Does electron capture decay matter?

Revisiting Electron Capture decay in the context of high-precision cosmic-ray data

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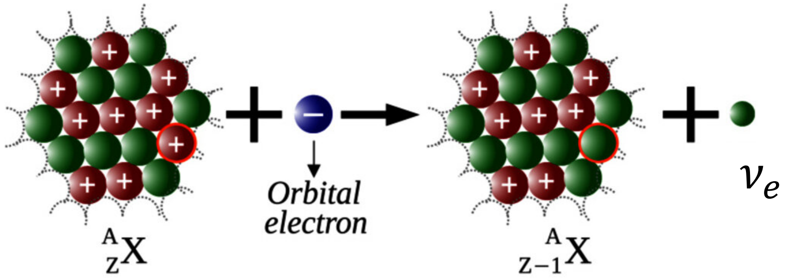
Electron capture decay



e.g. $^{59}_{29}\mathrm{Ni} + e^- \rightarrow \,^{59}_{28}\mathrm{Co} + \nu_e$

- Electron capture (EC) decaying nuclei decay by capturing a K-shell electron
- Most Cosmic-Ray (CR) nuclei are completely ionized.
- EC decay in CR nuclei depends on attachment and stripping processes

Scientific motivations

Direct CRs detection experiments are providing data that allow investigating new (astro)physical phenomena (e. g. dark matter) :

- AMS-02 measured high-precision cosmic-ray fluxes up to Iron *(Aguilar et al. 2021)*
- Recent measurement of the isotopic composition for $29 < Z < 38$ by ACE-CRIS *(Binns et al. 2022)*

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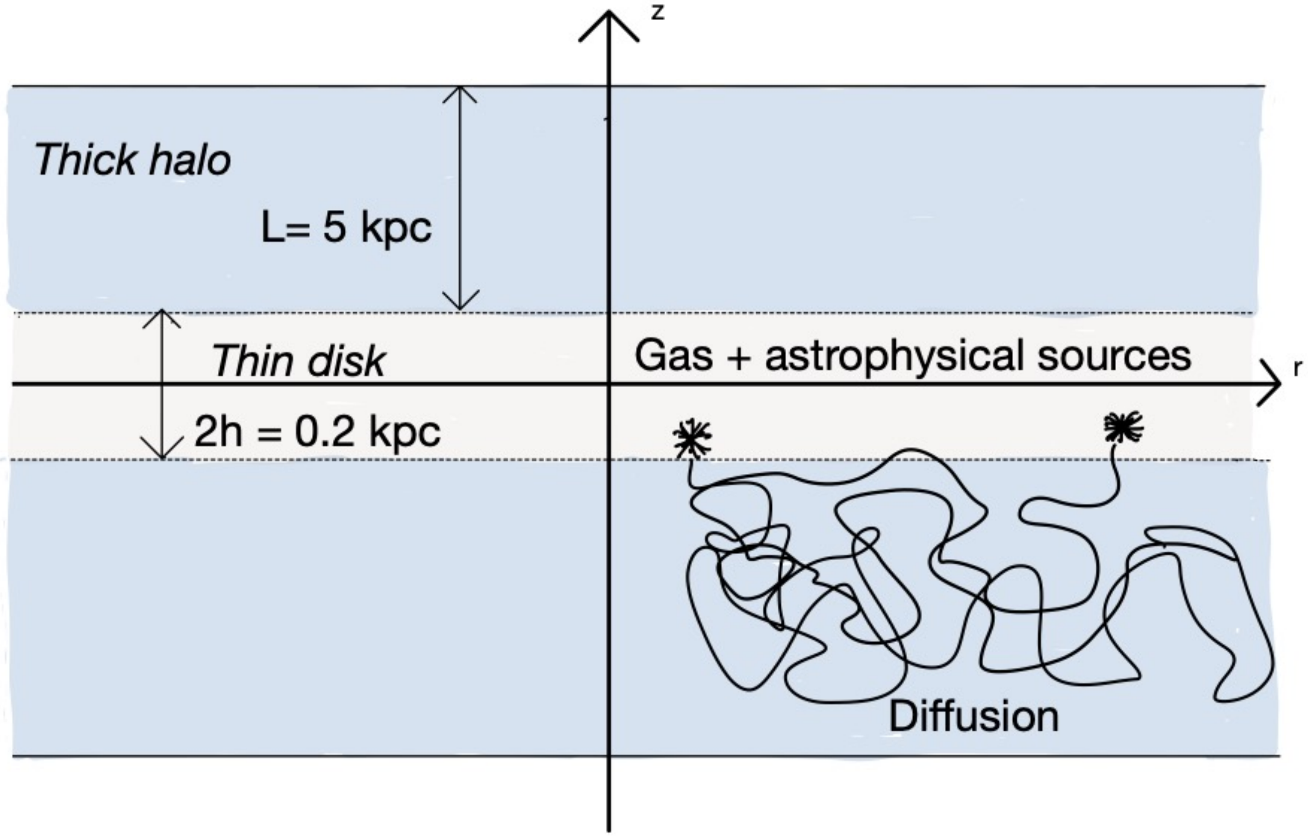
Is electron capture decay relevant for the interpretation of these cosmic-ray data?

Galaxy model

Good first-order description of the Milky Way for Galactic CR fluxes.



- 1D, observer at z=0
- Thin disk: gas (density n_{ISM}) and CR sources
- Thick halo: diffusion and confinement of CR

CR propagation

Transport equations: coupled differential equations for the CRs number density.

$$\begin{cases} -D\dfrac{\partial^2 n_0}{\partial^2 z^2} + 2h\delta(z)\{\Gamma^i n_0 + \Gamma^a n_0 - \Gamma^s n_1\} = 2h\delta(z)\, q \\ -D\dfrac{\partial^2 n_1}{\partial^2 z^2} + 2h\delta(z)\{\Gamma^i n_1 - \Gamma^a n_0 + \Gamma^s n_1\} + \Gamma^{EC} n_1 = 0 \end{cases}$$

CR number density

$n = n_0 + n_1$

n_0 = fully ionized

n_1 = one electron attached

Assuming:

- Steady state
- no energy losses
- 2 populated charged states

CR propagation

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Diffusion (random walk) on magnetic inhomogeneites (disk and halo)

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Generic source term (disk)

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Inelastic interaction rate on gas (disk)

$$\Gamma^i = n_{ISM}\, v\, \sigma_{inel}$$

CR propagation

Diffusion (random walk) on magnetic inhomogeneites (disk and halo)

Attachment rate of e⁻ (disk)

$$\Gamma^a = n_{ISM}\, v\, \sigma_{att}$$

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Inelastic interaction rate on gas (disk)

$$\Gamma^{i} = n_{ISM}\, v\, \sigma_{inel}$$

Stripping rate of e⁻ (disk)

$$\Gamma^{s} = n_{ISM}\, v\, \sigma_{strip}$$

CR propagation

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Inelastic interaction rate on gas (disk)

$\Gamma^i = n_{ISM}\, v\, \sigma_{inel}$

Stripping rate of e⁻ (disk)

$\Gamma^s = n_{ISM}\, v\, \sigma_{strip}$

EC decay rate Γ^{EC} (only if e⁻ attached)

Characteristic timescales

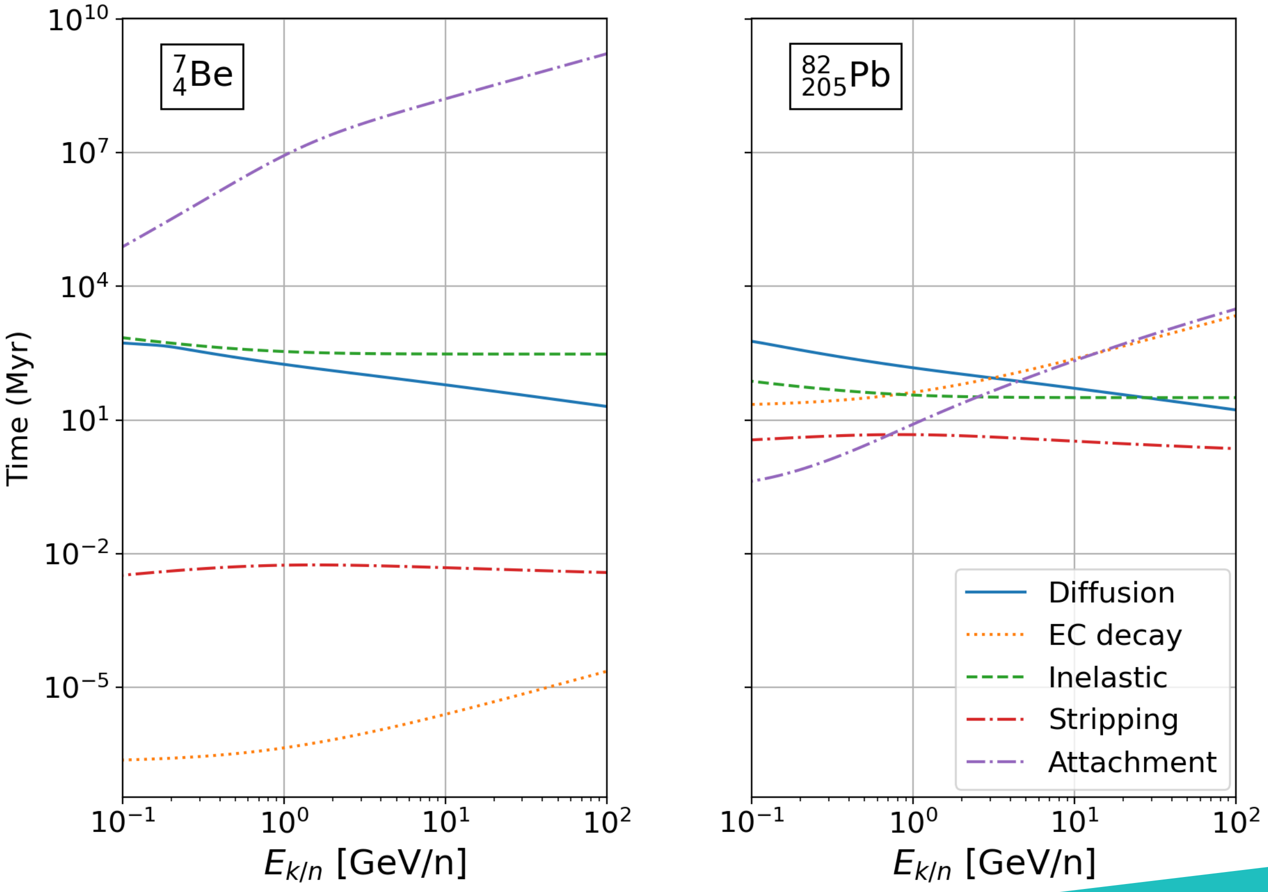
Diffusion	$t_D = \frac{L^2}{2D}$	$D \propto E^{0.5}$
Inelastic scattering	$t_{inel} = \frac{1}{n_{ISM}\, v\, \sigma_{inel}}$	$\sigma_{inel} \propto A^{2/3}$
Attachment	$t_a = \frac{1}{n_{ISM}\, v\, \sigma_{att}}$	$\sigma_{att} \propto \sigma(E)Z^2$
Stripping	$t_s = \frac{1}{n_{ISM}\, v\, \sigma_{strip}}$	$\sigma_{strip} \propto \sigma(E)Z^{-2}$
EC decay	$t_{EC} = \gamma\tau_{EC}$	$t_{EC} \propto E$

The lower the time, more dominant is the corresponding process

Characteristic timescales

- Diffusion dominates above a few GeV/n
- Attachment more efficient than stripping for large Z

→ Net effect of EC decay depends on interplay between t_{att}, t_{strip} and t_{EC}
→ EC decay expected to be relevant at low E and large Z



Solving the transport equations

The trasport equations have been solved analitycally:

- In thin disk approximation
- at z=0, to allow comparison with data

$$\begin{cases} N_0 = \dfrac{q}{\dfrac{D}{hL} + \Gamma^i + \Gamma^a - \dfrac{\Gamma^s\Gamma^a}{f_1 + \Gamma^i + \Gamma^s}} \\ N_1 = \dfrac{\Gamma^a N_0}{f_1 + \Gamma^i + \Gamma^s} \end{cases}$$

with

$$f_1 = \sqrt{\frac{D\Gamma^{EC}}{h^2}}\coth\left(\sqrt{\frac{\Gamma^{EC}}{D}}L\right)$$

Flux: J= vN/4π

EC decaying isotopes

We used a selection of EC decaying isotopes from *Letaw et al., 1984, ApJS, 56, 36.*

EC decaying isotopes can be classified in two categories:

Isotope	$\tau_{1/2}$ (Myr)	Isotopic fraction
$^{7}_{4}Be$	$1.46\ 10^{-7}$	0.55
$^{37}_{18}Ar$	$9.58\ 10^{-8}$	0.30
$^{41}_{20}Ca$	$1.00\ 10^{-1}$	0.07
$^{53}_{25}Mn$	3.70	0.35
$^{67}_{31}Ga$	$8.93\ 10^{-9}$	0.07
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EC decaying isotopes can be classified in two categories:

- Short-lived isotopes:

  $\tau_{EC} < 10^{-3}$ Myr

- Intermediate-lived isotopes:

  $10^{-3} < \tau_{EC} < 10^{2}$ Myr

NB: Escape from the Galaxy before decaying for $\tau_{EC} > 10^{2}$ Myr

Isotope	$\tau_{1/2}$ (Myr)	Isotopic fraction
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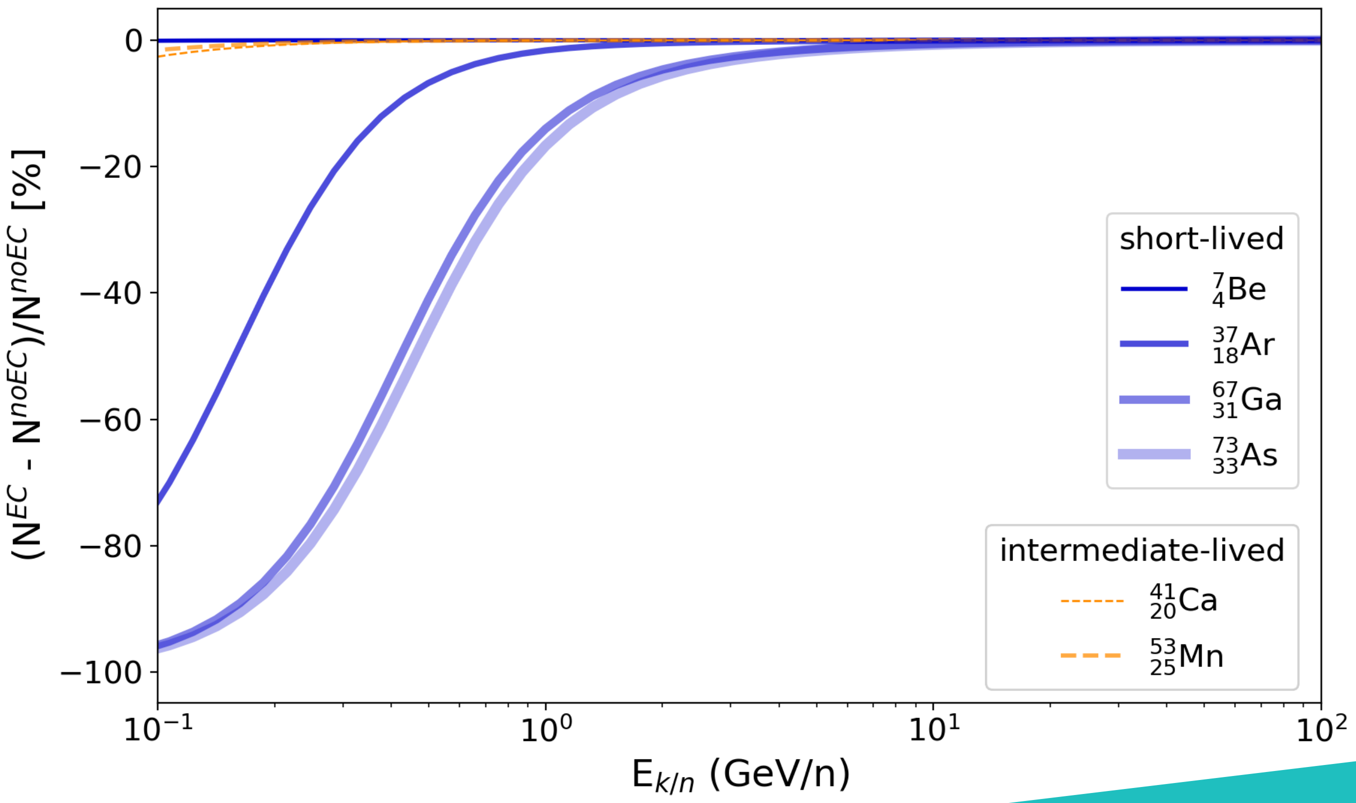
Impact on isotopic fluxes

→ Short-lived heavy nuclei all decay at low E

→ No effect on intermediate-lived isotopes and for E > few GeV/n

NB: ACE-CRIS data precision is ~ 50% for Ga and As

Percentage of CRs isotopes that decays by EC

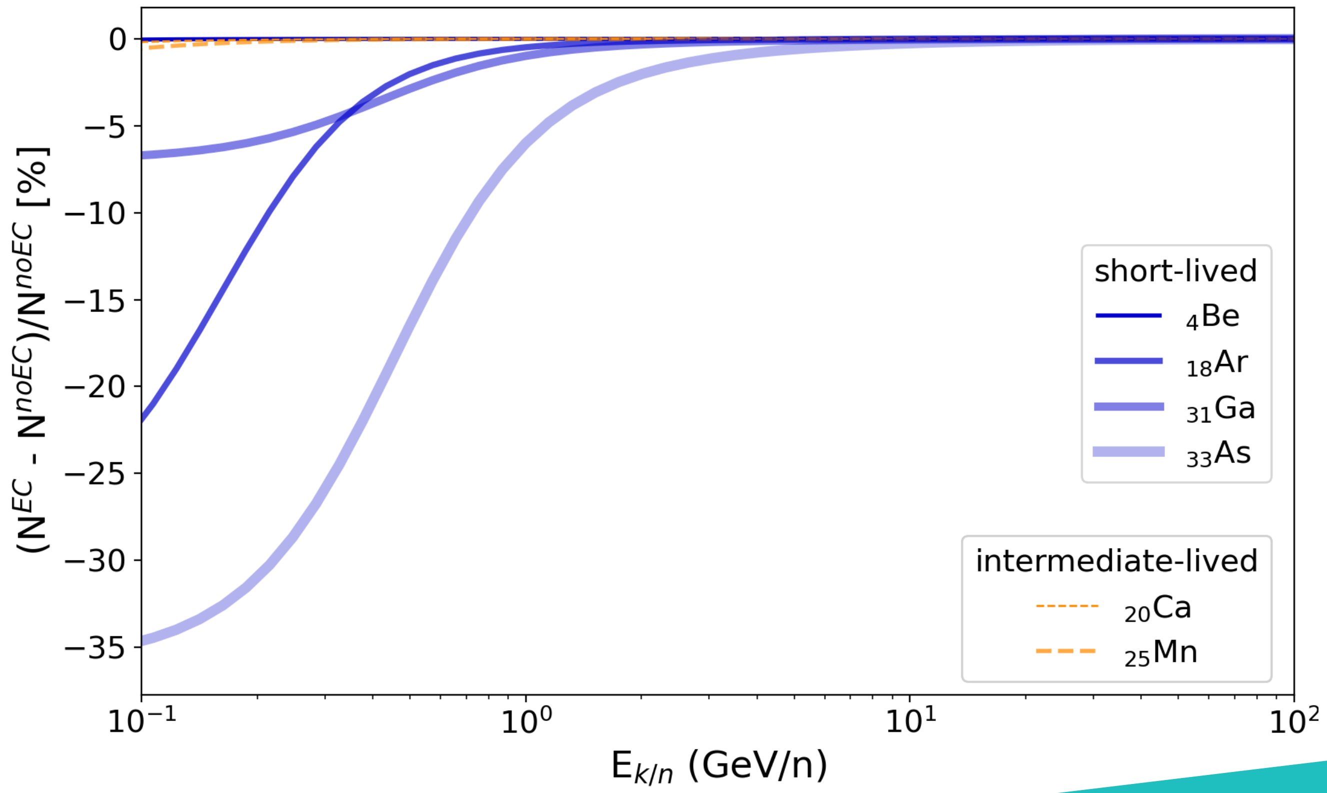


Impact on elemental fluxes

The impact of EC decay on elemental fluxes is weighted by isotopic abundances

- Short-lived CRs fully decay at low E in Ga and As but not in Ar
- No impact for intermediate-lived nuclei

Percentage of CRs nuclei that decays by EC



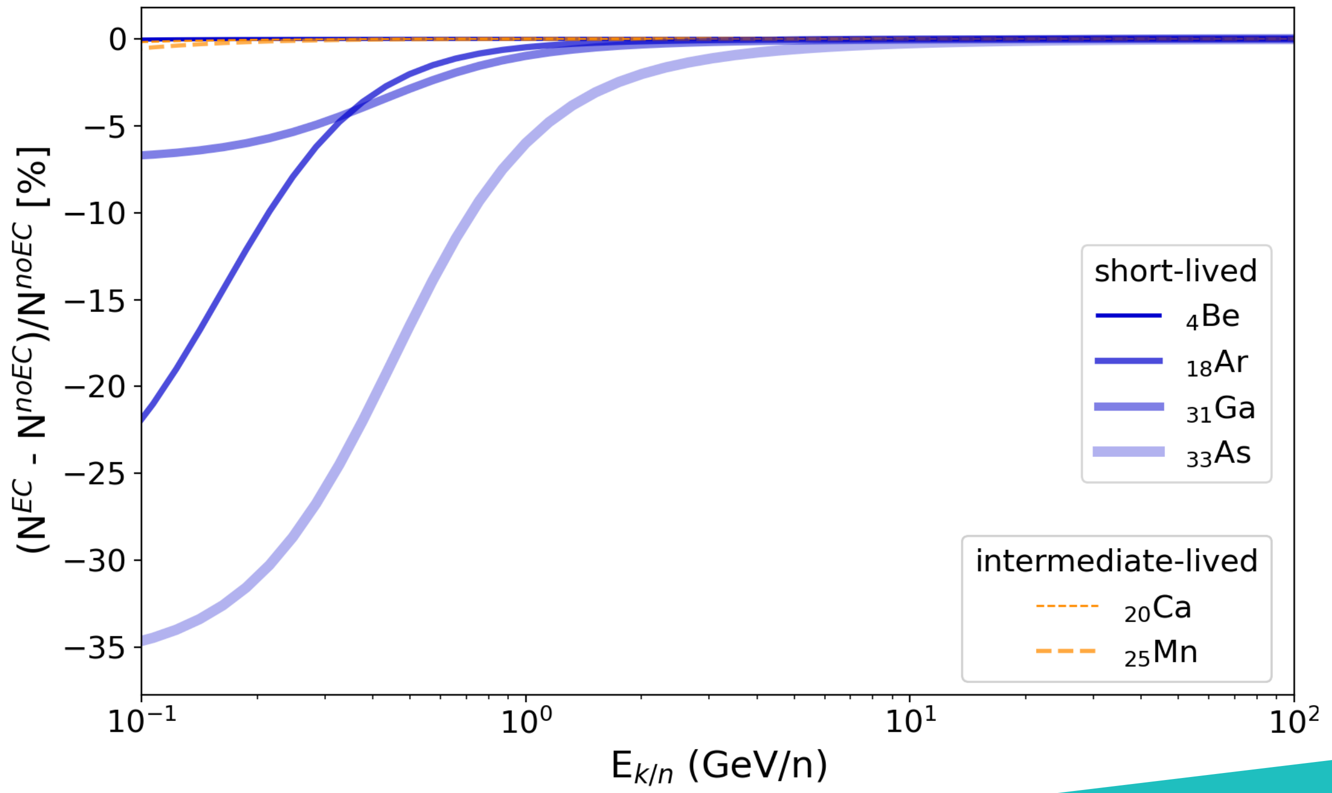
Impact on elemental fluxes

The impact of EC decay on elemental fluxes is weighted by isotopic abundances

NB: data precision at few hundreds MeV/n is

- Less than 5% (expected) for Ar with AMS-02
- ~ 7% for Ga and 30% for As with ACE-CRIS

Percentage of CRs nuclei that decays by EC



Conclusions and perspectives

What we did:

- We computed relevant timescales for GCR fluxes
- We derived solutions for EC decaying isotopes (2-level model)
- We computed the impact of EC decay on isotopic and elemental fluxes

What we found:

→ The net effect of EC decay depends both on Z and τ_{EC}

→ Impact on isotopic fluxes ~ ACE-CRIS precision

→ Impact on elemental fluxes slightly larger than AMS-02 precision

Conclusions and perspectives

Still to be done:

→ Further improvement of this analytical model

→ Implementing EC in the USINE code to account for:

- energy losses and Solar modulation
- detailed production of the various isotopes


That's all Folks!

Backup

Characteristic timescales

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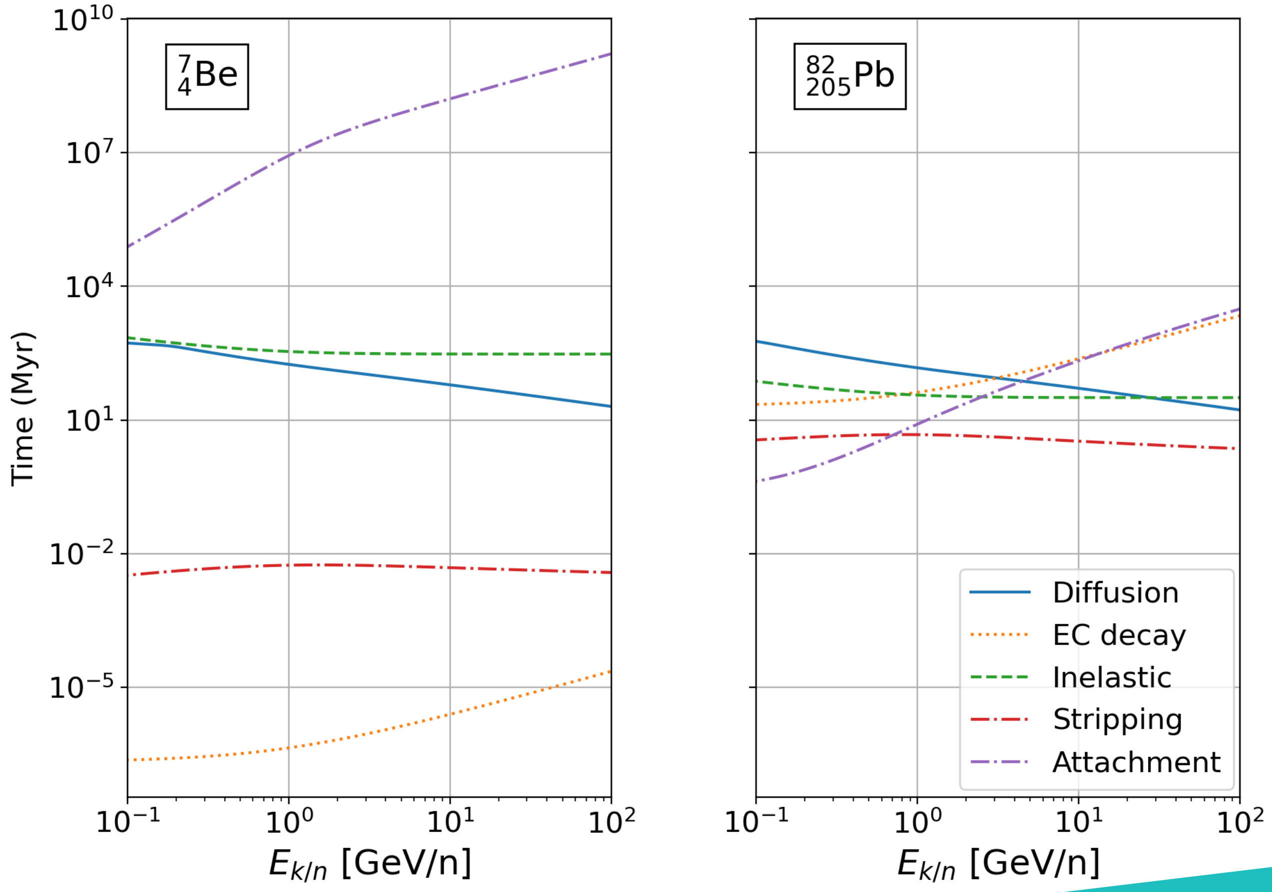

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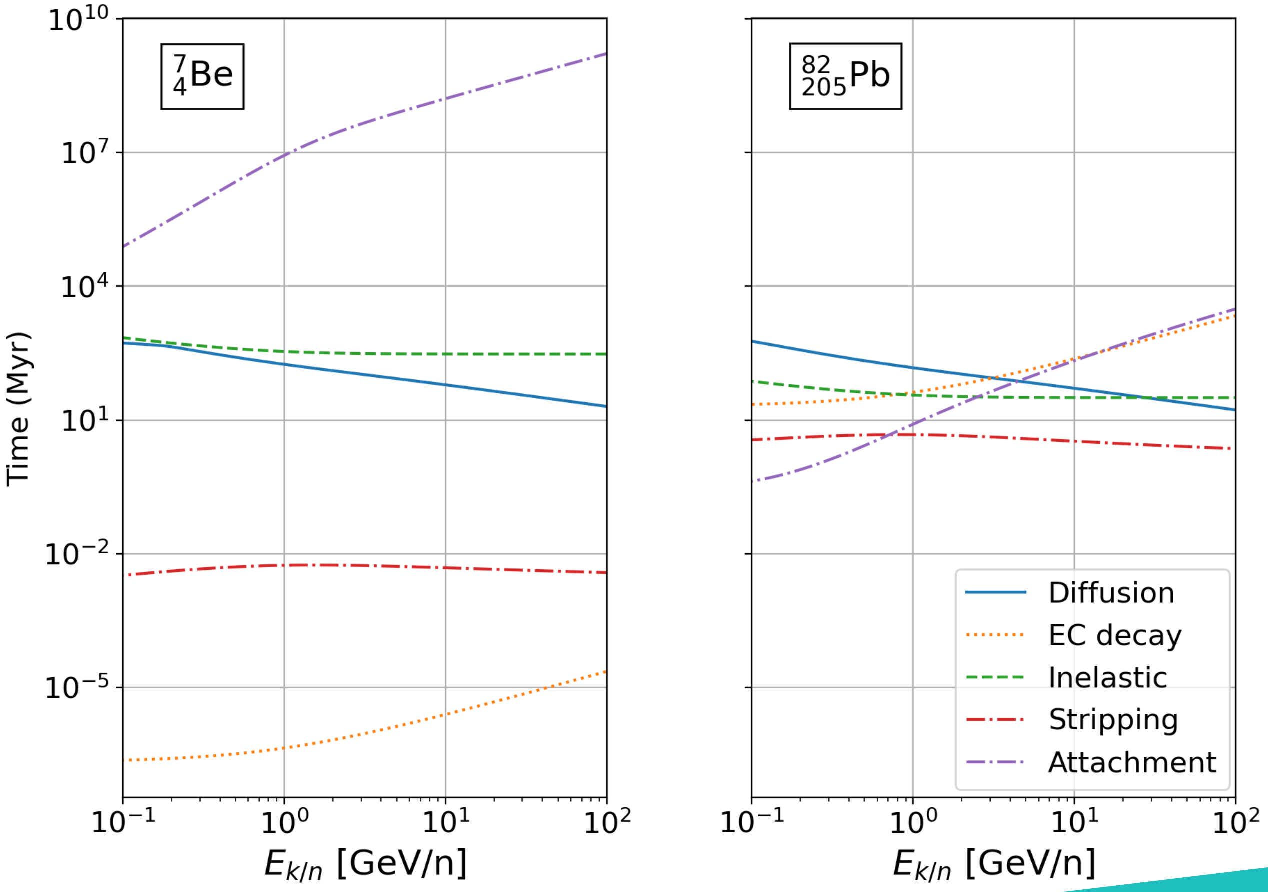
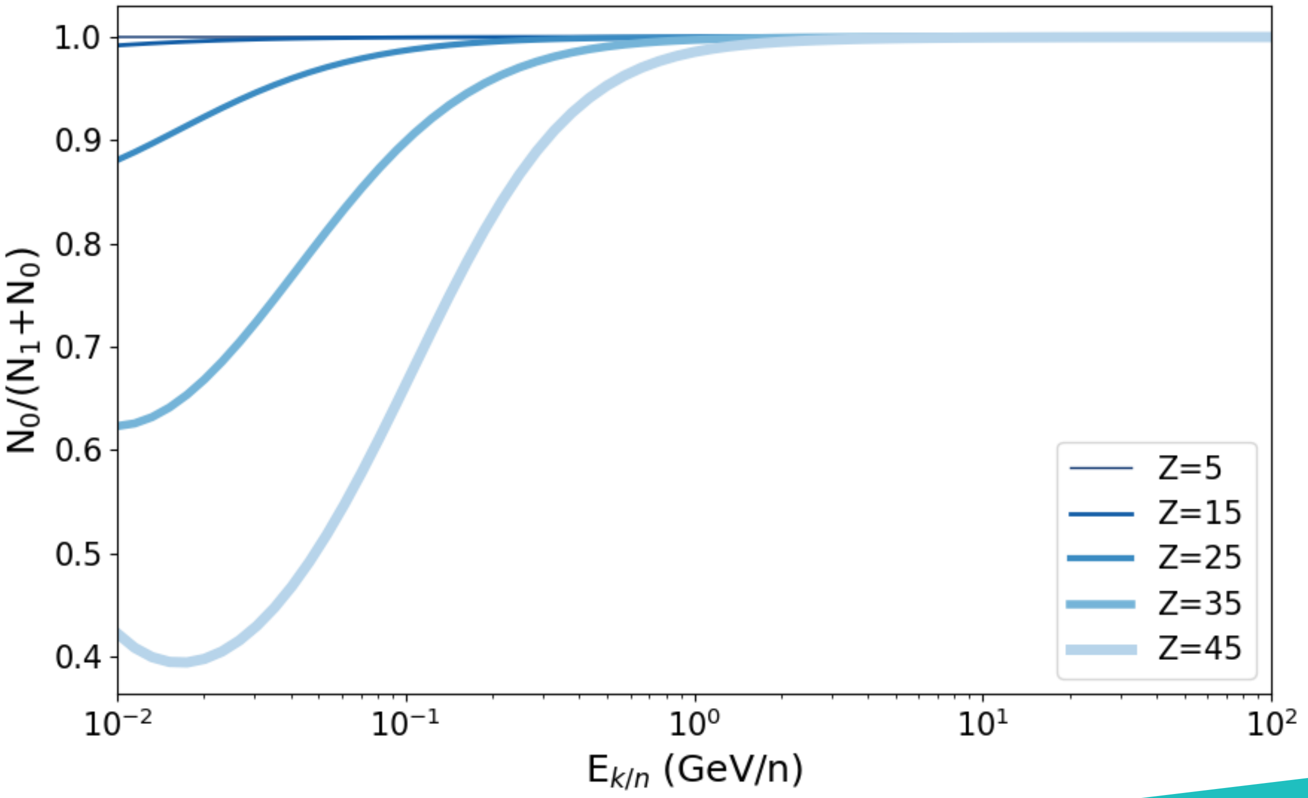


Attachment and stripping

We want to follow CRs passing from one charge state to the other:

- Stable isotopes: $\Gamma^{EC} = 0$
- Charges from 5 to 45

Fraction of CRs that do not attach an e^-



Attachment and stripping

We want to follow CRs passing from one charge state to the other:

- Stable isotopes: $\Gamma^{\mathrm{EC}} = 0$
- Charges from 5 to 45

→ No e⁻ attached above a few GeV/n
→ Heavier CRs attach more e⁻ than light CRs

Fraction of CRs that do not attach an e^-