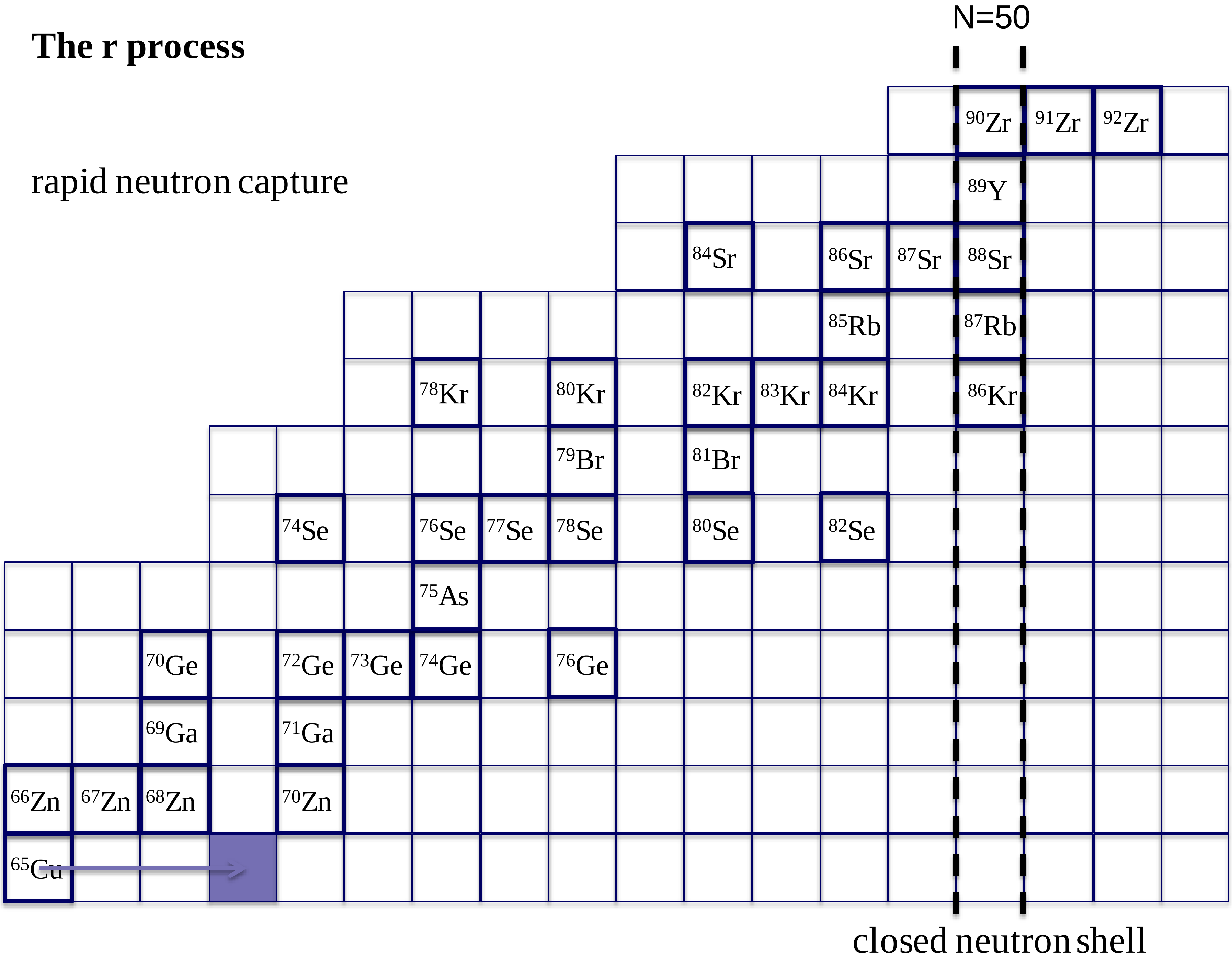

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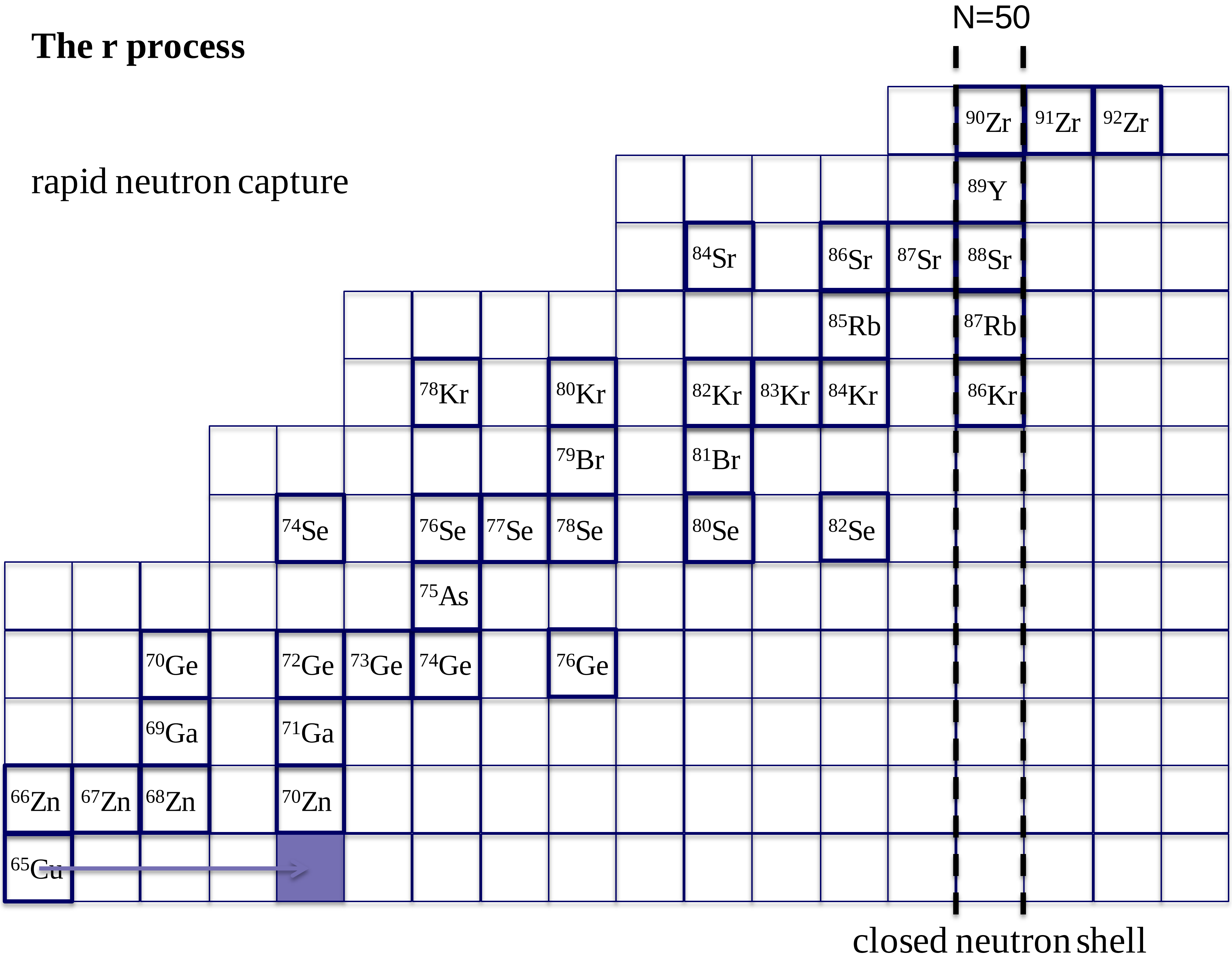

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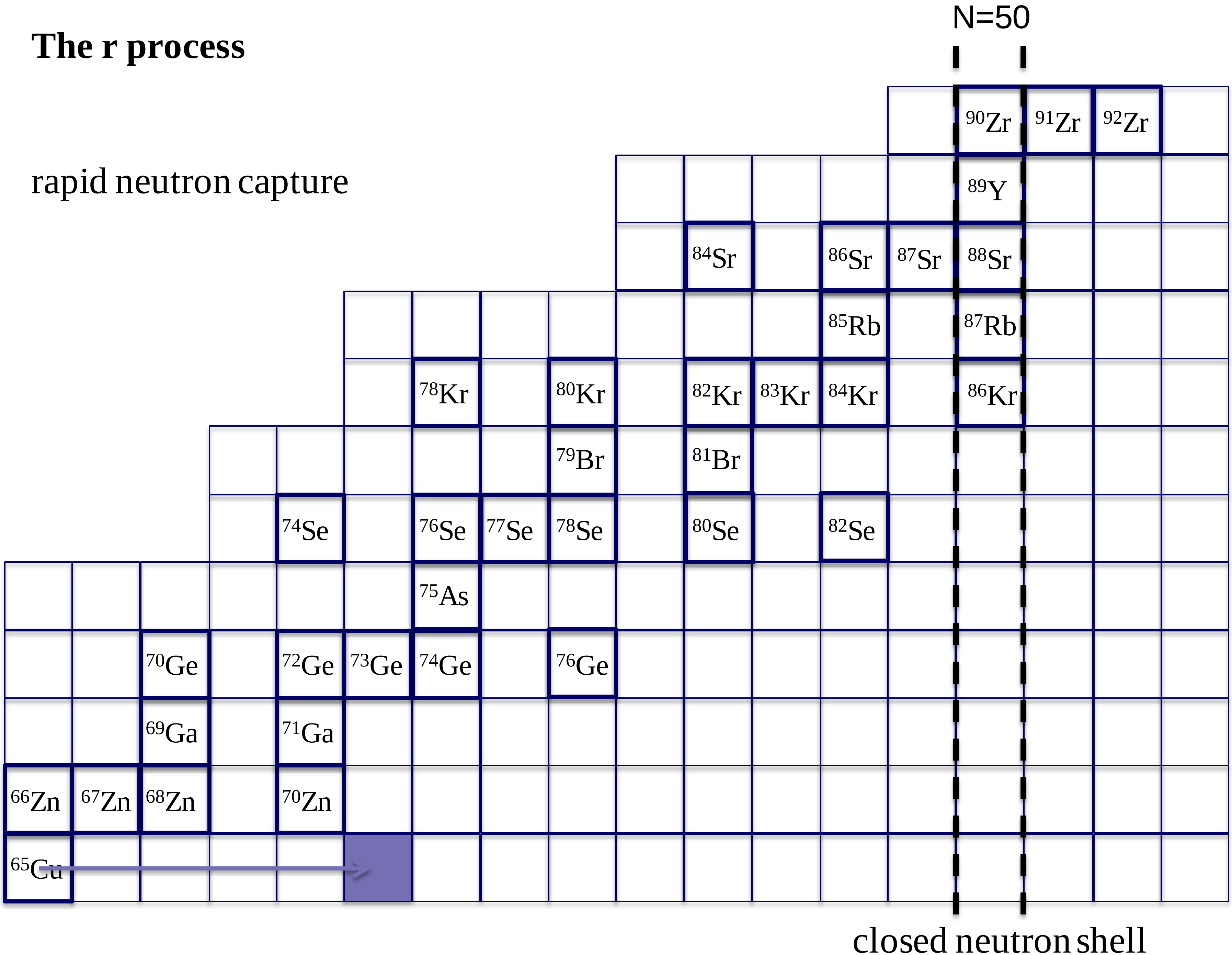

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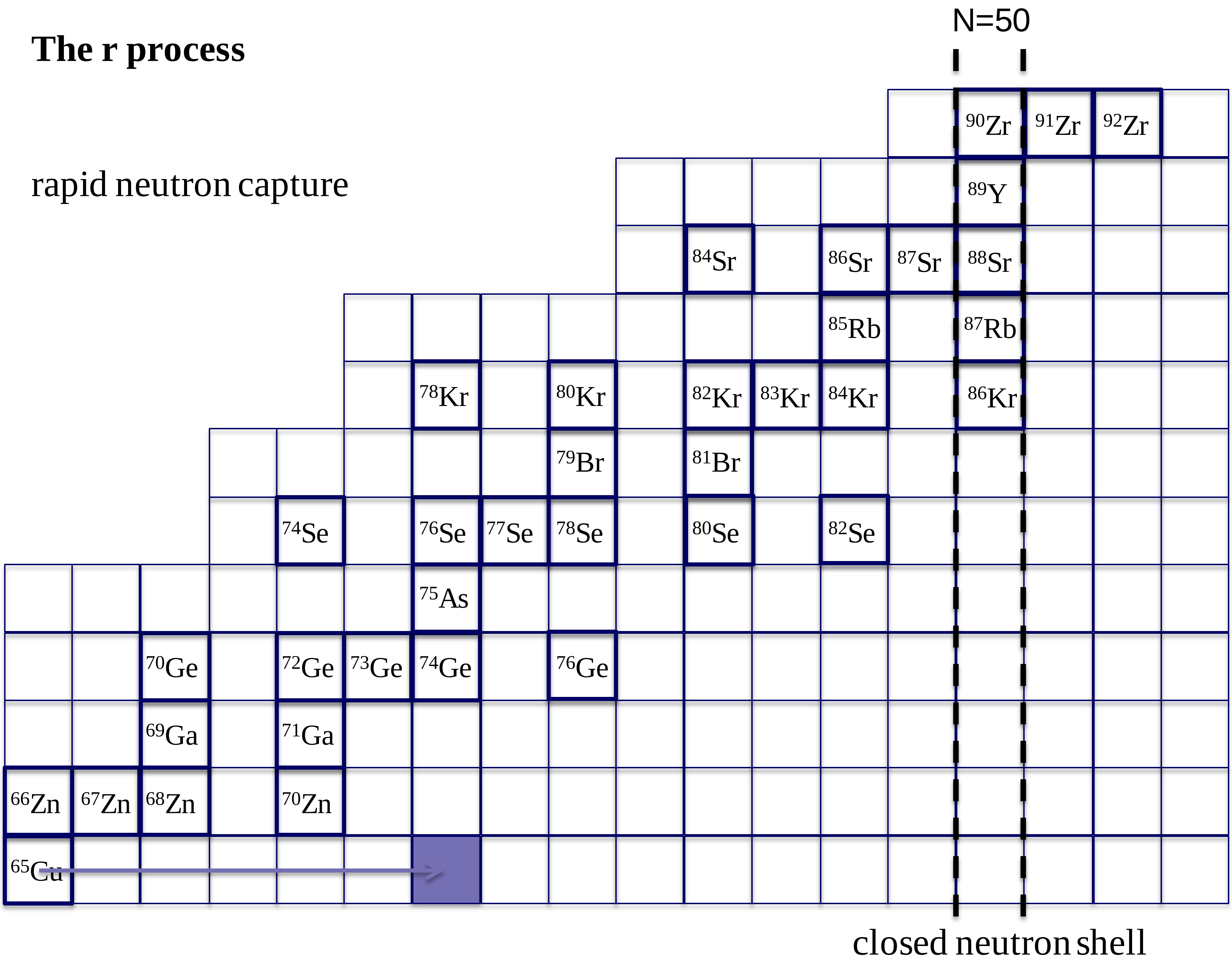

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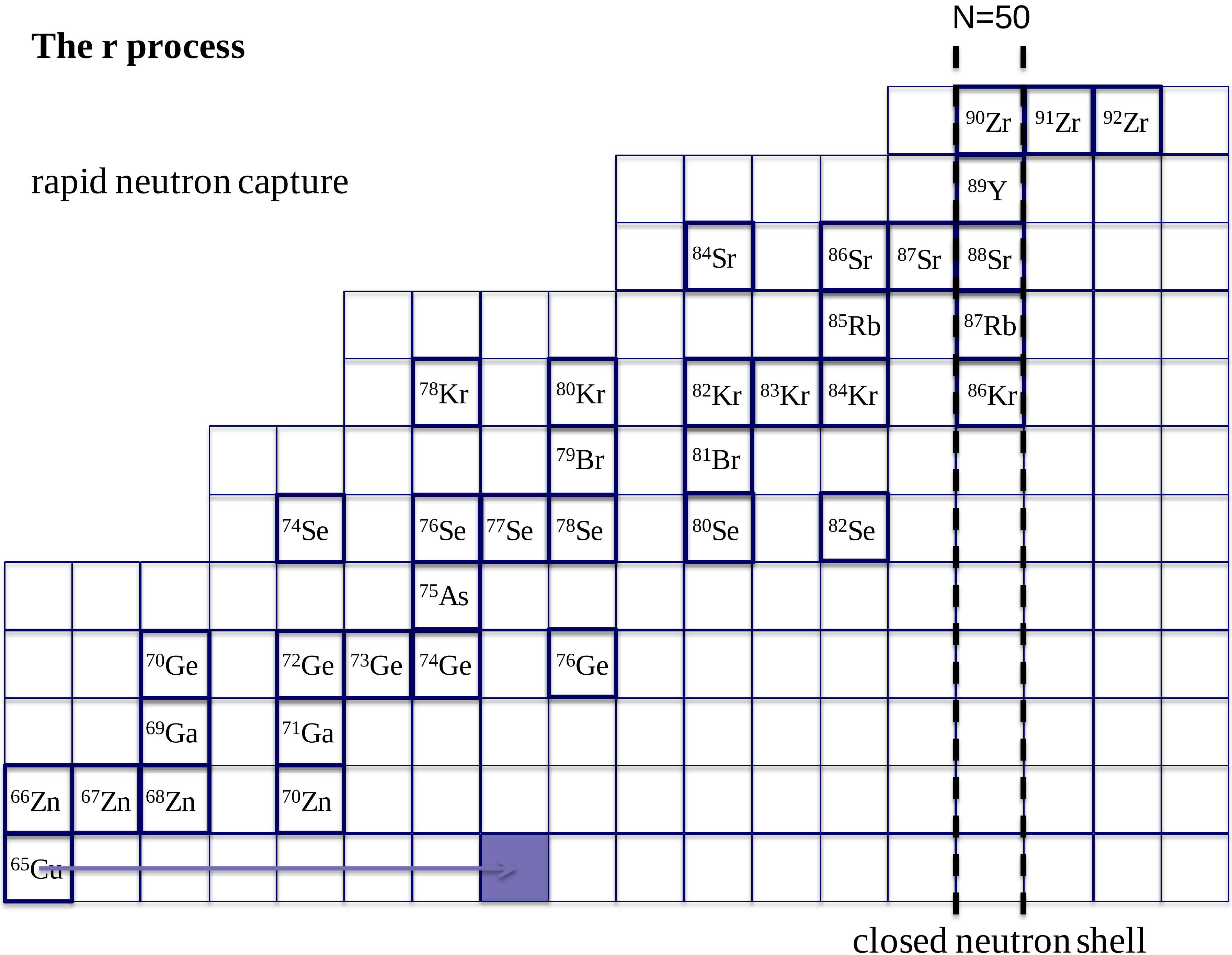

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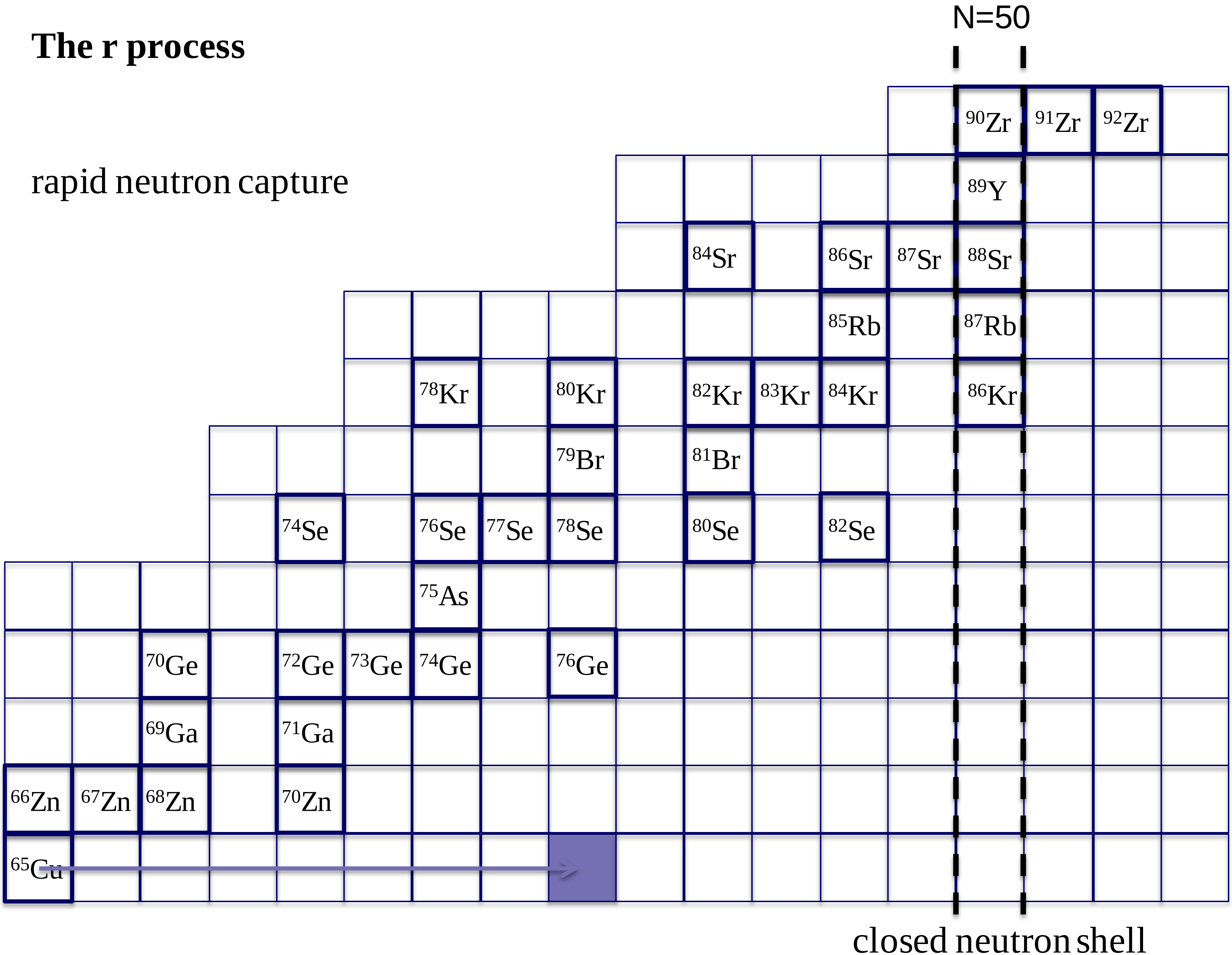

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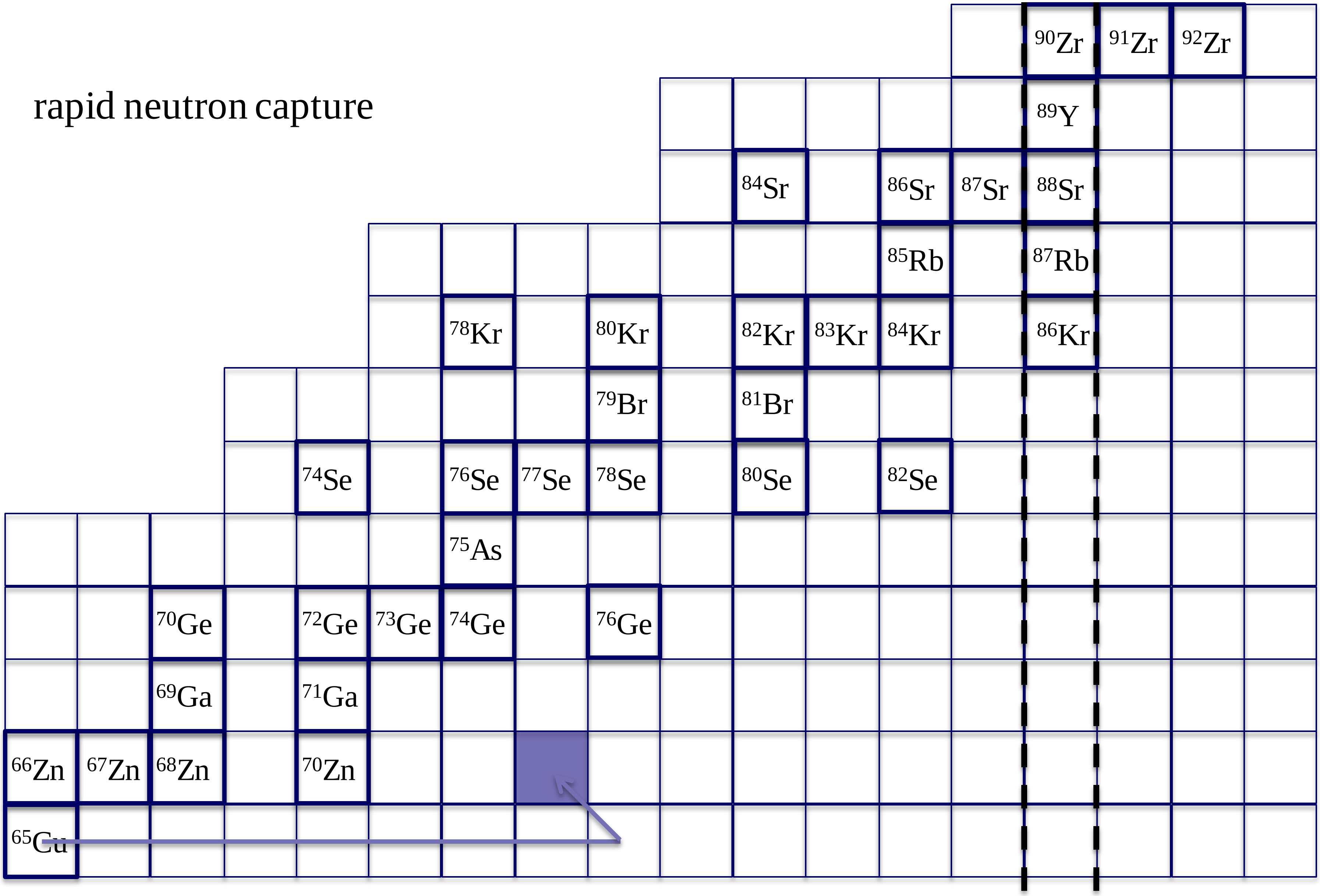

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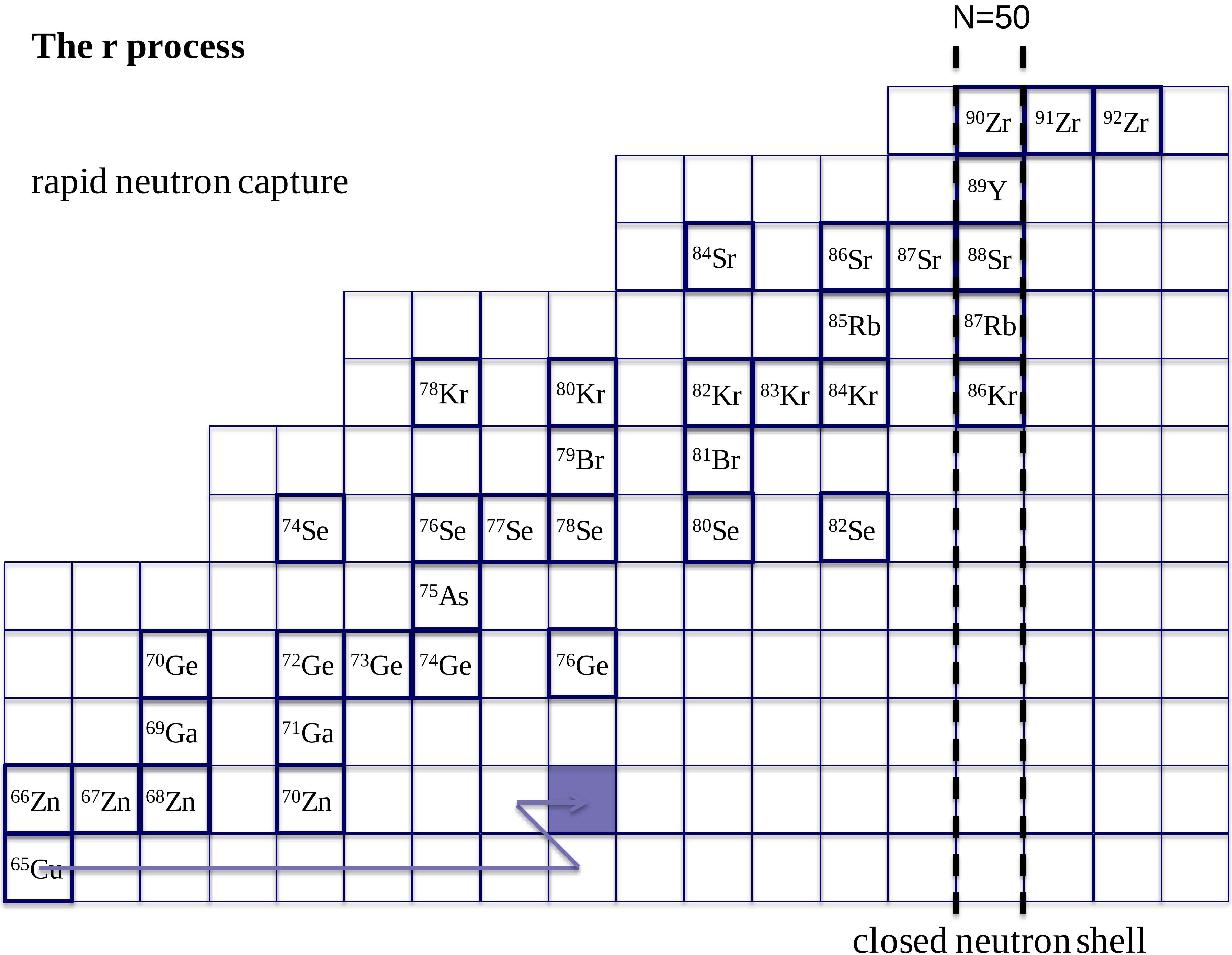

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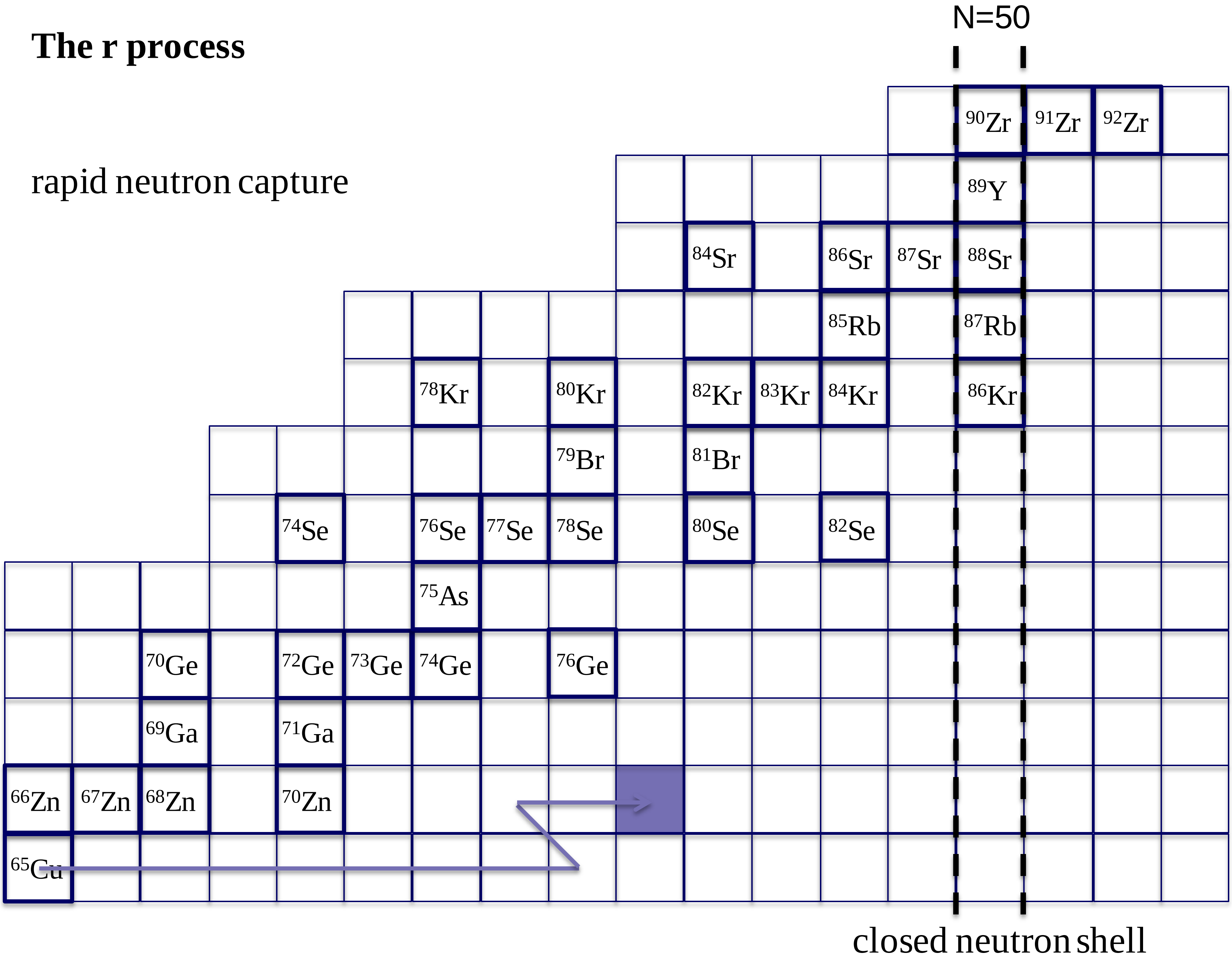

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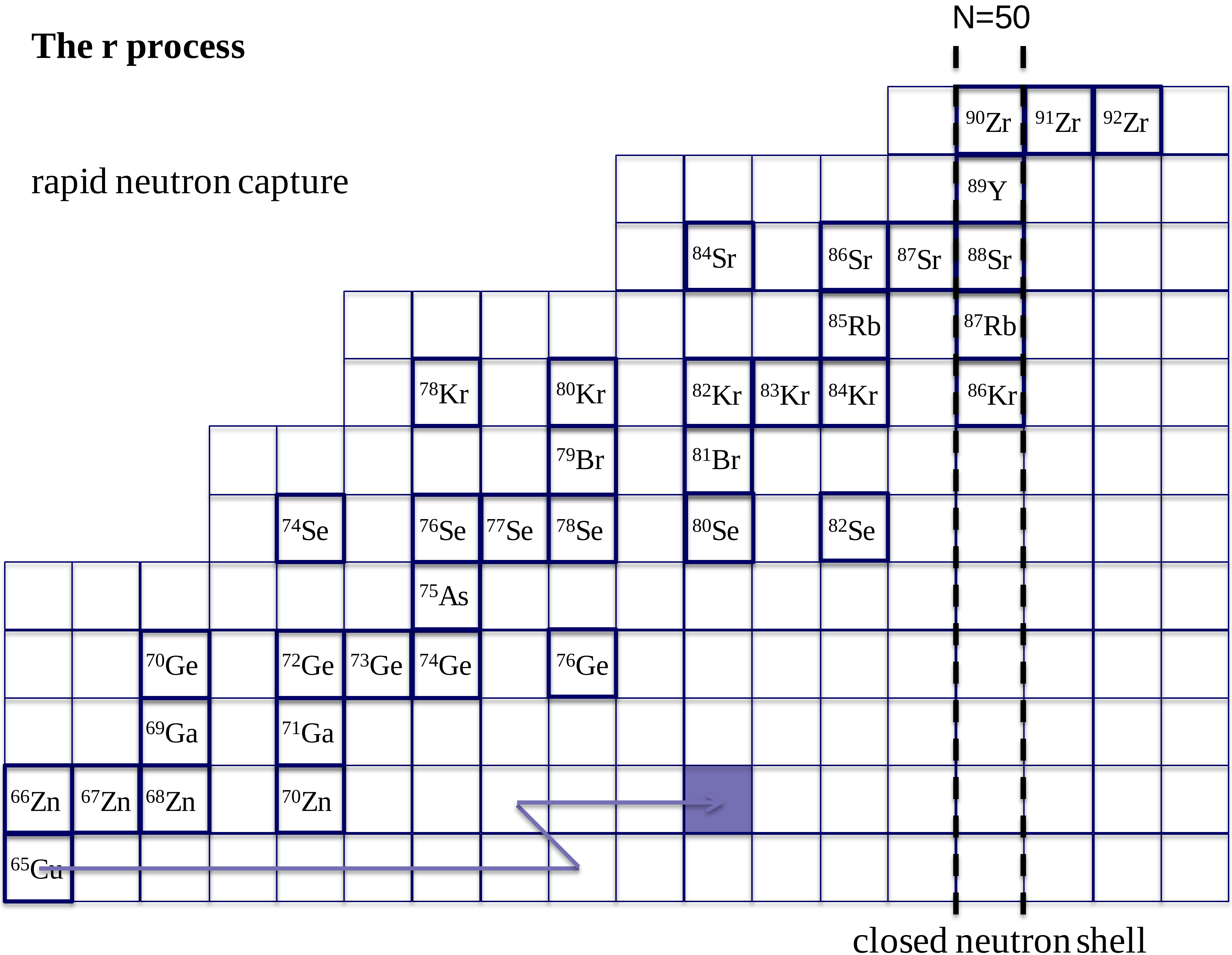

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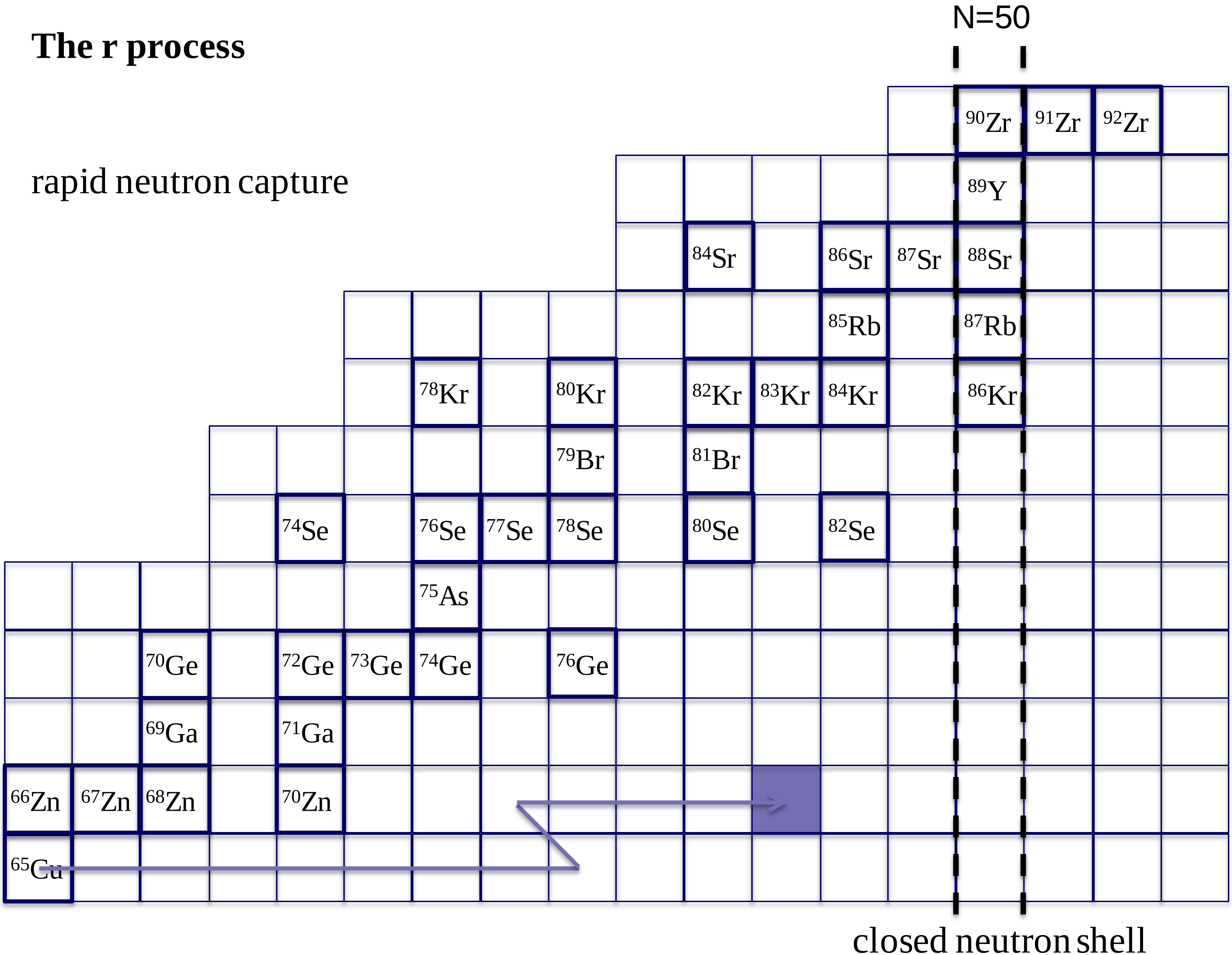

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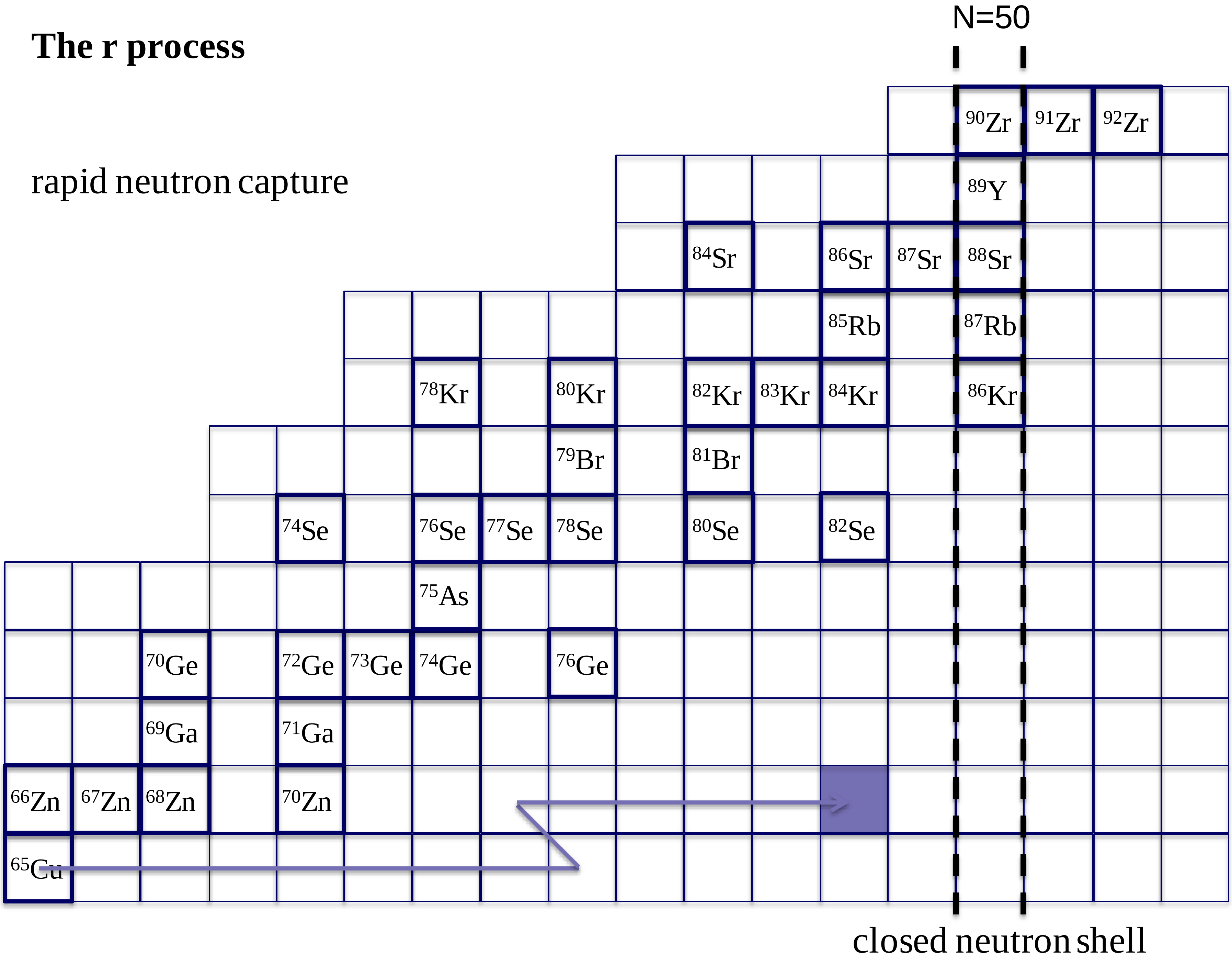

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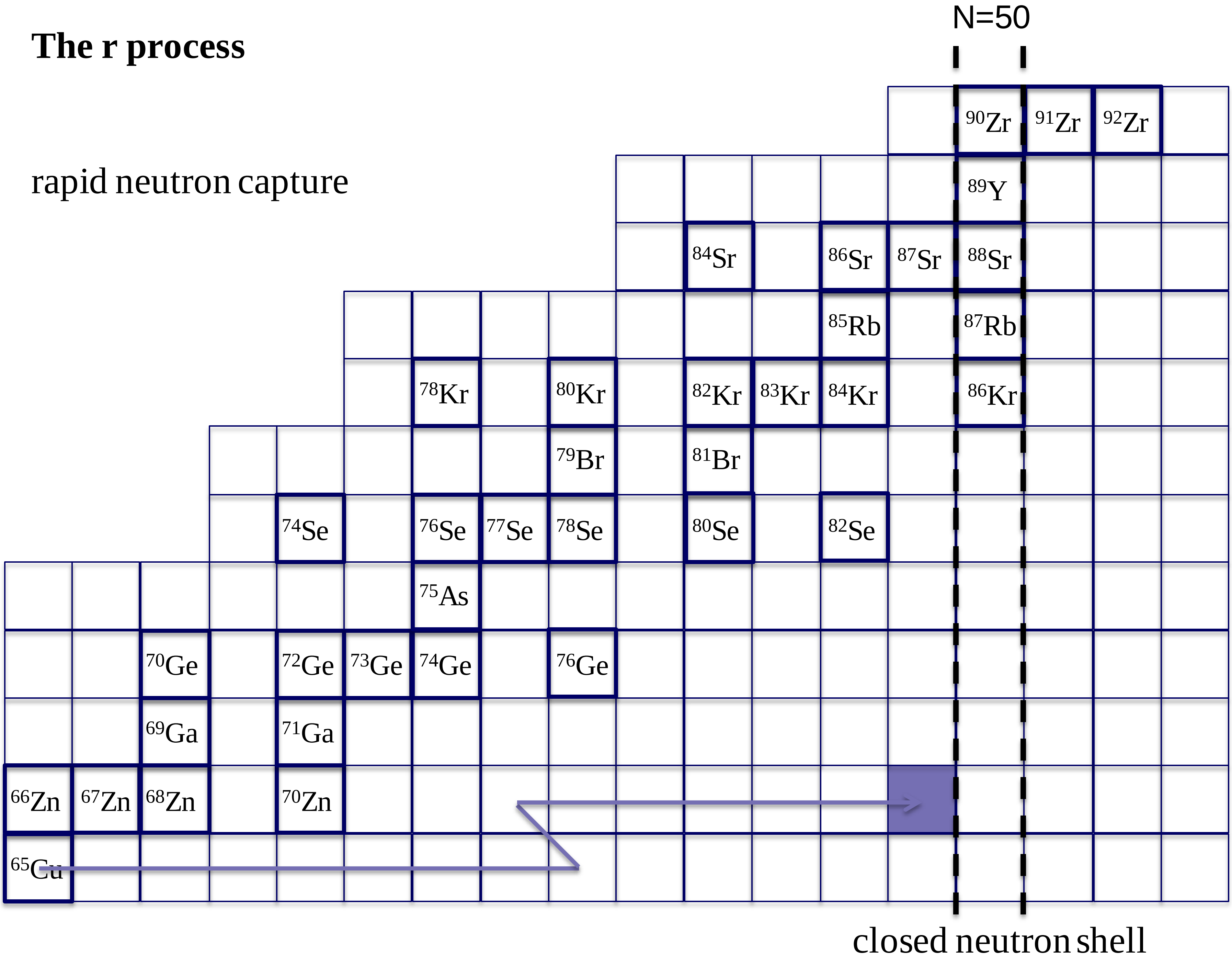

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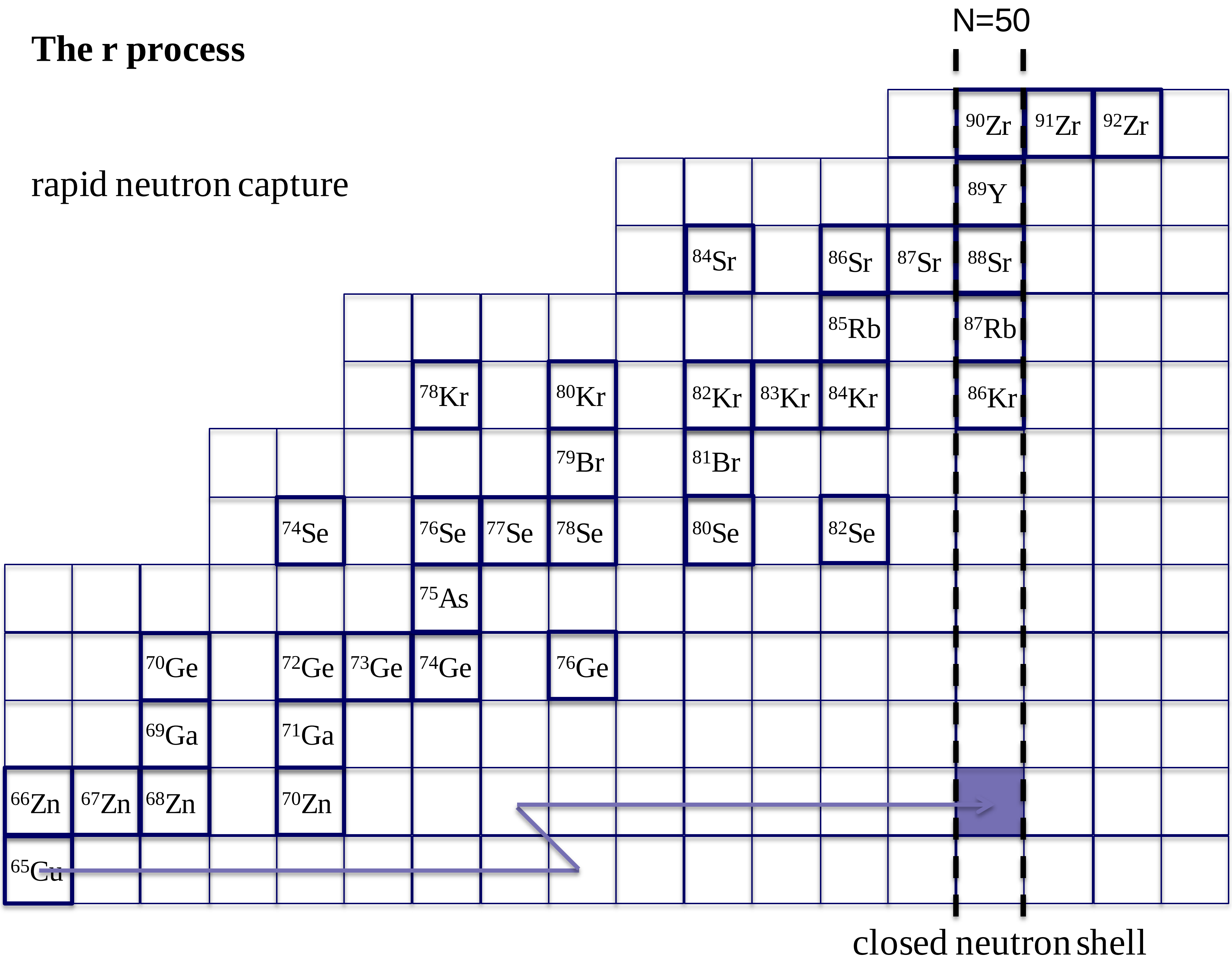

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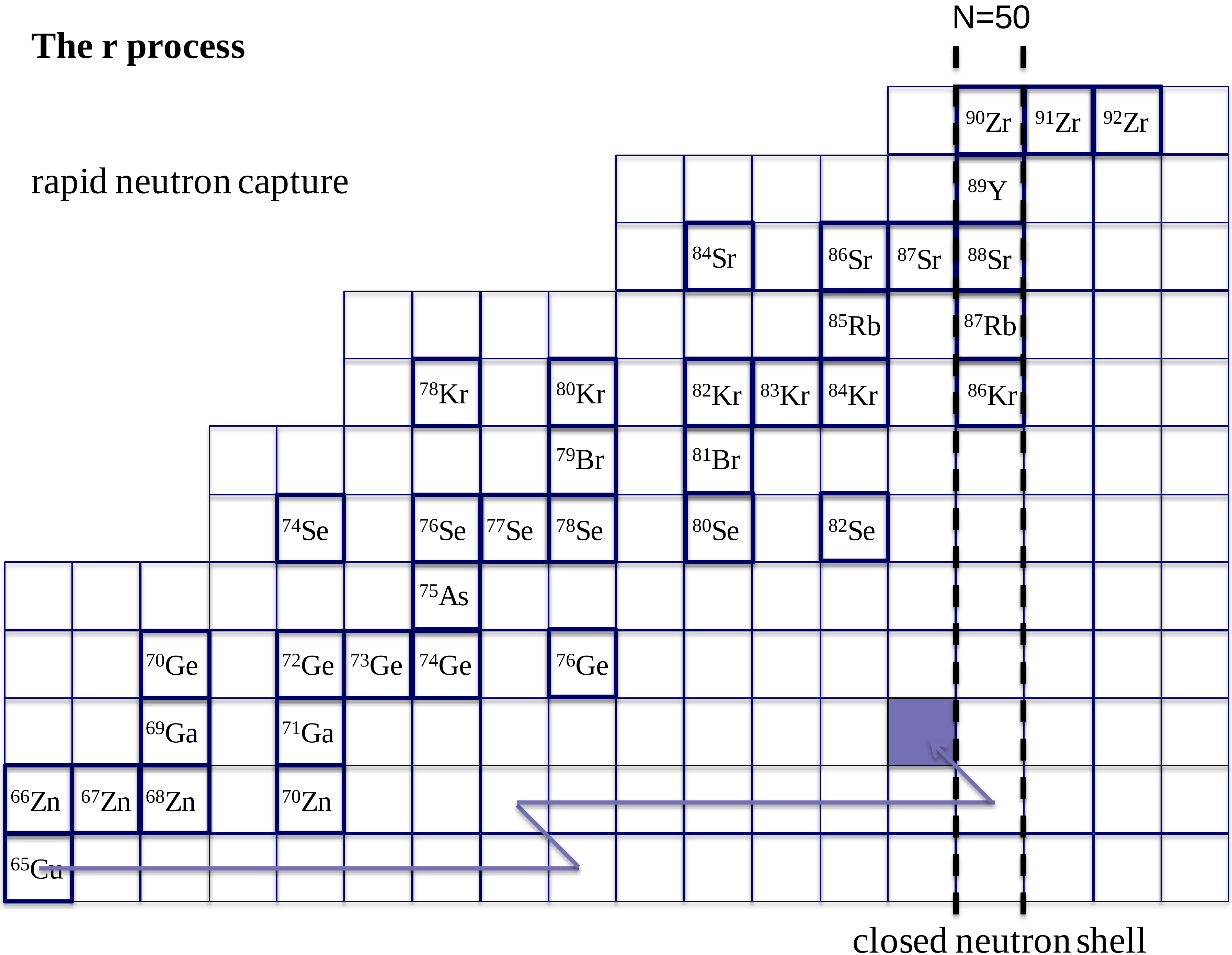

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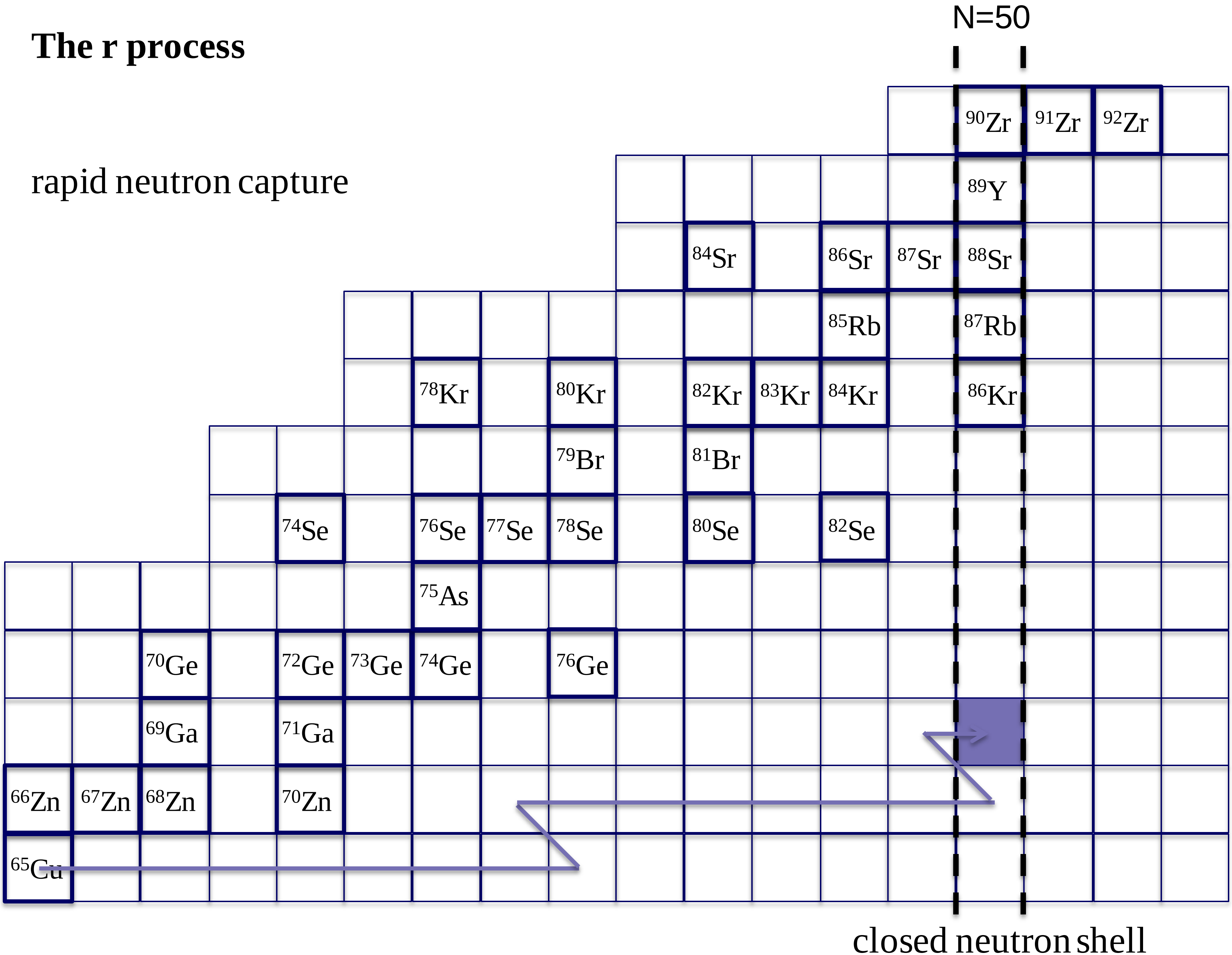

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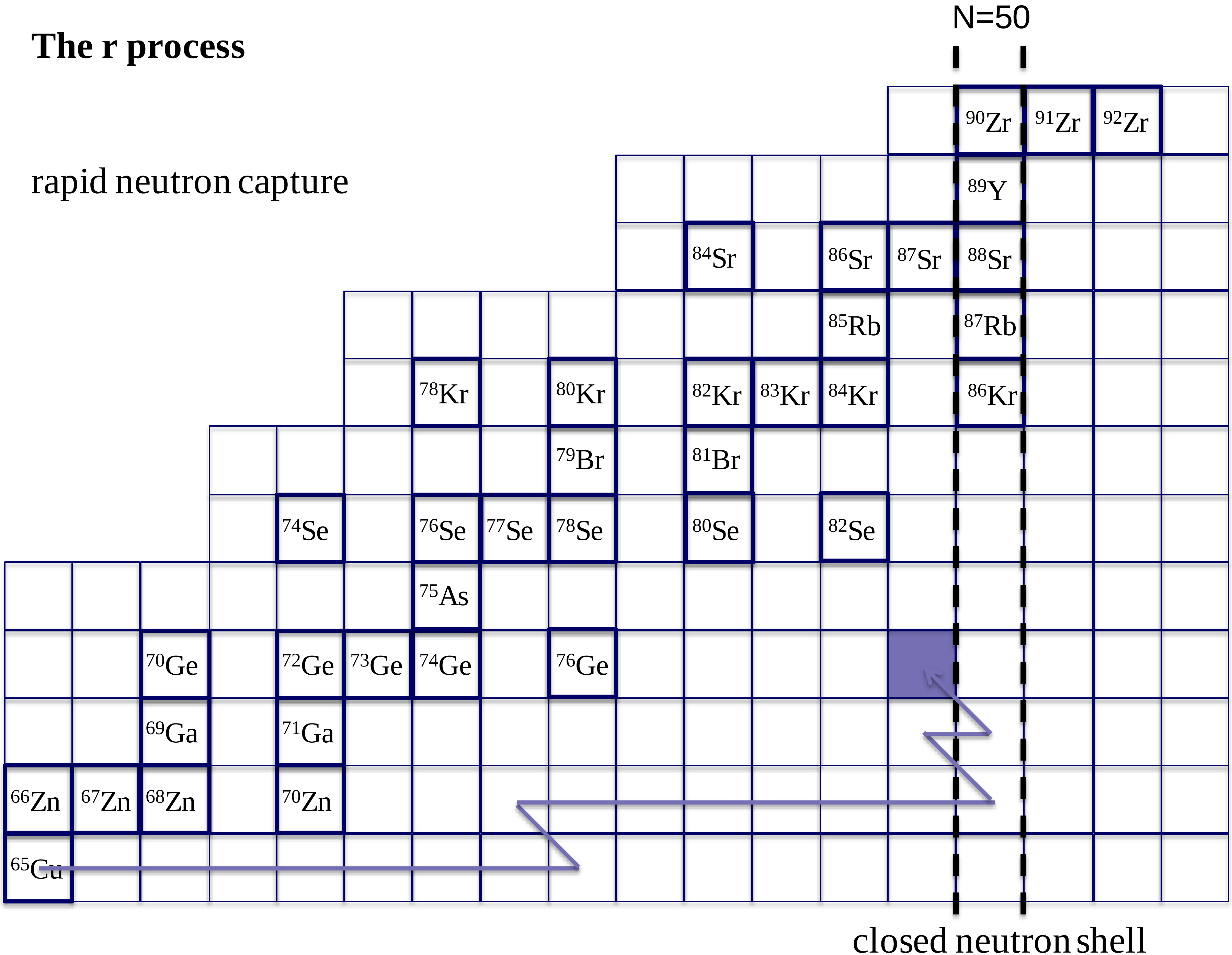

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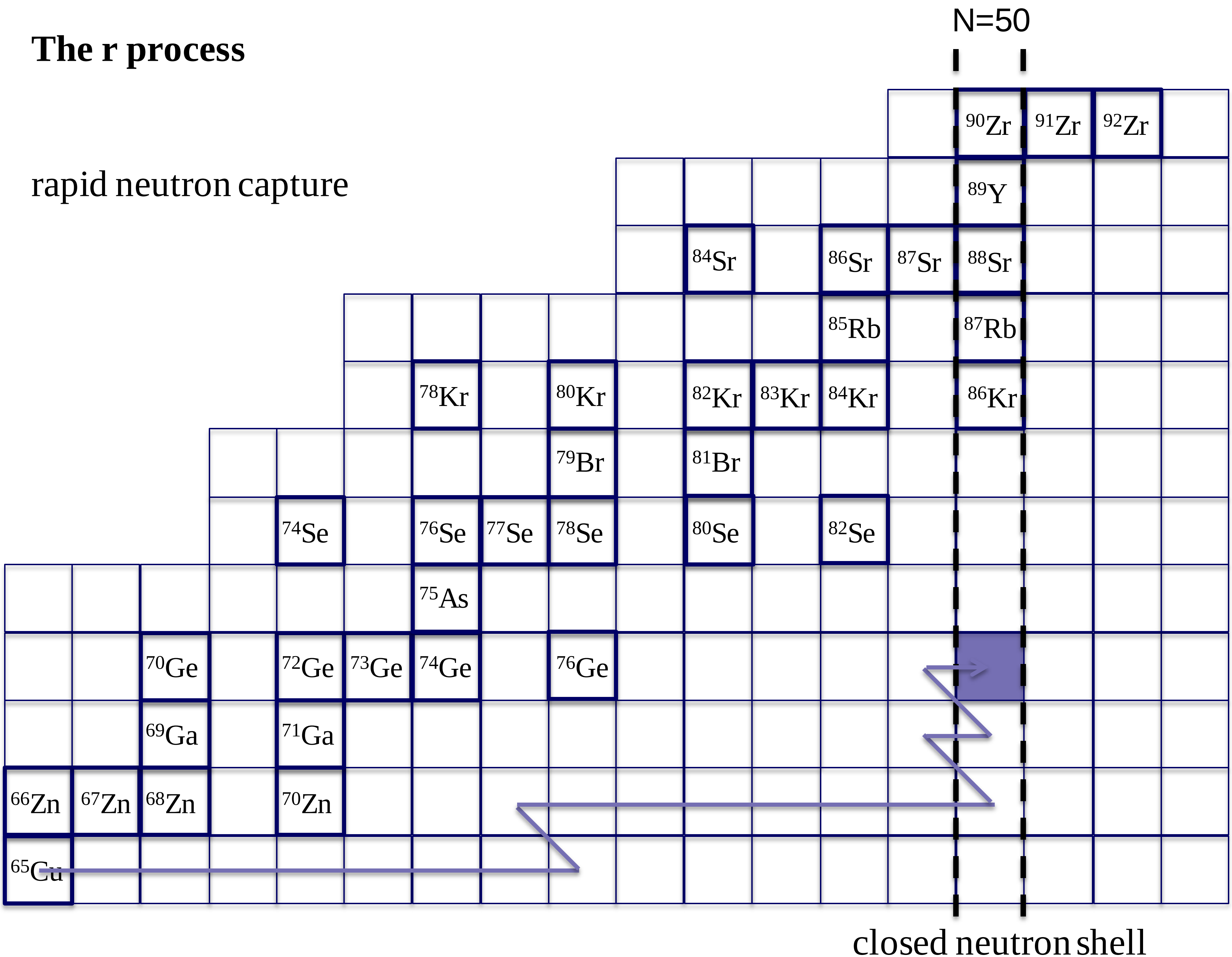

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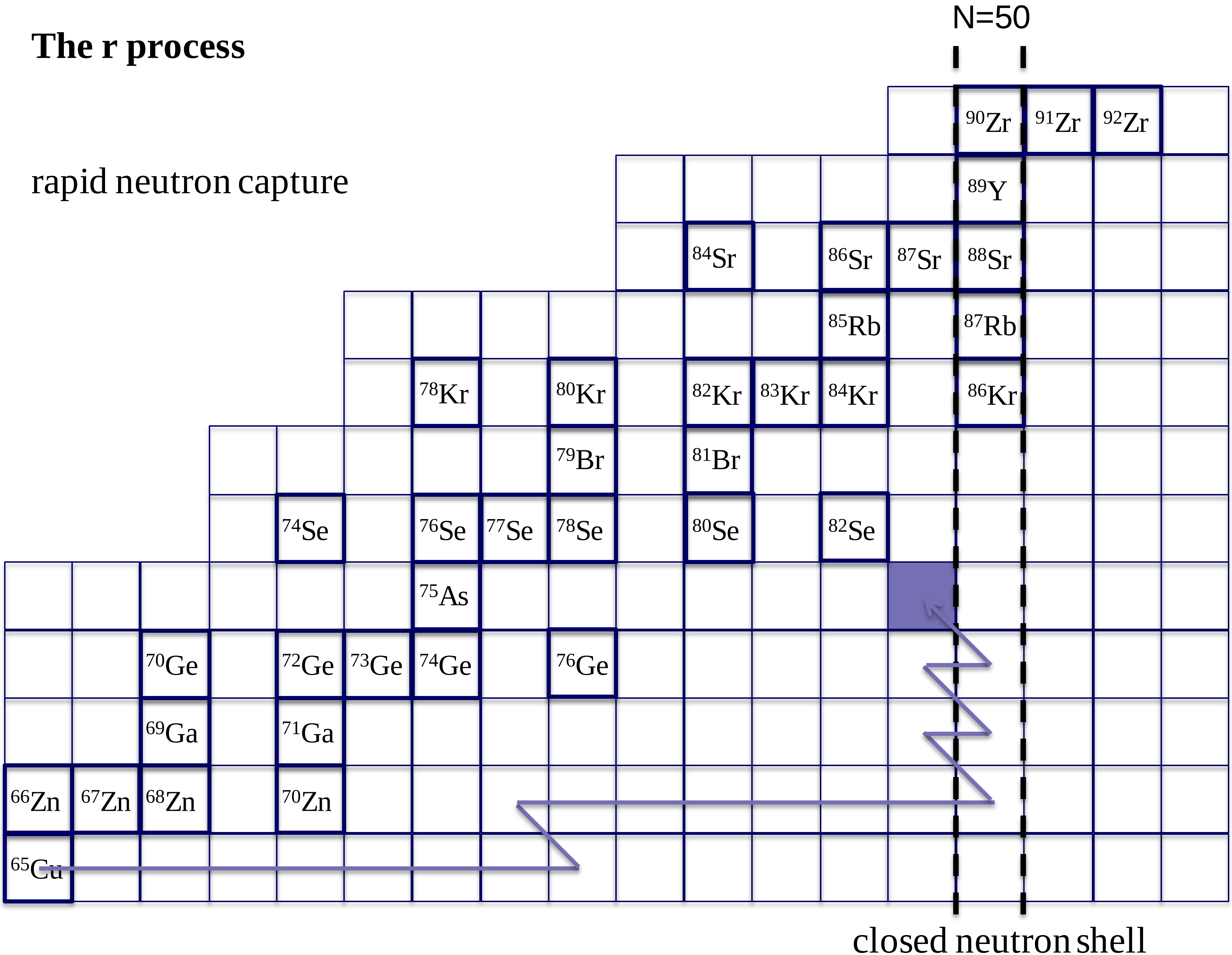

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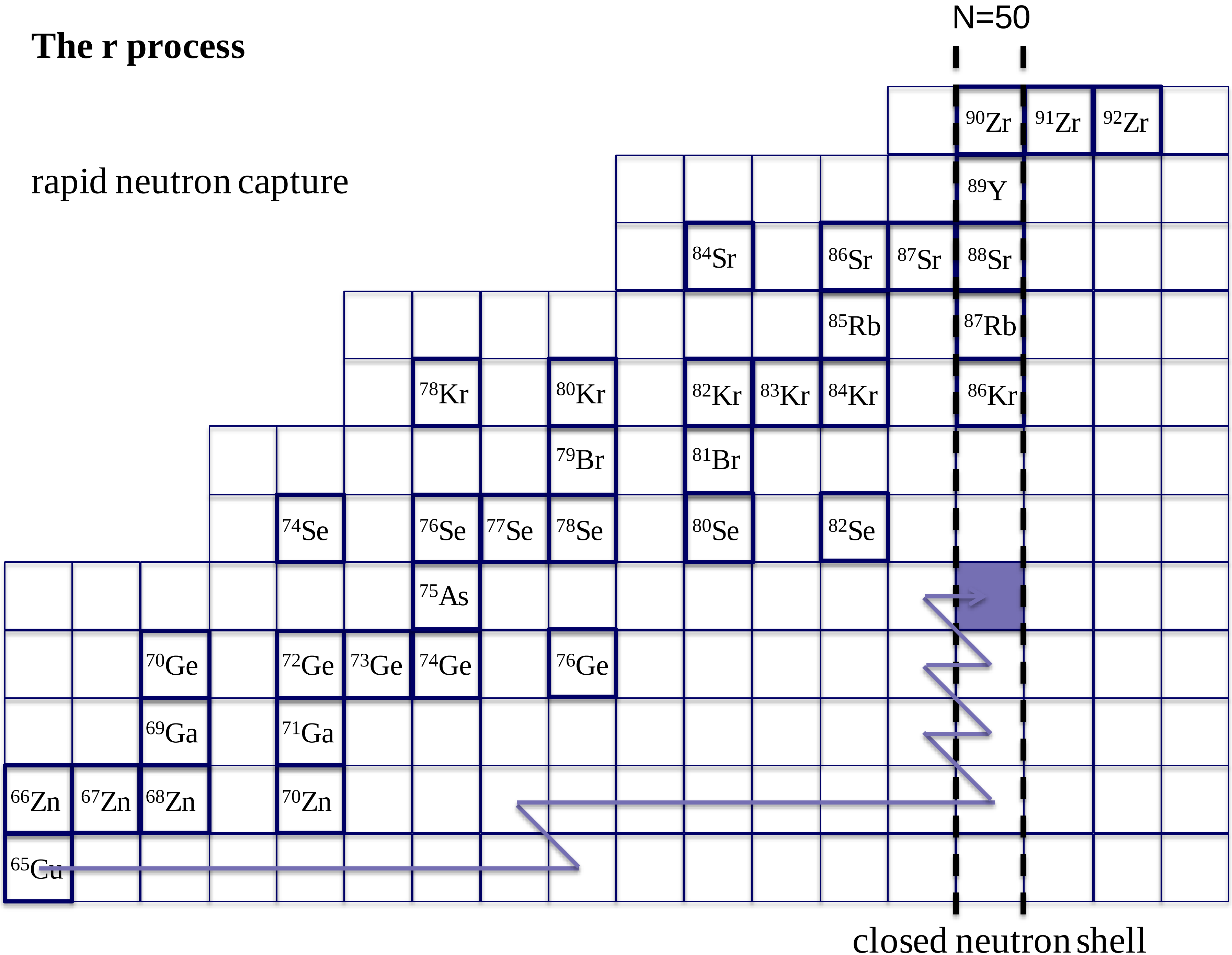

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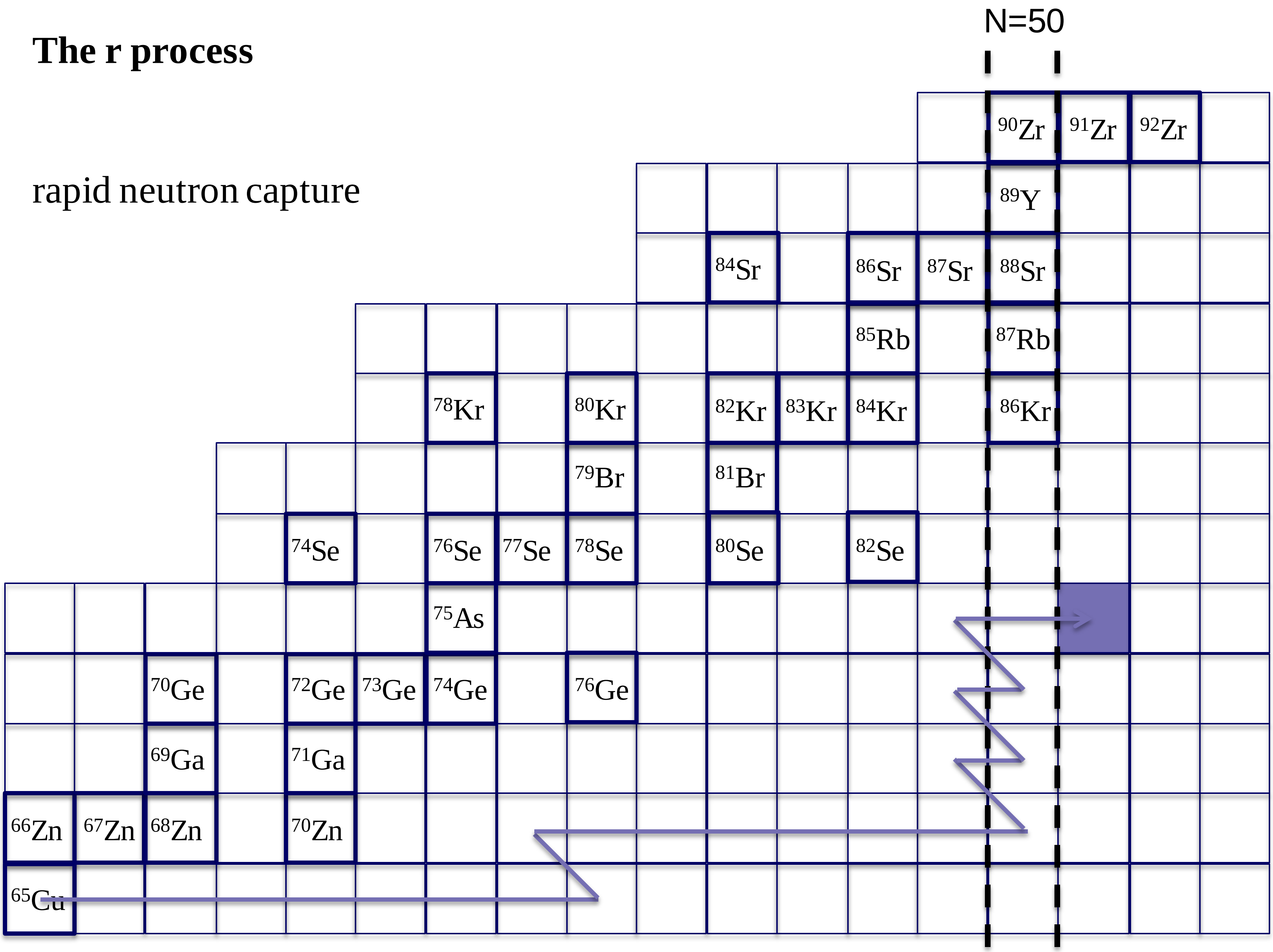

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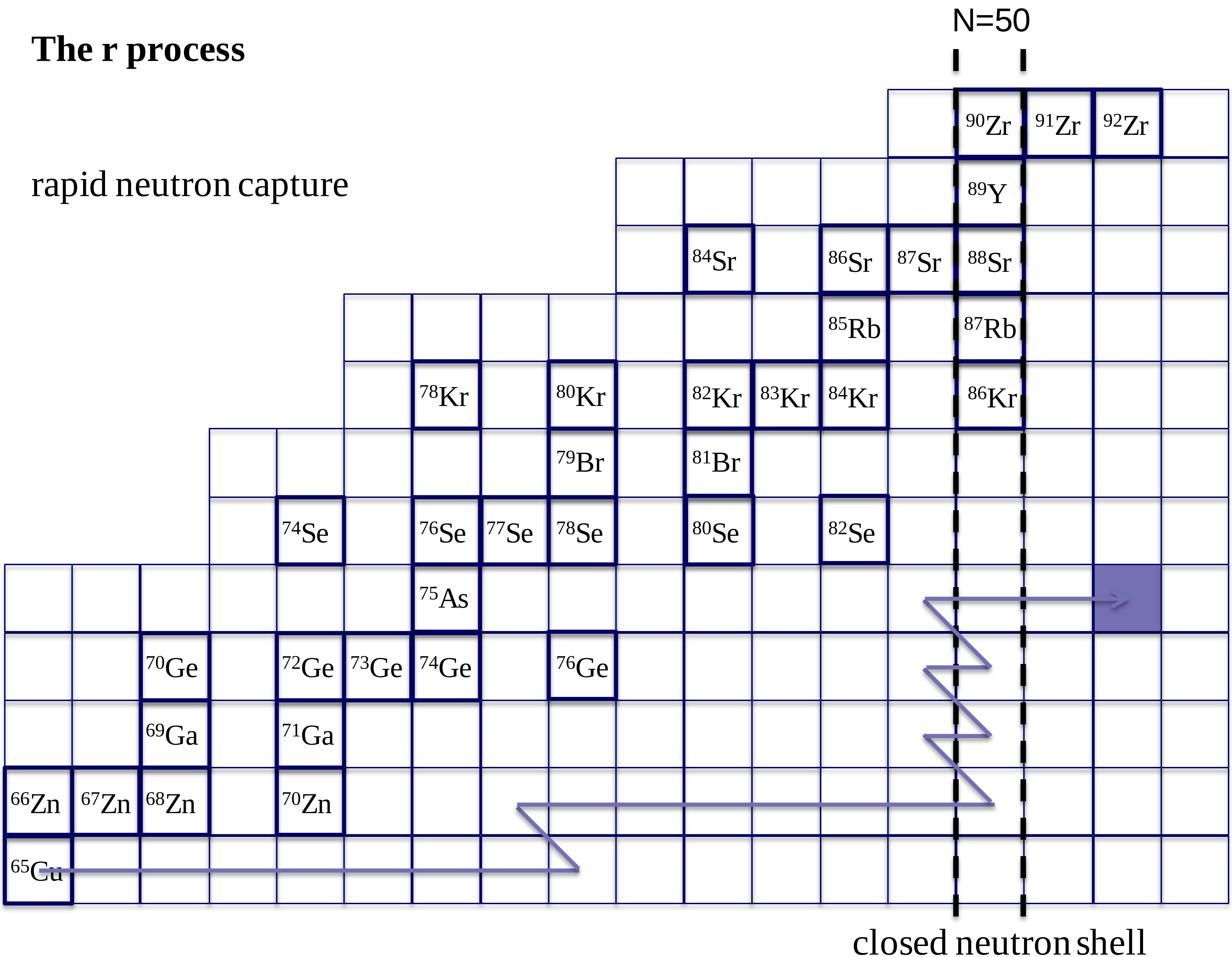

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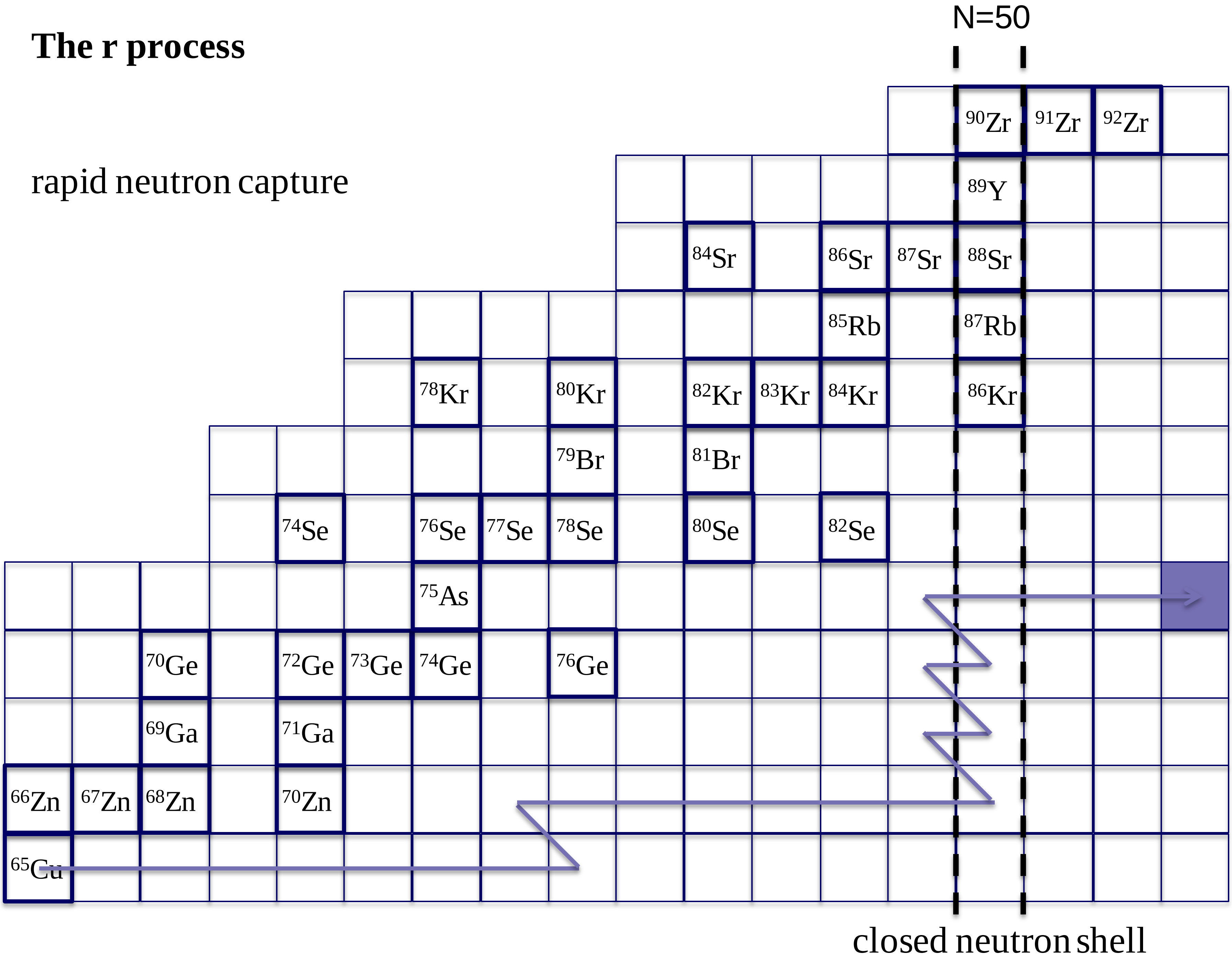

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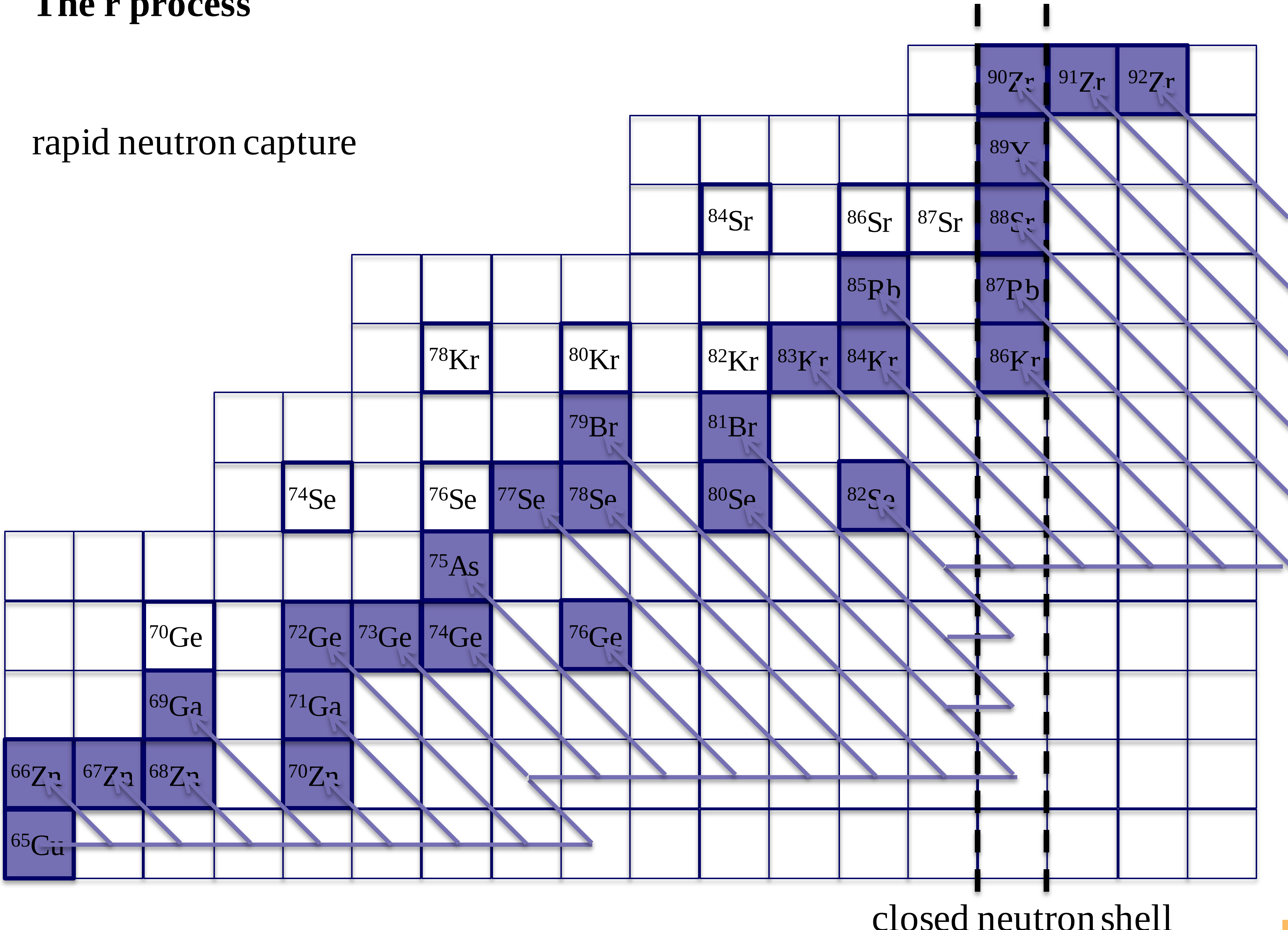
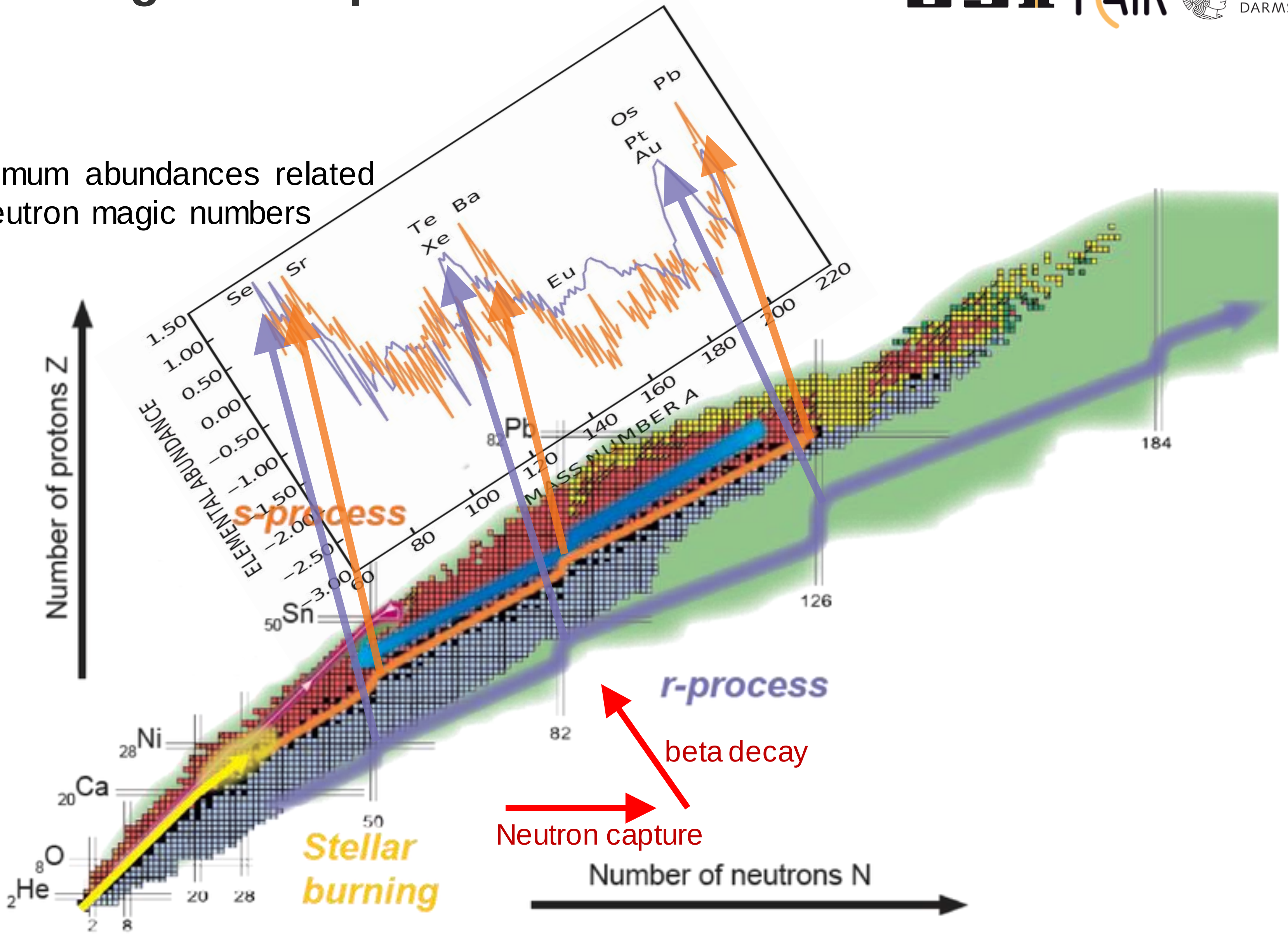


Working s and r process

Maximum abundances related to neutron magic numbers



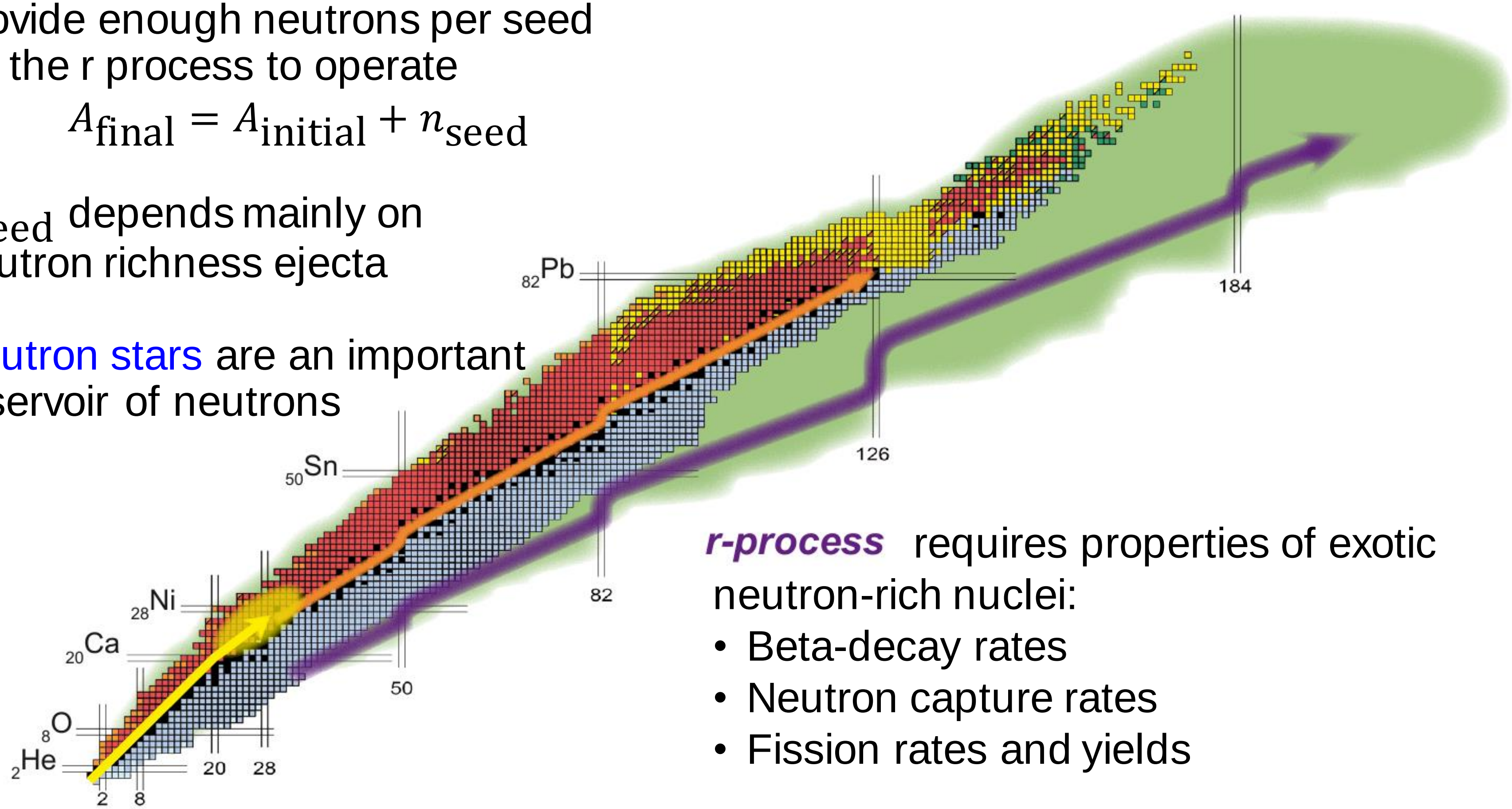
R process modelling

Astrophysical environment should provide enough neutrons per seed for the r process to operate

$$A_{\text{final}} = A_{\text{initial}} + n_{\text{seed}}$$

n_{seed} depends mainly on neutron richness ejecta

Neutron stars are an important reservoir of neutrons



r-process requires properties of exotic neutron-rich nuclei:

- Beta-decay rates
- Neutron capture rates
- Fission rates and yields

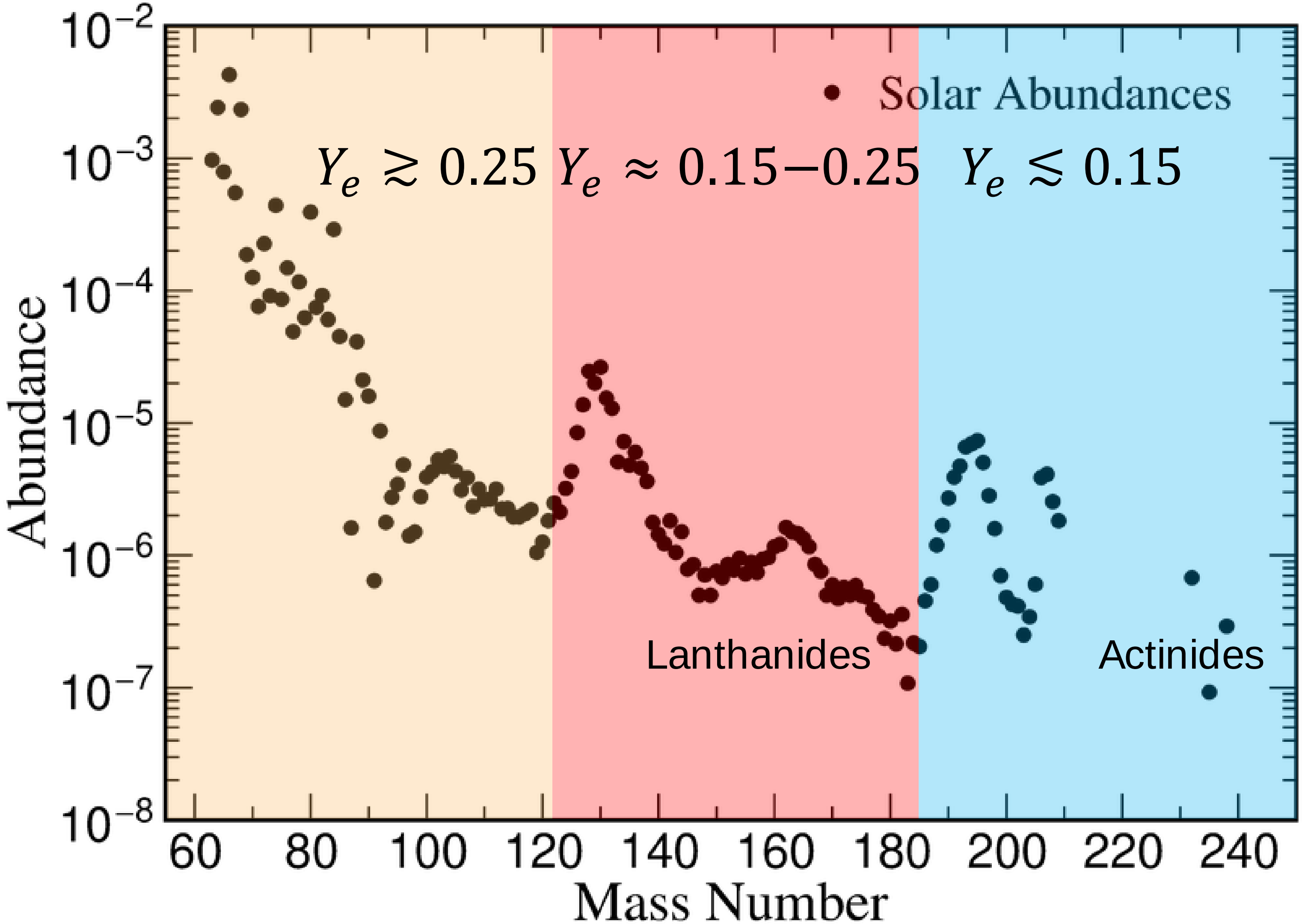
Benchmark against observations:

- Solar and stellar abundances (indirect)
- Electromagnetic emission, kilonova (direct), sensitive Atomic and Nuclear Physics

Nucleosynthesis dependence on Y_e

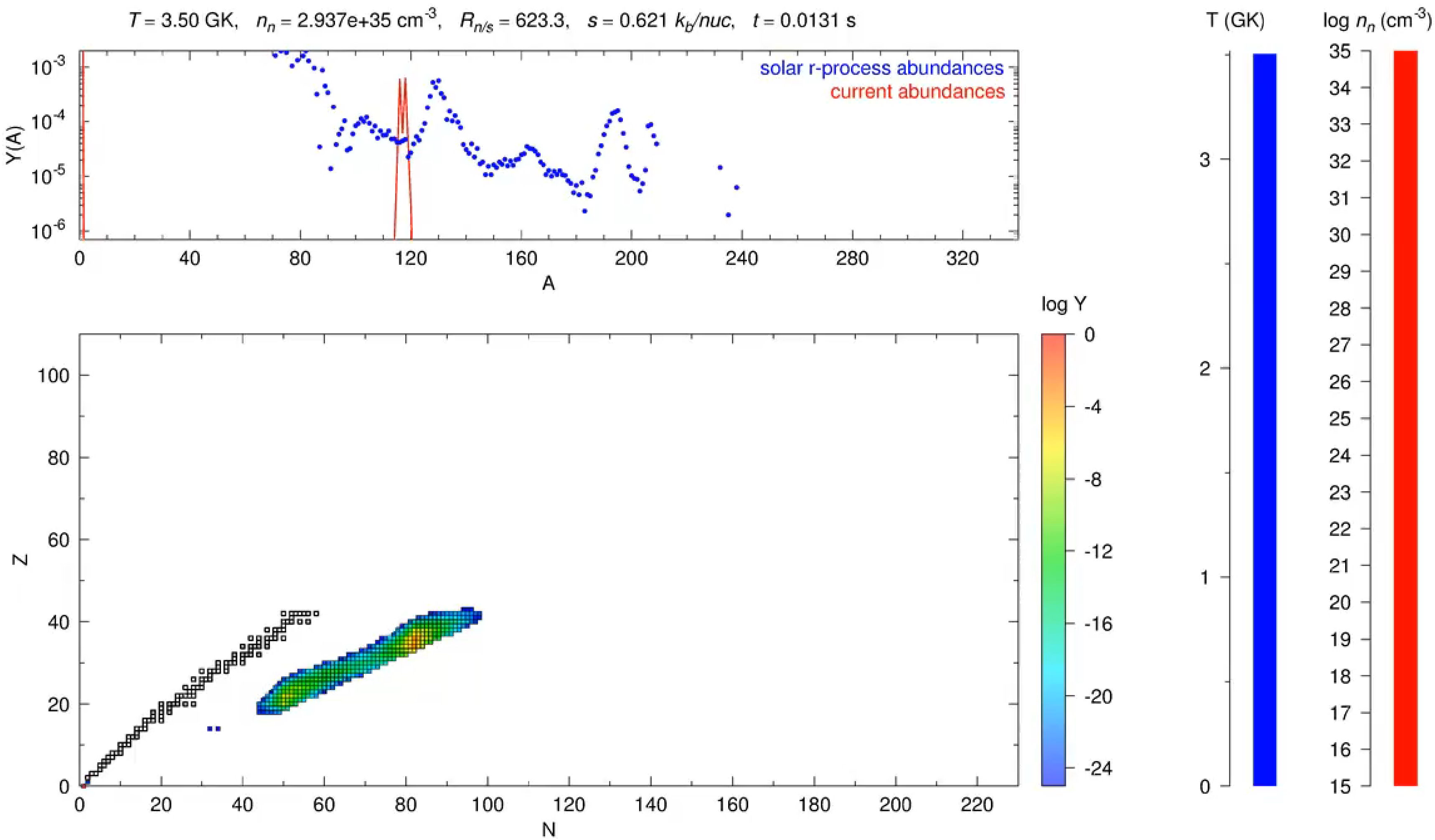
Nucleosynthesis mainly sensitive to proton-to-nucleon ratio, $Y_e = n_p/(n_n + n_p)$

$$\nu_e + n \rightleftarrows p + e^- \quad \text{vs} \quad \bar{\nu}_e + p \rightleftarrows n + e^+$$

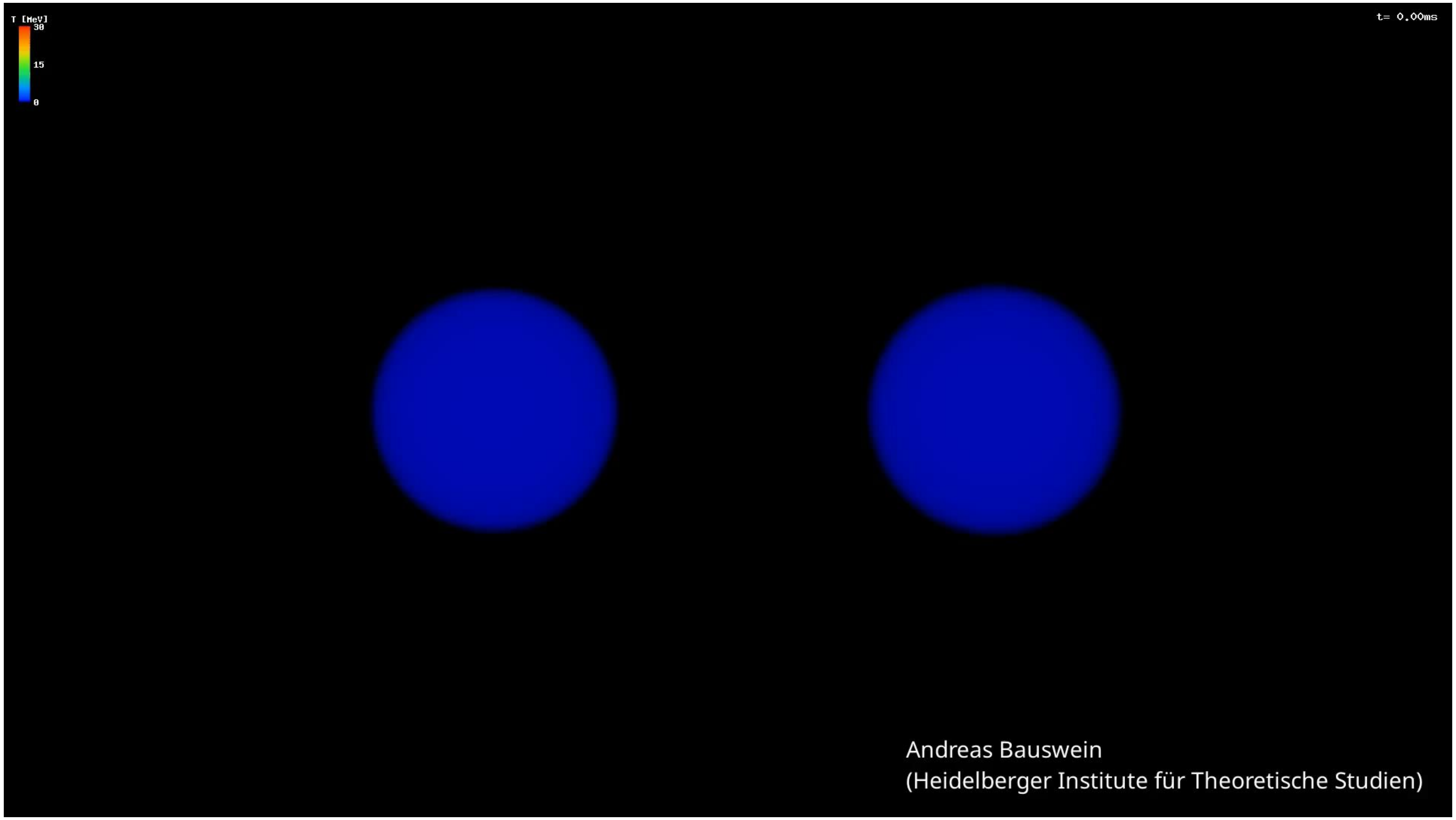


R process in merger ejecta

Heavy elements produced in merger ejecta. Radioactive decay liberates energy



Mass ejection neutron star merger



Two sources of ejecta:

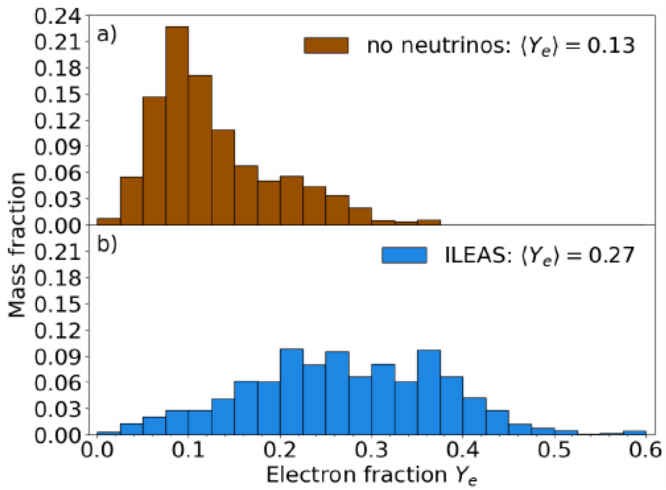
- Dynamical during the early phases of the merger
- Accretion disc on longer timescales

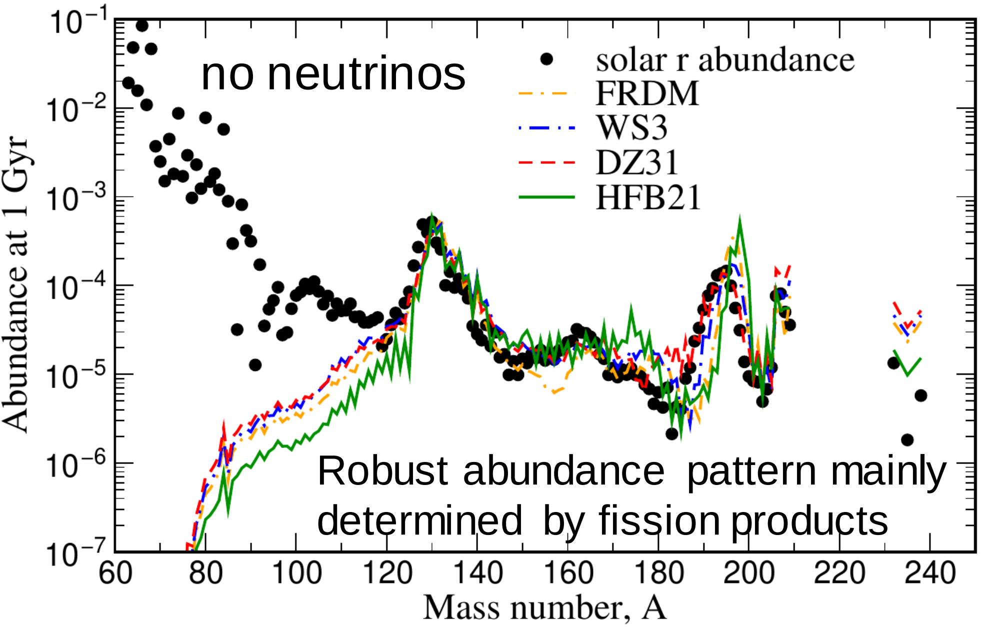
Ejecta properties depend on central remnant (neutron star or black hole). Determines the strength of neutrino emission and neutron richness

Dynamical ejecta (simulations)

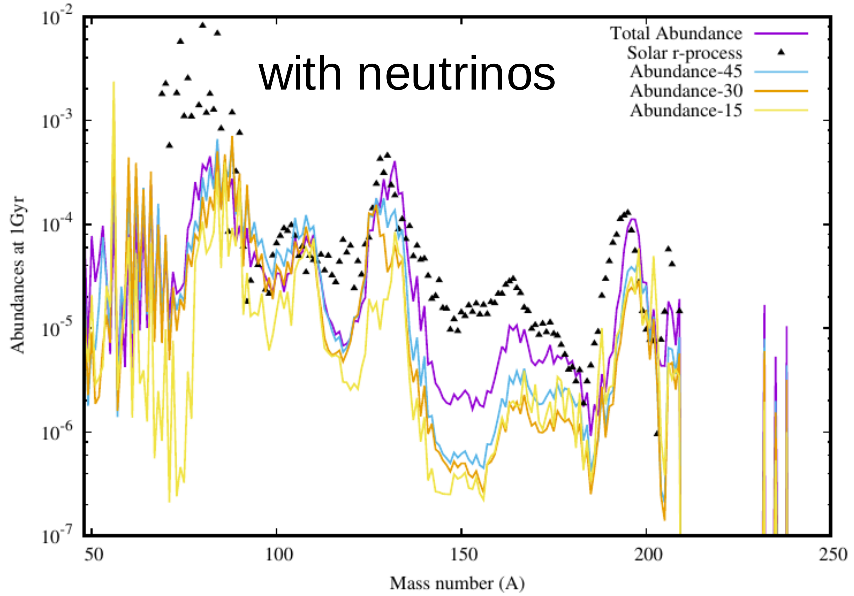
Kullmann et al, arXiv:2109.2509

- Initially dynamical ejecta was assumed to be very neutron rich ($Y_e \lesssim 0.1$).
- Starting with the work of Wanajo et al 2014, several studies have shown that weak processes modify the neutron-to-proton ratio
- Largest impact in the polar regions





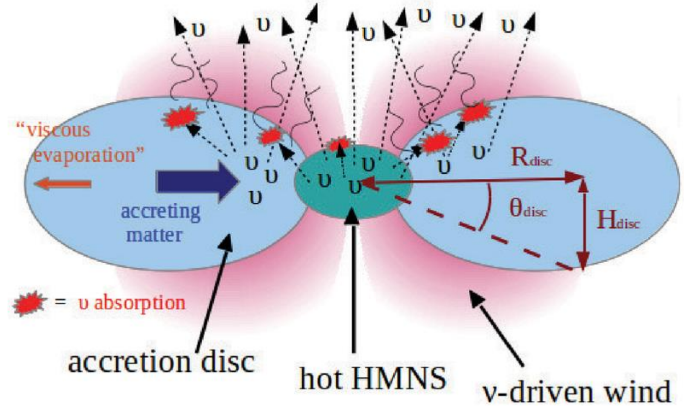
Mendoza-Temis, et al, PRC 92, 055805 (2015)



Systematic evaluation role of weak processes [Vimal Viajayan, PhD group A. Bauswein]

Disk (secular) ejecta

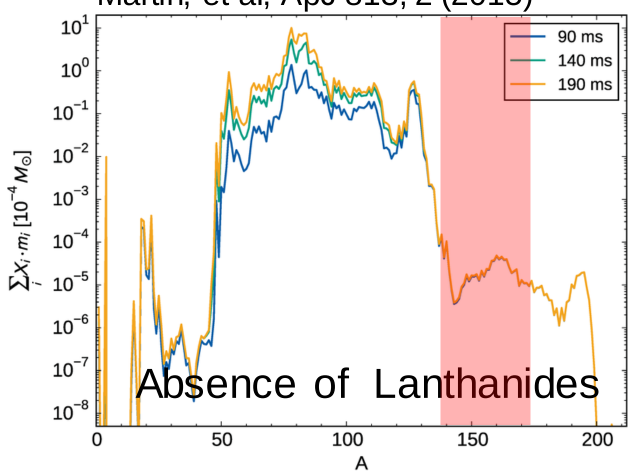
After the merger an hyper massive neutron star is formed that can be temporarily stable before collapsing to a black hole



Large neutrino fluxes mainly in polar region decrease neutron-to-proton ratio by reactions

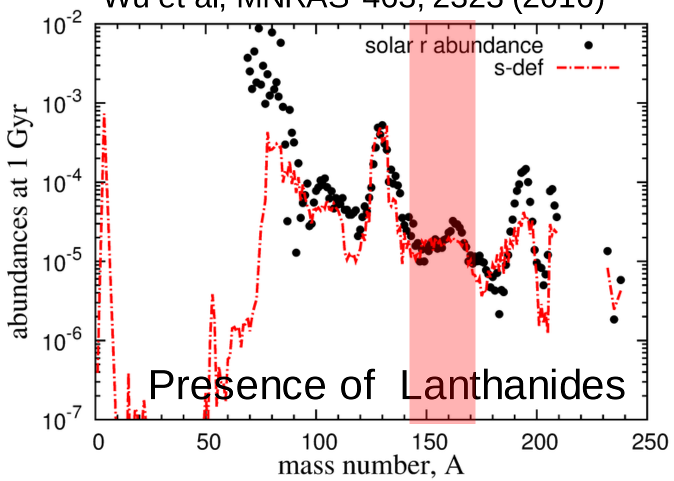
$$\nu_e + n \rightarrow p + e^-$$
$$\bar{\nu}_e + p \rightarrow n + e^+$$

Martin, et al, ApJ 813, 2 (2015)



Once neutron star collapses to a black hole neutrinos emission ceases. Larger neutron-to-proton ratio

Wu et al, MNRAS 463, 2323 (2016)

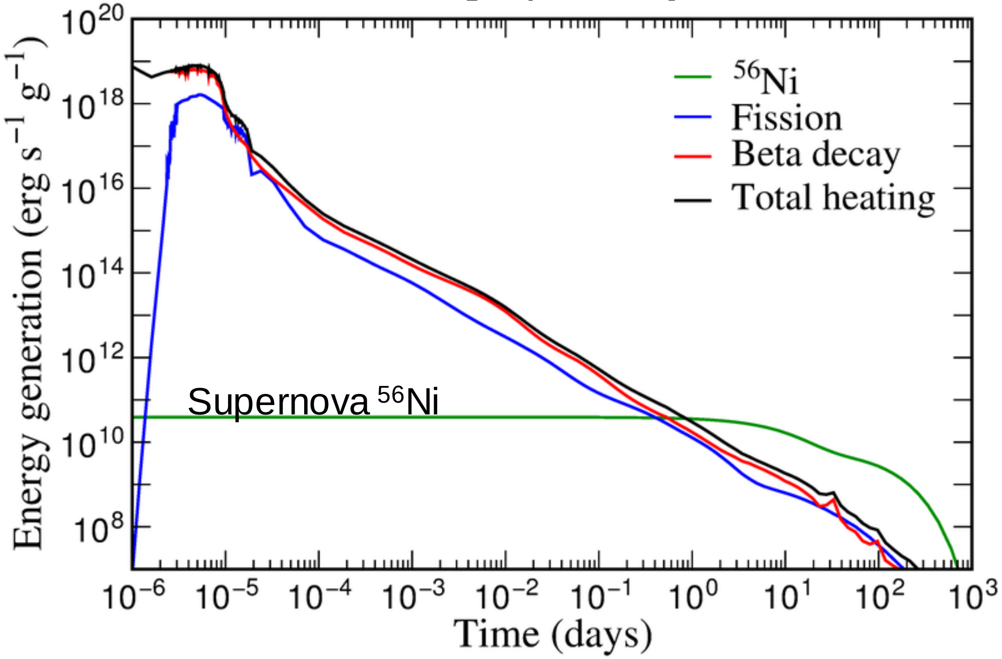


see also Lippuner et al, MNRAS 472 904 (2017)

See also Just et al, MNRAS **448**, 541 (2015), Siegel and Metzger PRL **119**, 231102 (2017).

Energy production from r process ejecta

At early times (days), the decay of r process products produces energy following a power law $\dot{\varepsilon} \sim t^{-1.3}$ (Way & Wigner 1948, Metzger et al 2010). Many nuclei decaying at the same time heating up the ejecta

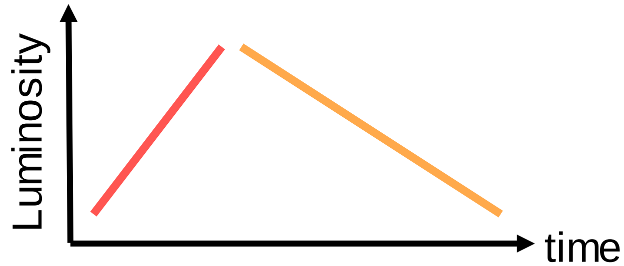


We expect an electromagnetic transient (Li & Paczyński 1998) with properties depending:

- Energy production rate
- Efficiency energy is absorbed by the gas (thermalization efficiency)
- Opacity of the gas (depends on composition, presence of Lanthanides/Actinides)

Ejected mass and velocity can be inferred from observations

Impact of opacity



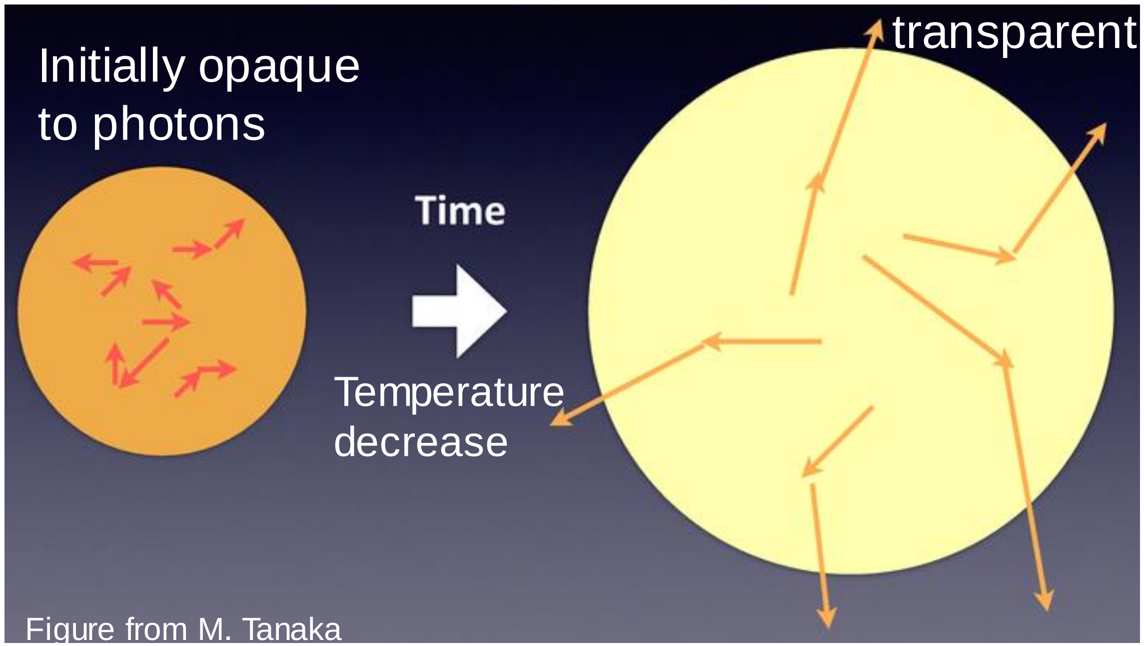
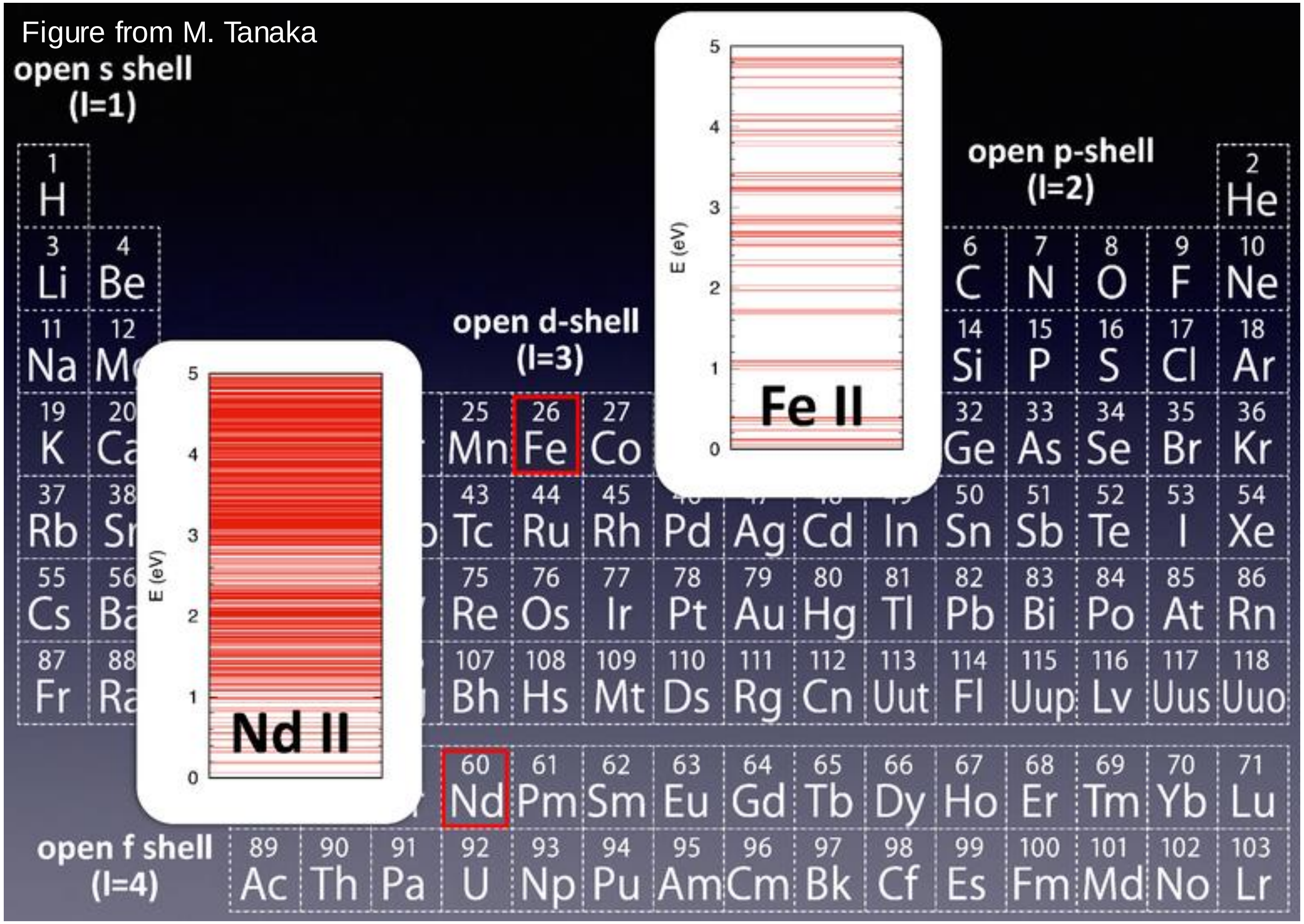


Figure from M. Tanaka

The transition from an opaque to transparent regime depends on the interaction probability of the photons (opacity). Depends on the structure of the atoms (presence of Lanthanides/Actinides)

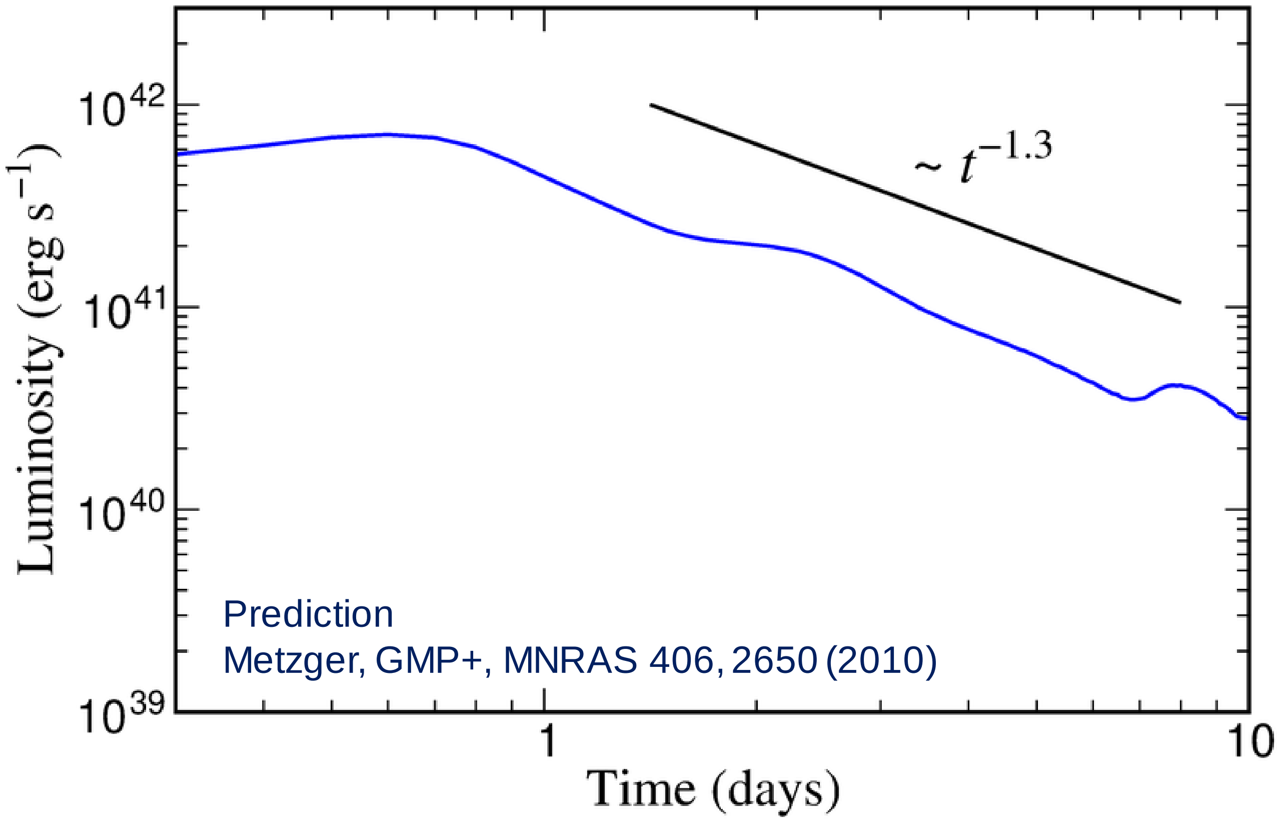
Low opacity: early emission from hot material at short wavelengths (blue)
High opacity: late emission from colder material at longer wavelengths (red)

Impact Lanthanides



Large number of states of Lanthanides/Actinides leads to a high opacity

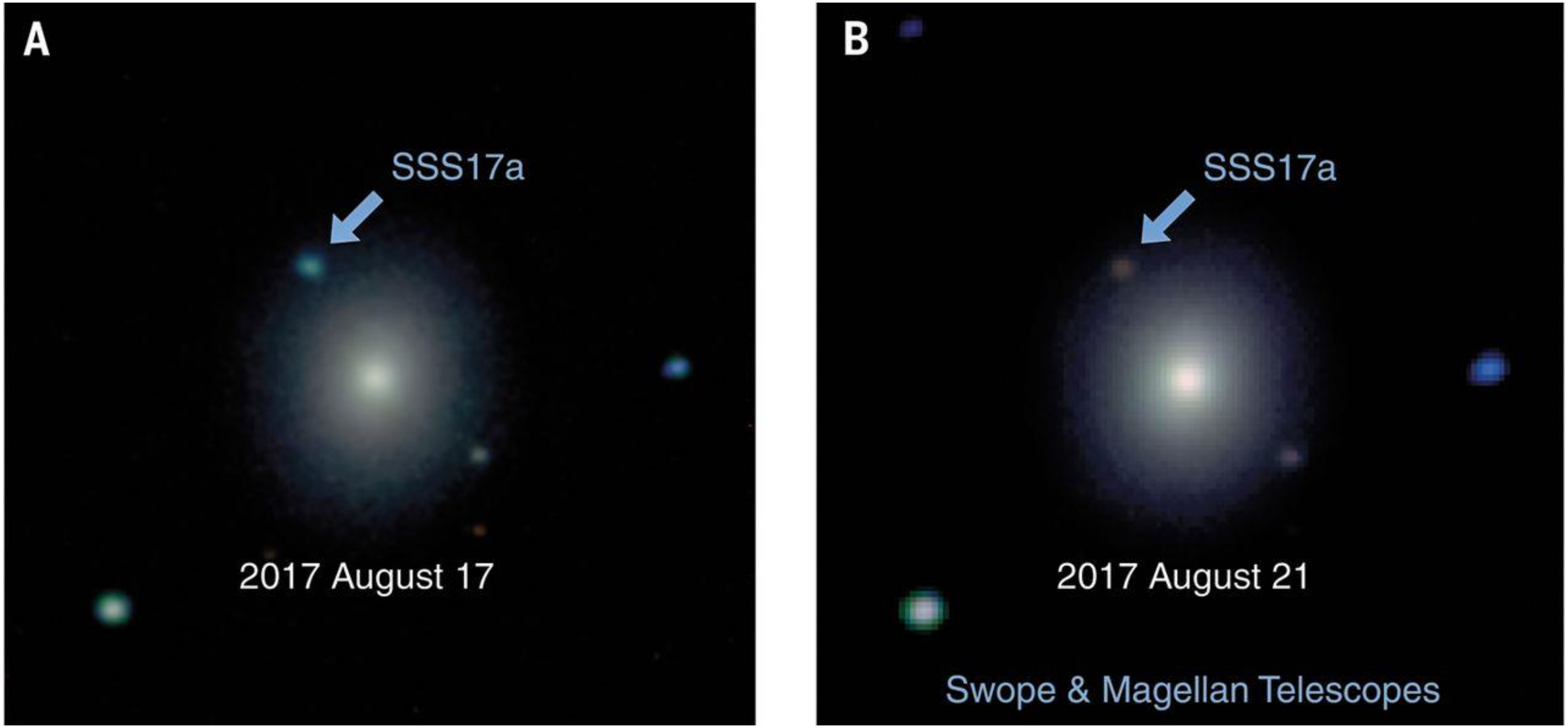
Kilonova: Electromagnetic signature of the r process



Luminosity equivalent to 1000 novas (kilonova) in timescales of days.
Depends on amount of ejected material, velocity and composition.

Electromagnetic transient GW170817

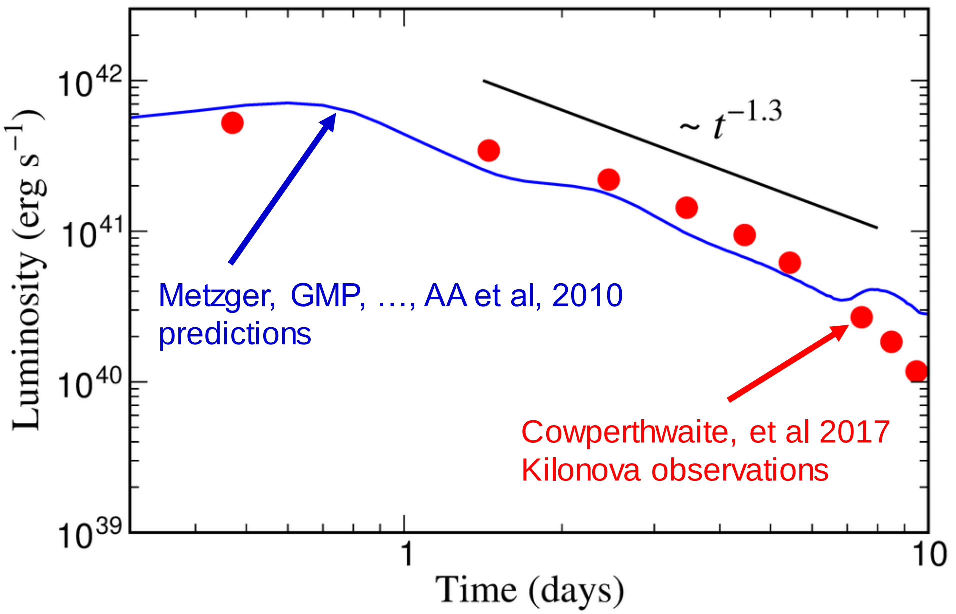
M. R. Drout et al. Science 2017;358:1570-1574



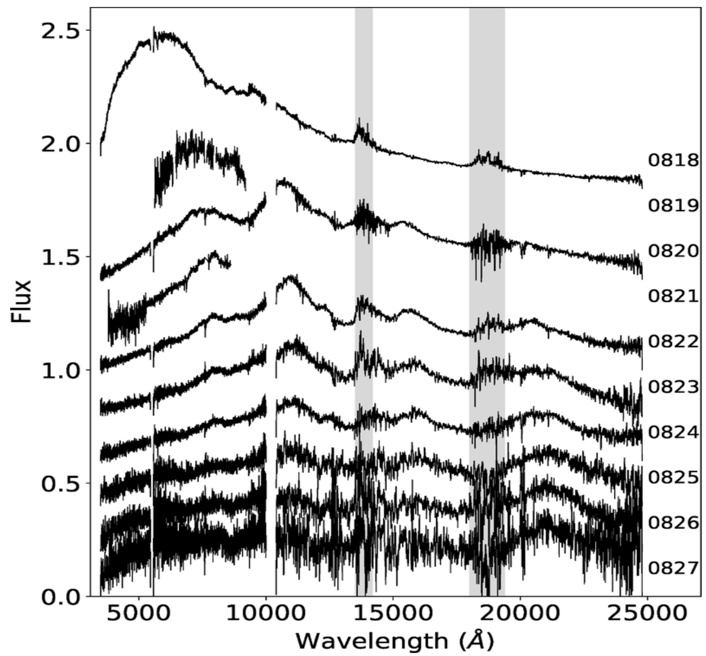
Novel fast evolving transient powered radioactive decay r-process material

Emission evolves from blue to red in a few days

Kilonova: Electromagnetic transient powered by decay of r-process nuclei



Pian et al., Nature 551, 67 (2017)



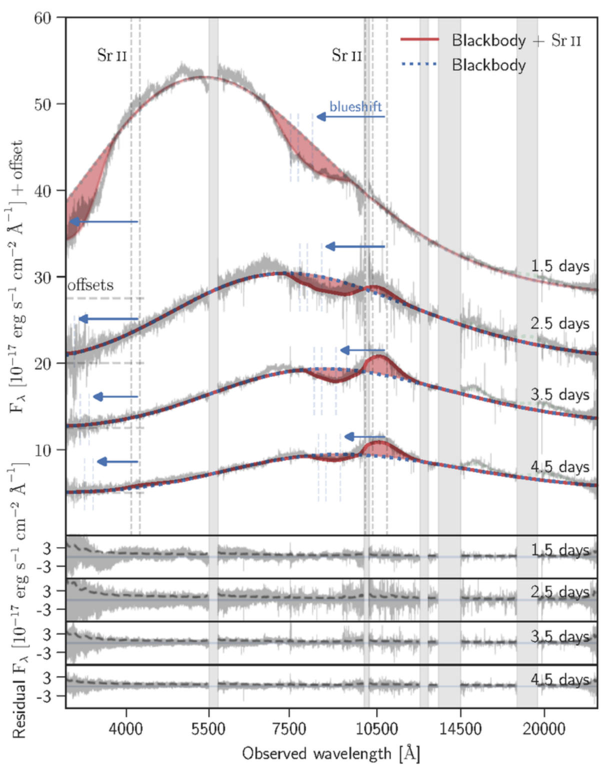
- Time evolution determined by the radioactive decay of r-process nuclei
- Two components (Kasen et al, Nature 551, 80 (2017)
  - Blue dominated by light elements (Z < 50) ($M = 0.025\ M_{\odot}, v = 0.3c, X_{\rm lan} = 10^{-4}$, dynamical ejecta?, signature neutrino interactions)
  - Red due to presence of Lanthanides ($M = 0.04\ M_{\odot}, v = 0.15c, X_{\rm lan} = 10^{-1.5}$, ejecta accretion disk?, points to the formation of a black hole)

Identification Sr in kilonova spectra

Watson et al, Nature **574**, 497 (2019)

Identification of strontium in the merger of two neutron stars

Darach Watson[1,2], Camilla J. Hansen[3,*], Jonatan Selsing[1,2,*], Andreas Koch[4], Daniele B. Malesani[1,2,5], Anja C. Andersen[1], Johan P. U. Fynbo[1,2], Almudena Arcones[6,7], Andreas Bauswein[7,8], Stefano Covino[9], Aniello Grado[10], Kasper E. Heintz[1,2,11], Leslie Hunt[12], Chryssa Kouveliotou[13,14] Giorgos Leloudas[1,5], Andrew Levan[15,16], Paolo Mazzali[17,18], Elena Pian[19] [See end for affiliations]

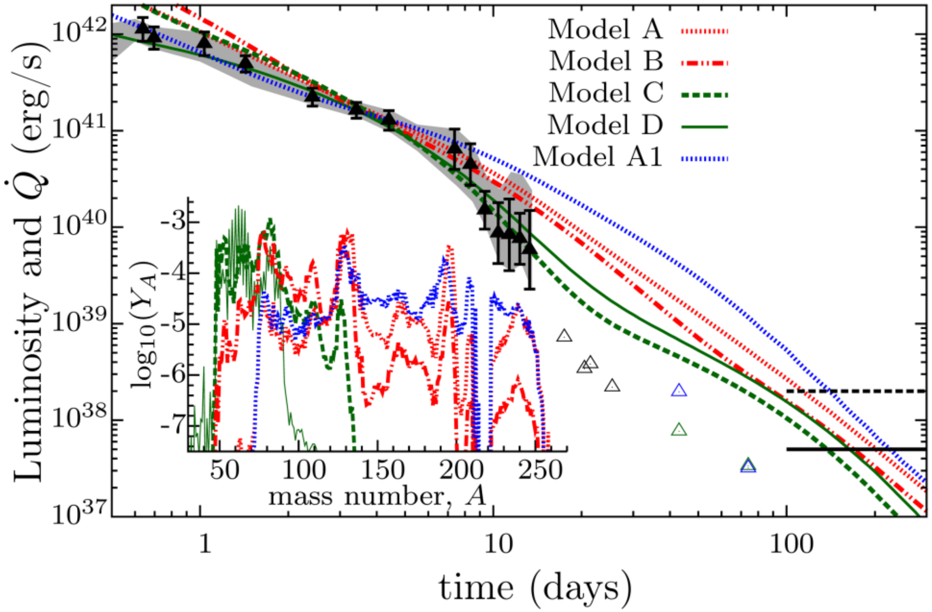


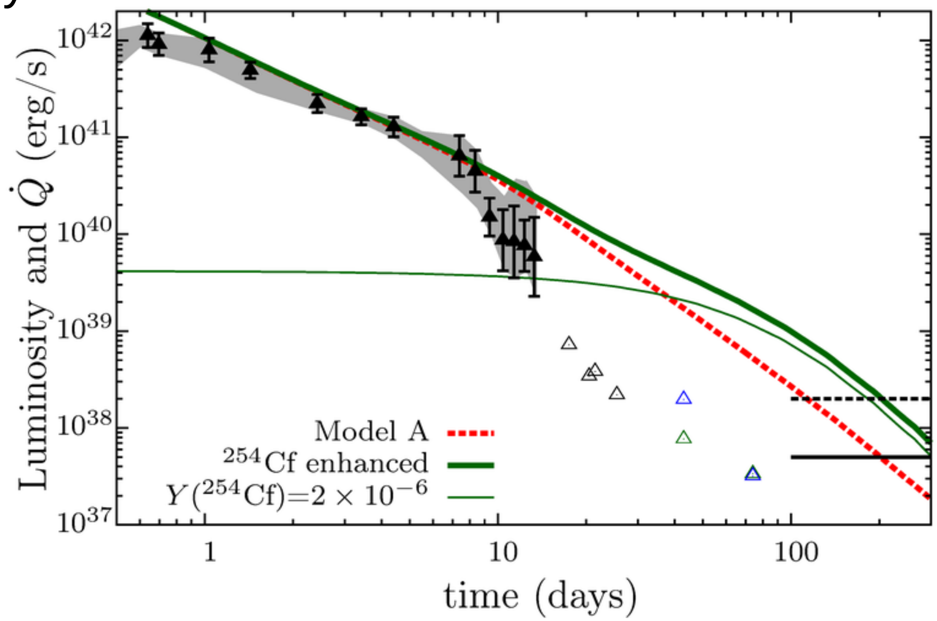
- First direct spectroscopic identification of r-process element
- Strontium is produced in High $Y_e \sim 0.35$ ejecta: direct evidence of the role of neutrinos in merger ejecta

No direct evidence of elements heavier than Lanthanides

Nuclear fingerprints light curve

Bolometric light curve is easy to determine theoretically ($L \sim M_{\rm ej}\dot{\epsilon}_{\rm eff}$)
but difficult to determine observationally





PHYSICAL REVIEW VOLUME 103, NUMBER 5 SEPTEMBER 1, 1956

Californium-254 and Supernovae*

G. R. Burbidge and F. Hoyle,† *Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California*

AND

E. M. Burbidge, R. F. Christy, and W. A. Fowler, *Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California*

(Received May 17, 1956)

At late times light curve is determined by nuclear heating. Opacity uncertainties play a smaller role (ejecta is transparent)

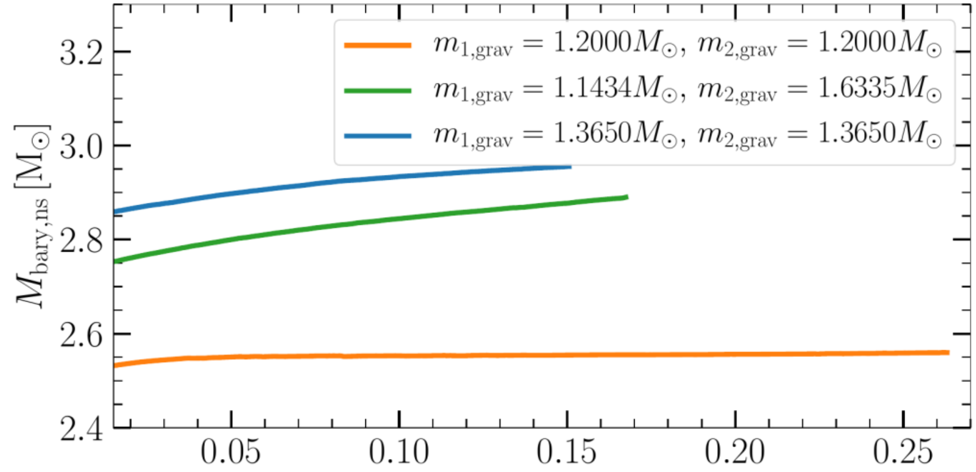
Observations between 10 and 100 days are sensitive to composition.
Light curve becomes dominated by individual decays: ^{254}Cf

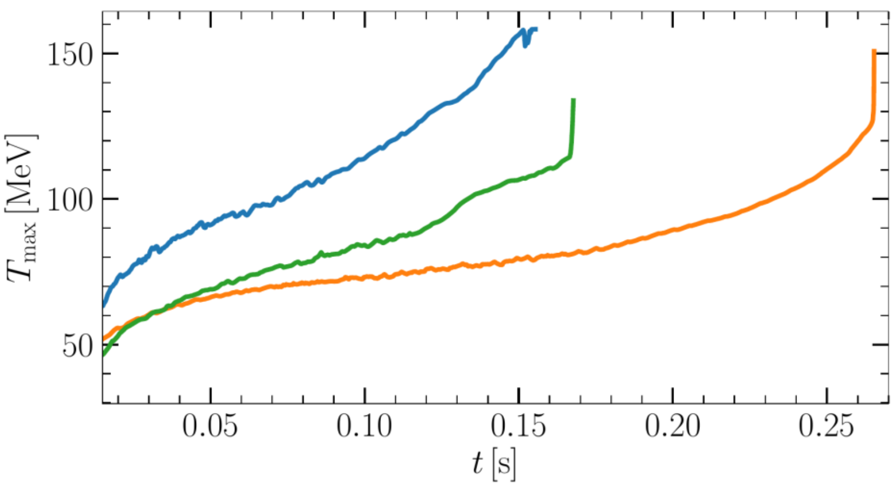
Wu, Barnes, GMP, Metzger, PRL 122, 062701 (2019)

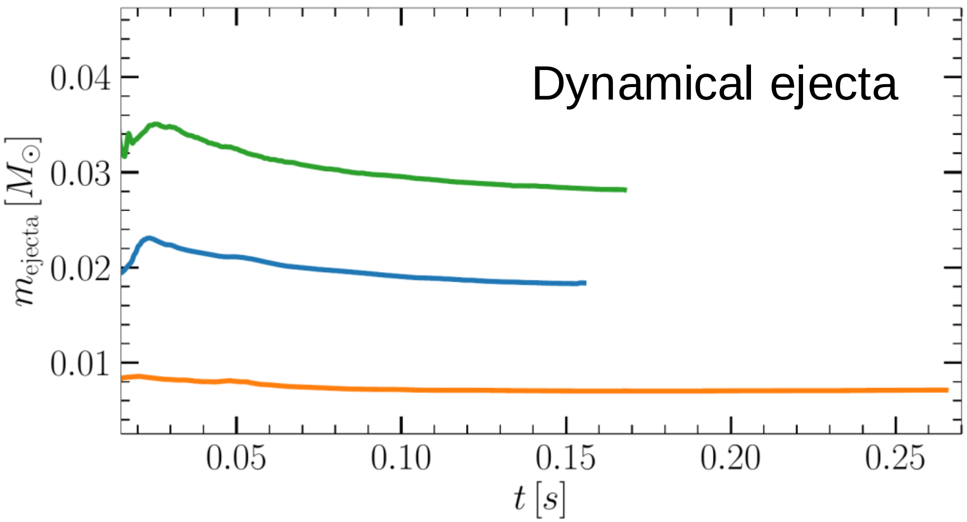
Evolution of central remnant

- Important to understand the evolution of central remnant and its dependence on progenitor mass and equation of state
- Determines impact neutrino reactions in the ejecta.
- Role of neutrino oscillations (Zewei Xiong)

Evolution till black-hole formation:
2D GR simulations by Ninoy Rahman



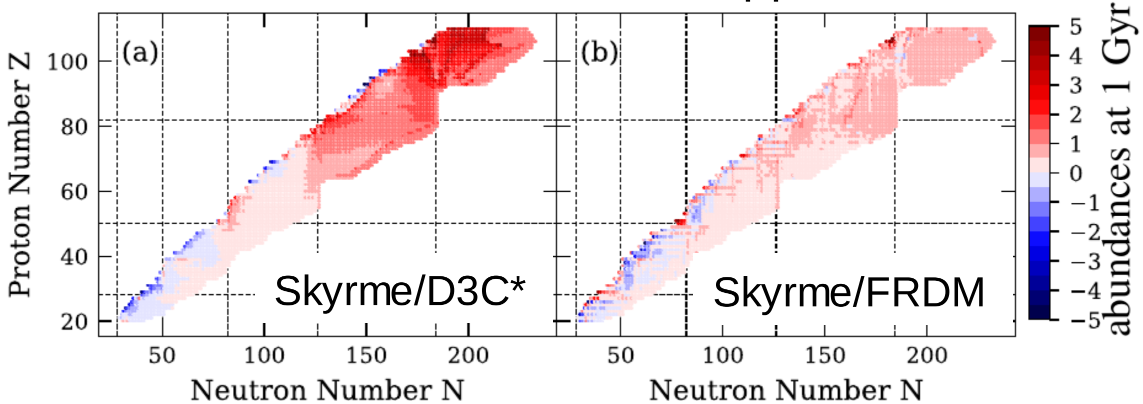


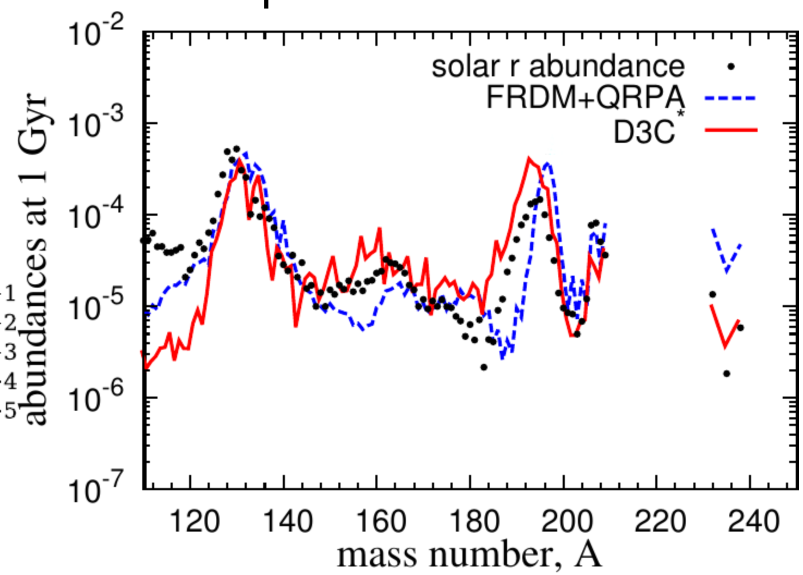


beta-decay half-lives

- Beta-decay half-lives determine the speed at which heavy elements are build starting from light ones
- Theoretical advances allow for global microscopic calculations:
  Marketin+, PRC 93, 25805 (2016) [DC3*], Ney+, PRC 102, 034326 (2020) (Skyrme)
- Half-lives have a strong impact on the position of the A ~ 195 peak

Ratio half-lives different approaches

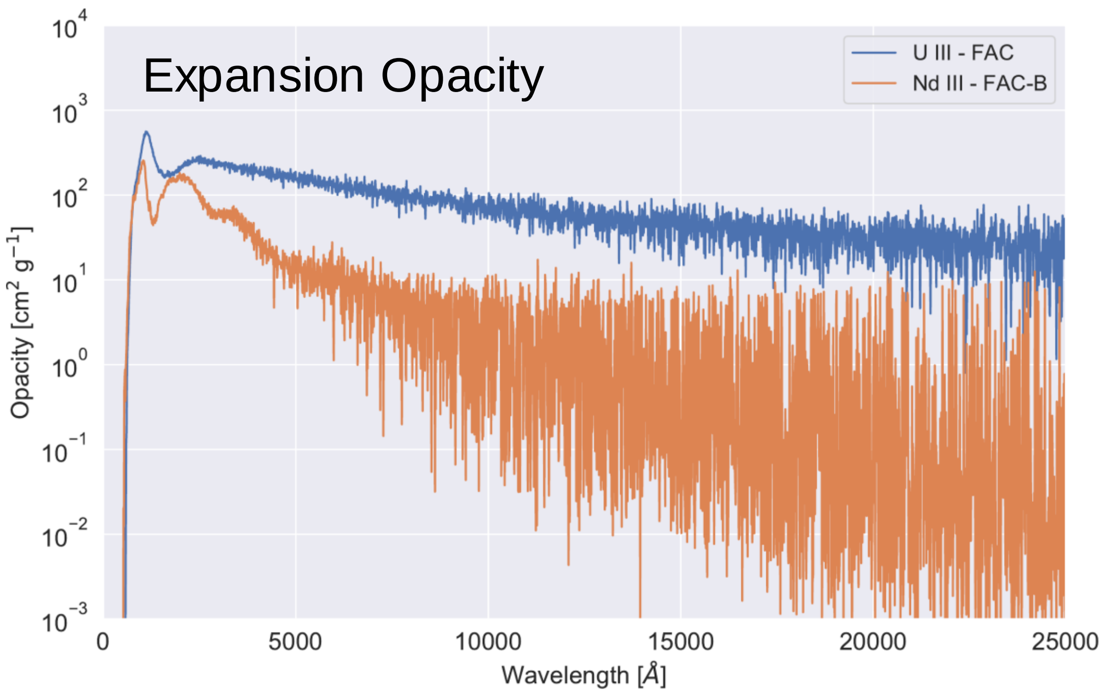




- Need to understand differences in half-lives for heavy nuclei
- Extension of beyond QRPA approach (Caroline Robin)

Atomic opacities

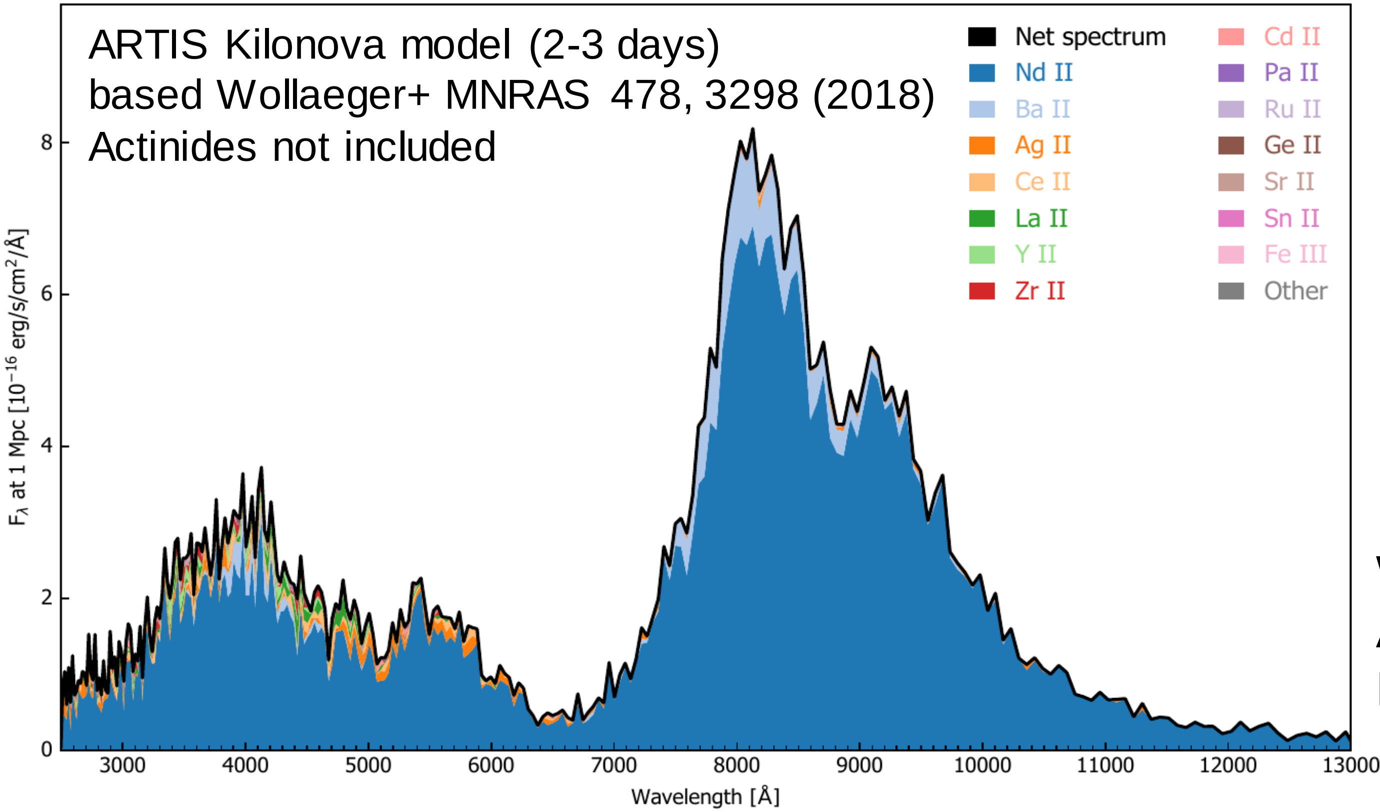
- Opacity of the ejecta determined by bound-bound atomic transitions. No data available for most of the ions.
- Systematic calculation of opacities for all relevant ions including both Lanthanides and Actinides using the Flexible Atomic Code (collaboration U. Lisboa)



Actinides have substantially larger opacities than Lanthanides. Offers a method to characterize presence of Actinides in spectra.

Radiation transfer modelling

- Opacities, together with the nuclear energy deposition and thermalization constitute the basic input for light curve and spectra modelling
- Extension of Supernova Spectral Synthesis codes TARDIS (1D) and ARTIS (3D) to kilonova modelling (collaboration U. Belfast)



Work lead by:
Andreas Flörs
Luke Shingles

R-process review

REVIEWS OF MODERN PHYSICS, VOLUME 93, JANUARY–MARCH 2021

Origin of the heaviest elements: The rapid neutron-capture process

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