Does electron capture decay matter?

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

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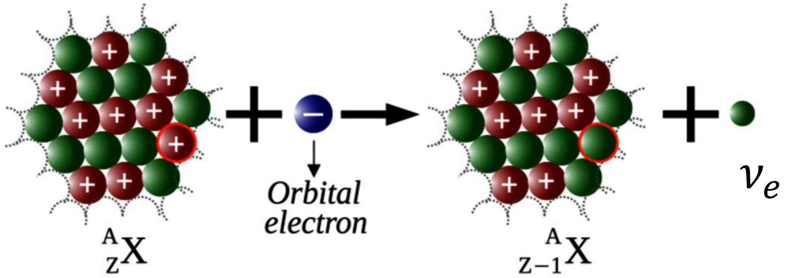
Electron capture decay



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

Why to study EC decay?

Direct CRs detection experiments are providing high-precision data on GCR fluxes and are extending the measurements on heavy elements :

AMS-02 high-precision cosmic-ray TOA fluxes up to Iron (Aguilar et al. 2021)

Measurements Voyager IS fluxes from H to Ni (Cummings et al. 2016)

Isotopic composition for 29 < Z < 38 by ACE-CRIS (Binns et al. 2022)

Elemental ratios for 26 < Z < 40 by SuperTIGER (Murphy et al. 2016)

→We need models as accurate as possible for comparison with data

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Iso

CRIS (Binns et al. 2022)

ER

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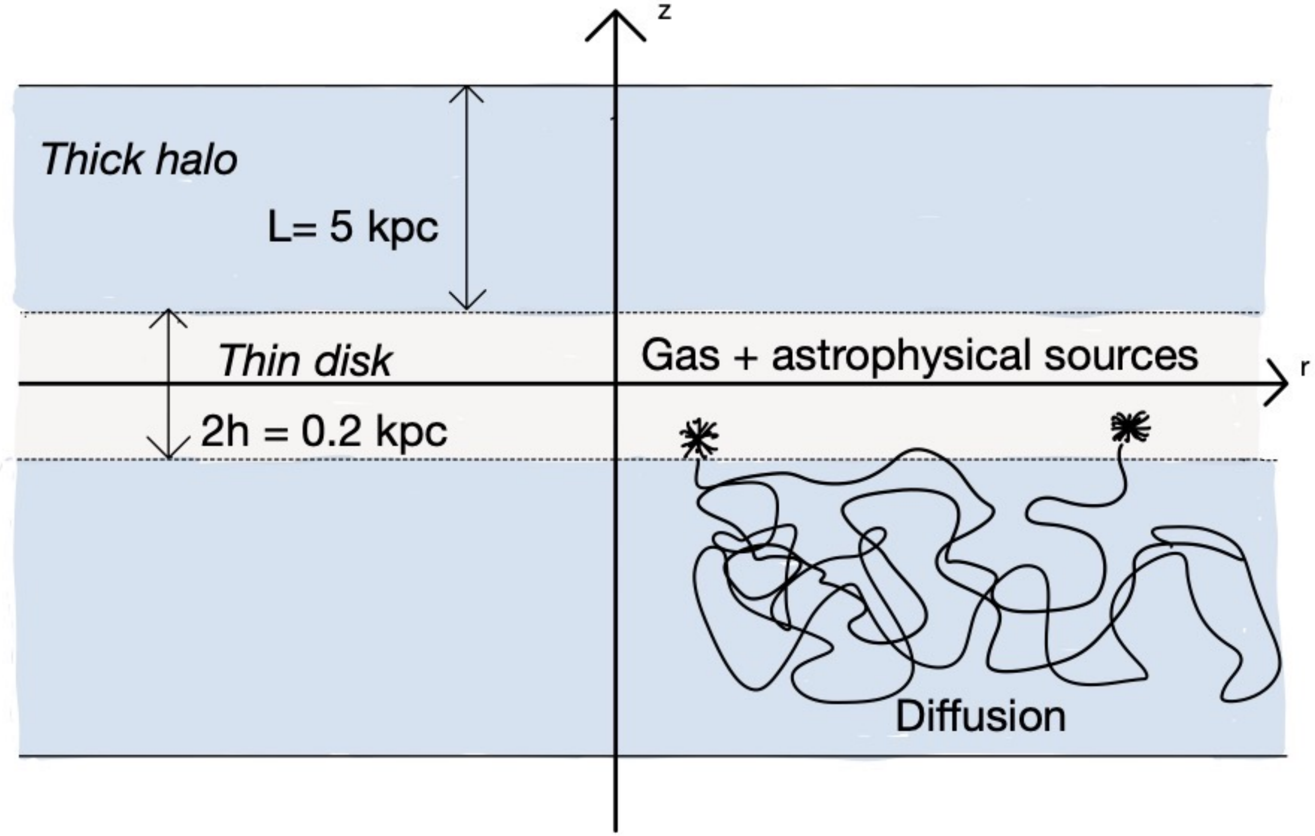
Is electron capture decay relevant for the interpretation of galactic cosmic-ray data?

→We need models as accurate as possible for comparison with 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

Steady-state transport equation for an EC-unstable species

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

Assuming:

- No convection
- no energy losses
- 2 populated charged states

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CR number density

$$n = n_0 + n_1$$

n_0 = fully ionized

n_1 = one electron attached

CR propagation

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

$$\begin{cases} -\boxed{\mathrm{D}}\dfrac{\partial^2\,\mathrm{n}_0}{\partial^2\mathrm{z}^2} + 2\mathrm{h}\delta(\mathrm{z})\left\{\Gamma^{\mathrm{i}}\mathrm{n}_0 + \Gamma^{\mathrm{a}}\mathrm{n}_0 - \Gamma^{\mathrm{s}}\mathrm{n}_1\right\} = 2\mathrm{h}\delta(\mathrm{z})\,\mathrm{q} \\ -\boxed{\mathrm{D}}\dfrac{\partial^2\,\mathrm{n}_1}{\partial^2\mathrm{z}^2} + 2\mathrm{h}\delta(\mathrm{z})\left\{\Gamma^{\mathrm{i}}\mathrm{n}_1 - \Gamma^{\mathrm{a}}\mathrm{n}_0 + \Gamma^{\mathrm{s}}\mathrm{n}_1\right\} + \Gamma^{\mathrm{EC}}\mathrm{n}_1 = 0 \end{cases}$$

CR propagation

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

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)

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Stripping rate of e⁻ (disk)

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

CR propagation

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

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Inelastic interaction rate on gas (disk)

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Stripping rate of e⁻ (disk)

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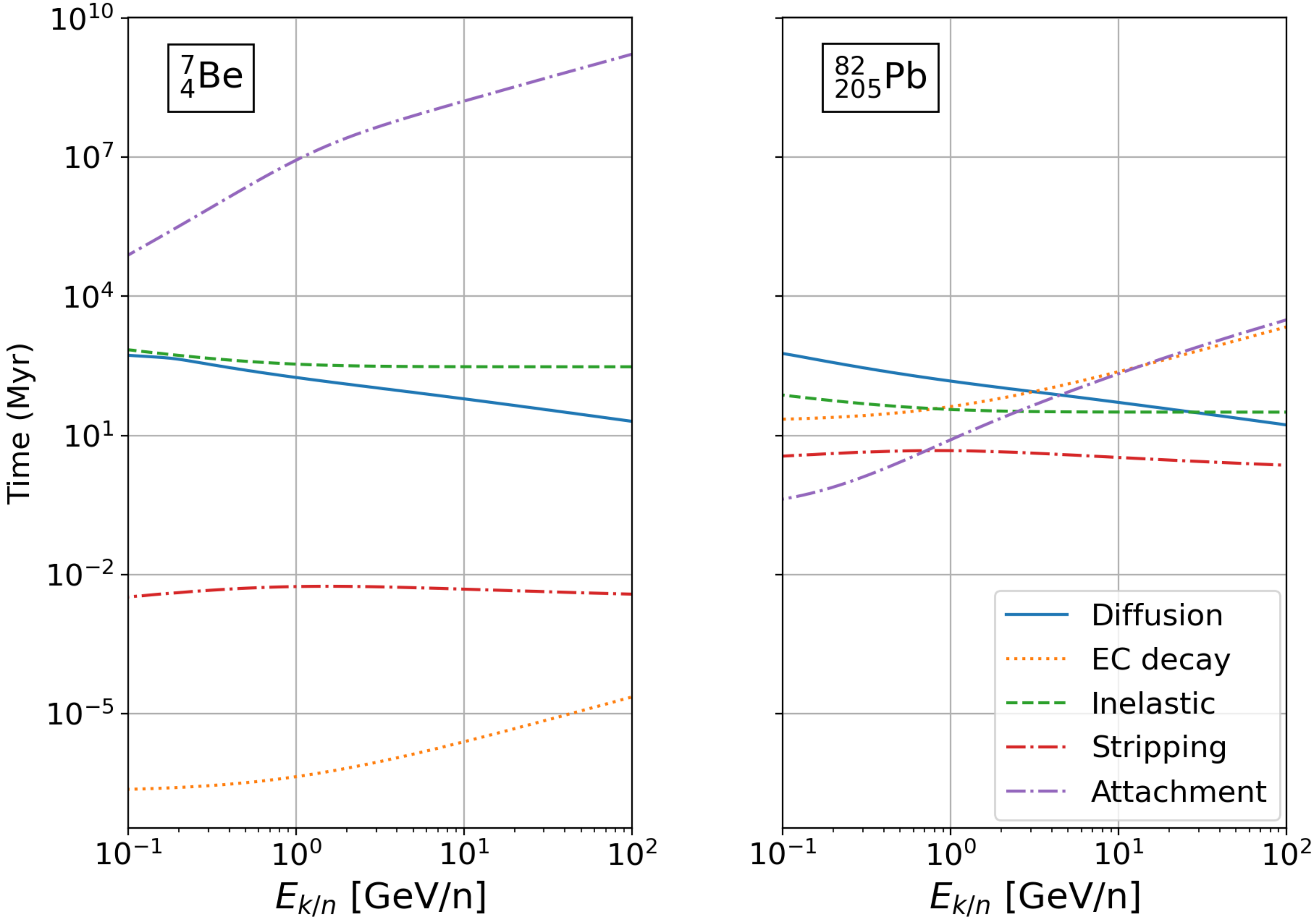
EC decay rate Γ^{EC} (only if e⁻ attached)

Characteristic timescales



Borchiellini et al., PoS ICRC2023 (2023) 066

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

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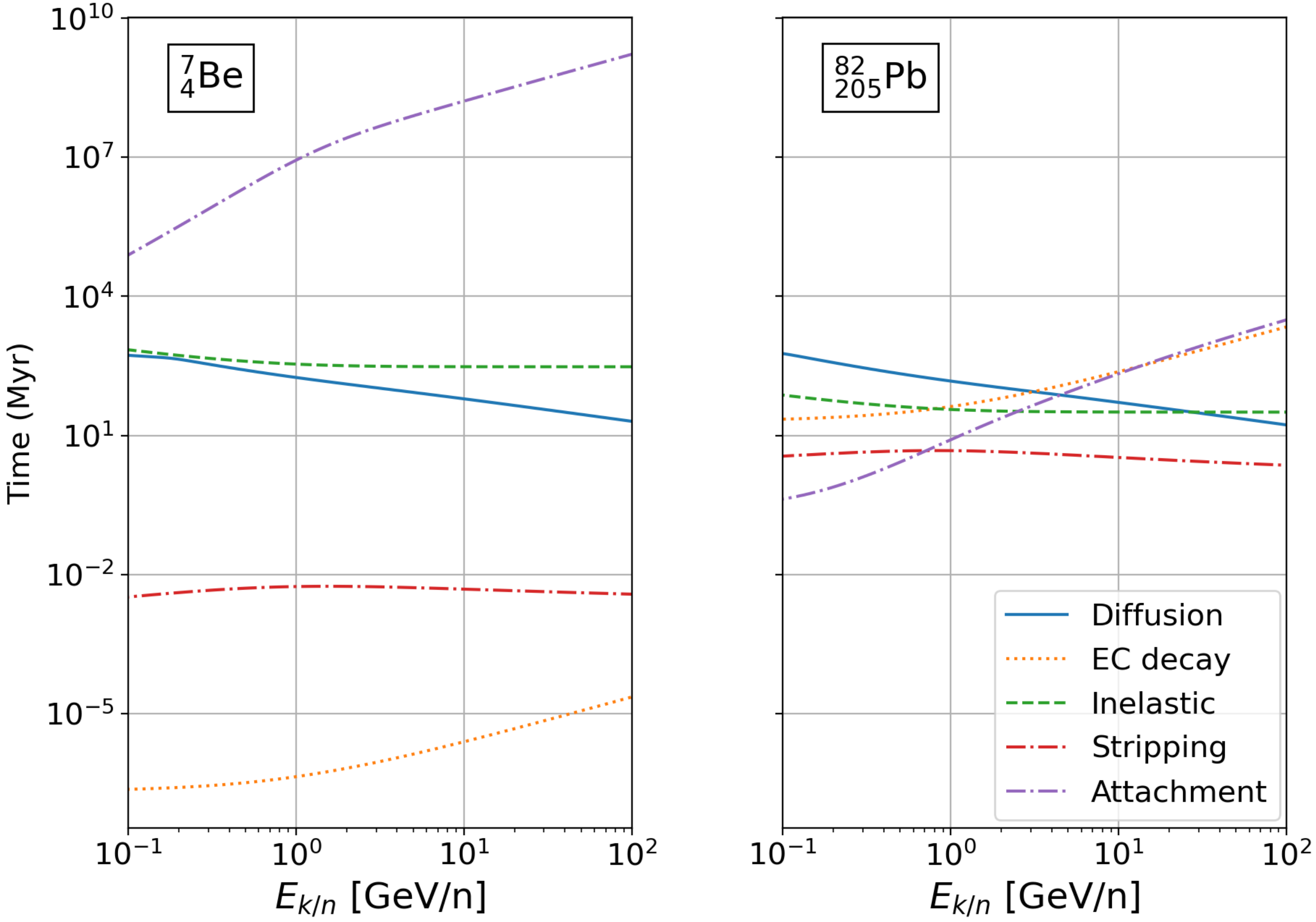

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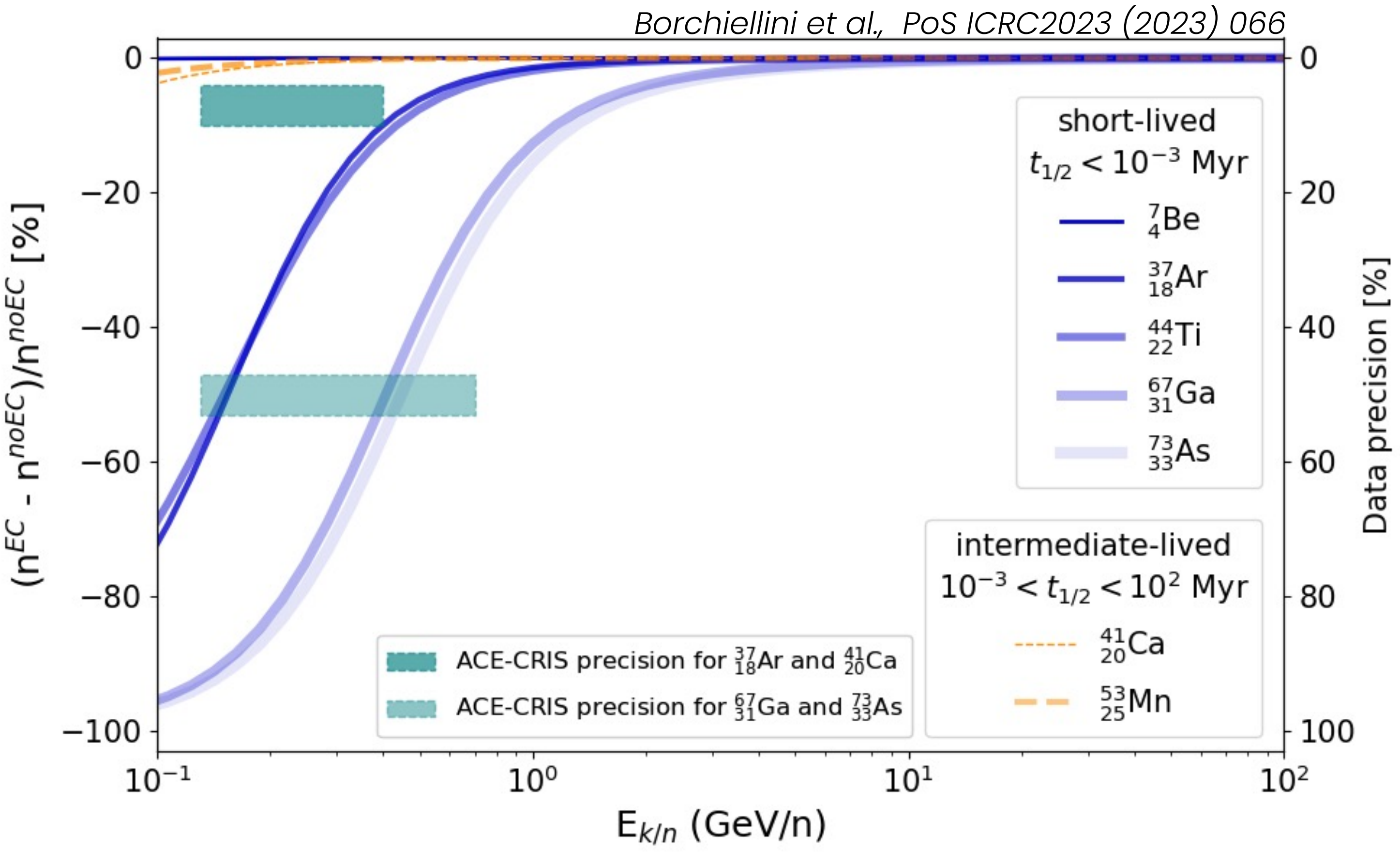
- Diffusion dominates above a few GeV/n
- Attachment more efficient than stripping for large Z

→ 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

Impact on isotopic fluxes

Percentage of CRs isotopes that decays by EC



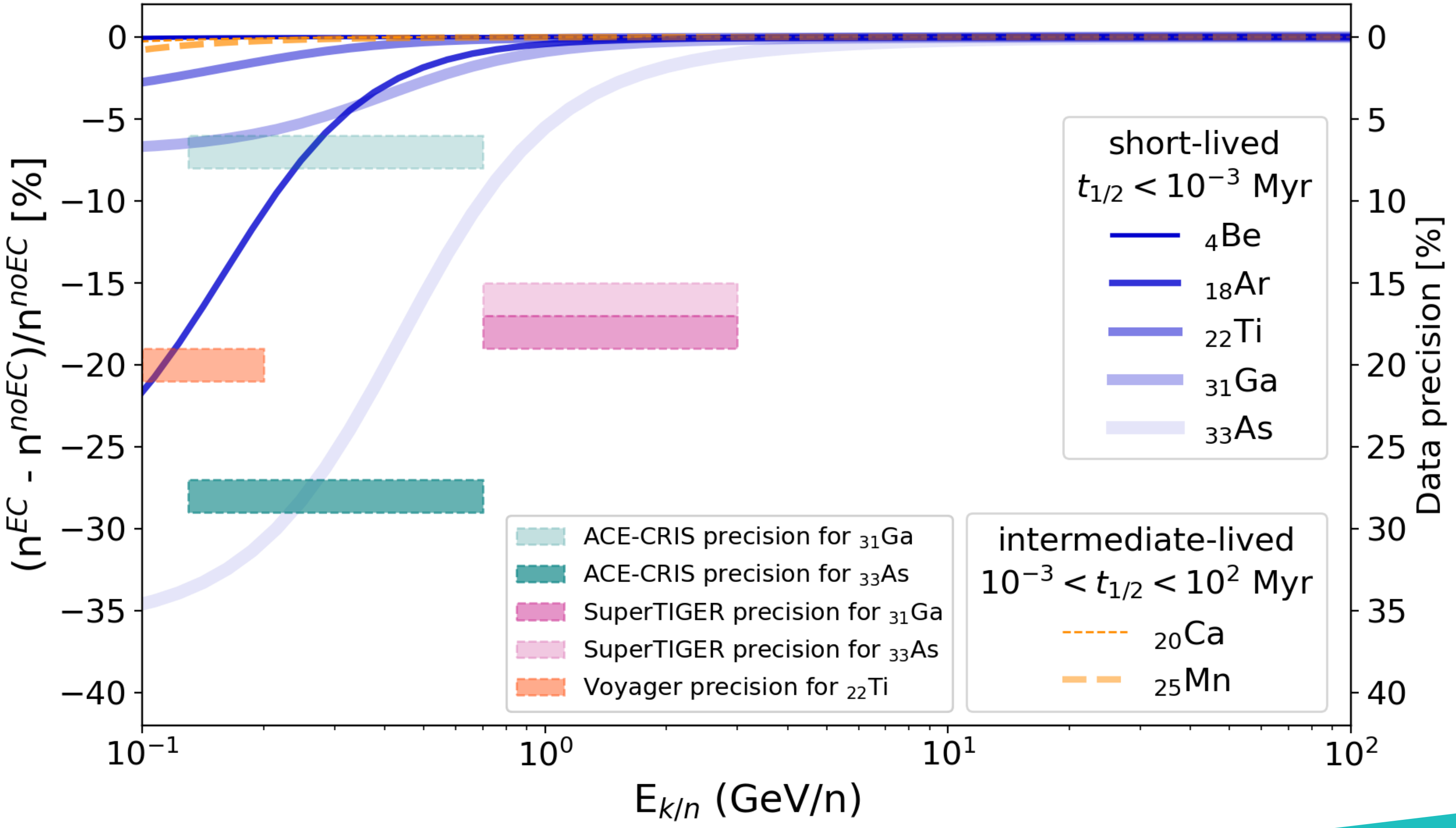
→ No effect on intermediate-lived isotopes and for E > few GeV/n

→ Short-lived heavy nuclei all decay at low E

Impact on elemental fluxes

Percentage of CRs nuclei that decays by EC

Borchiellini et al., PoS ICRC2023 (2023) 066



- Impact of EC decay on elemental fluxes weighted by isotopic abundances
- Short-lived CRs fully decay at low E in Ga and As but not in Ar

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 $\gtrsim$ ACE-CRIS precision

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

~ ACE-CRIS precision

Conclusions and perspectives

Overall, the effect has to be taken properly into account when modelling GCR transport.

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

Thank you!

Backup

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

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

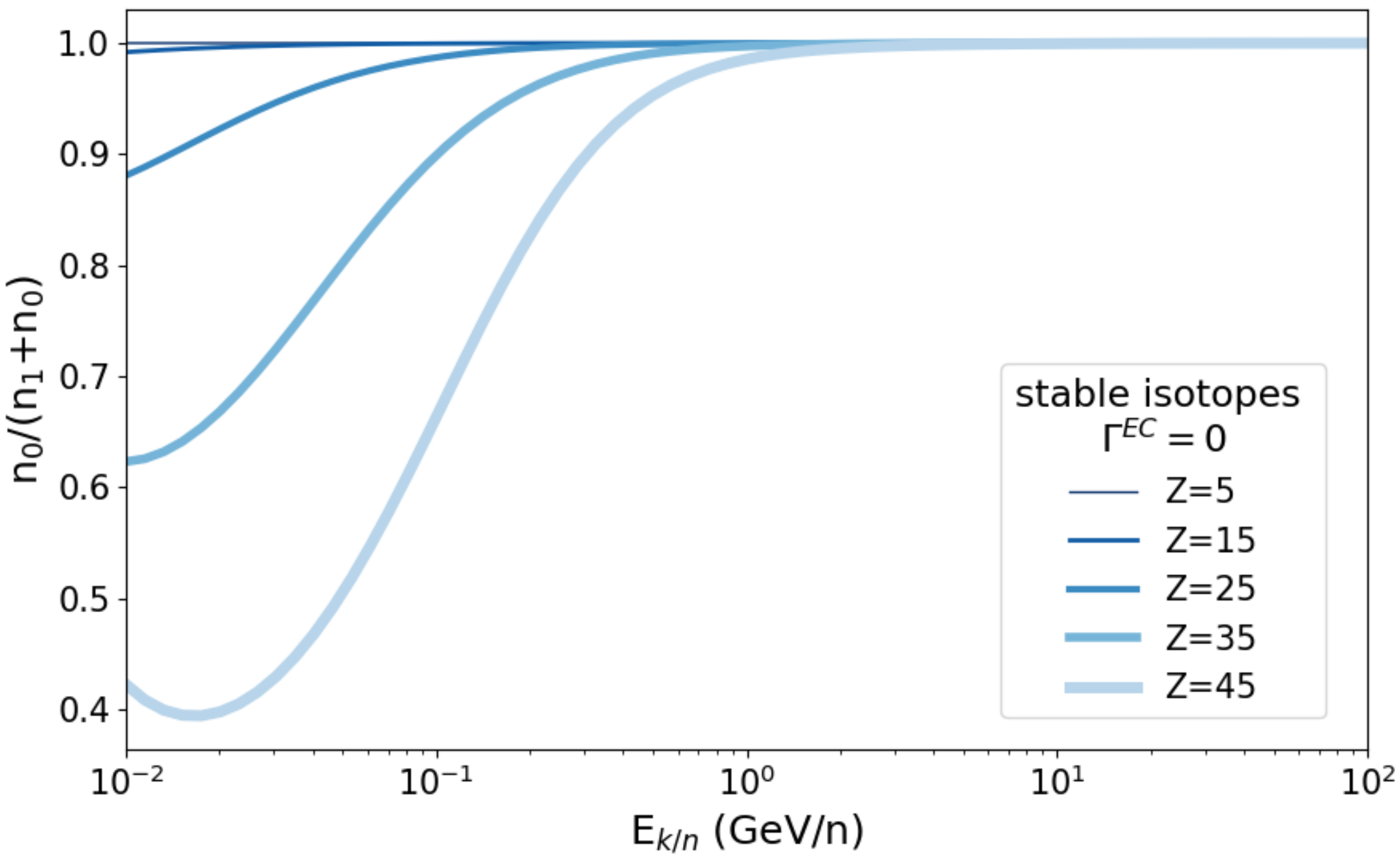
Flux: $J = vN/4\pi$

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

Attachment vs stripping



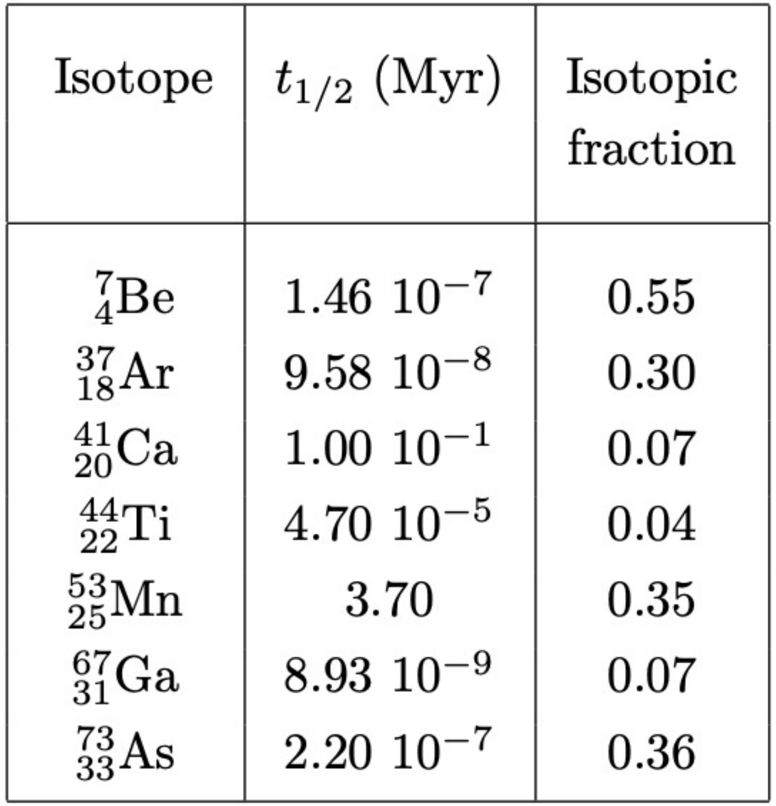
Fraction of particle that do not attach an e-

- no particle attach e- for E> 1 GeV/n
- Heavier CRs attach more e- tha light ones

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	$t_{1/2}$ (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
$^{44}_{22}$Ti	$4.70\ 10^{-5}$	0.04
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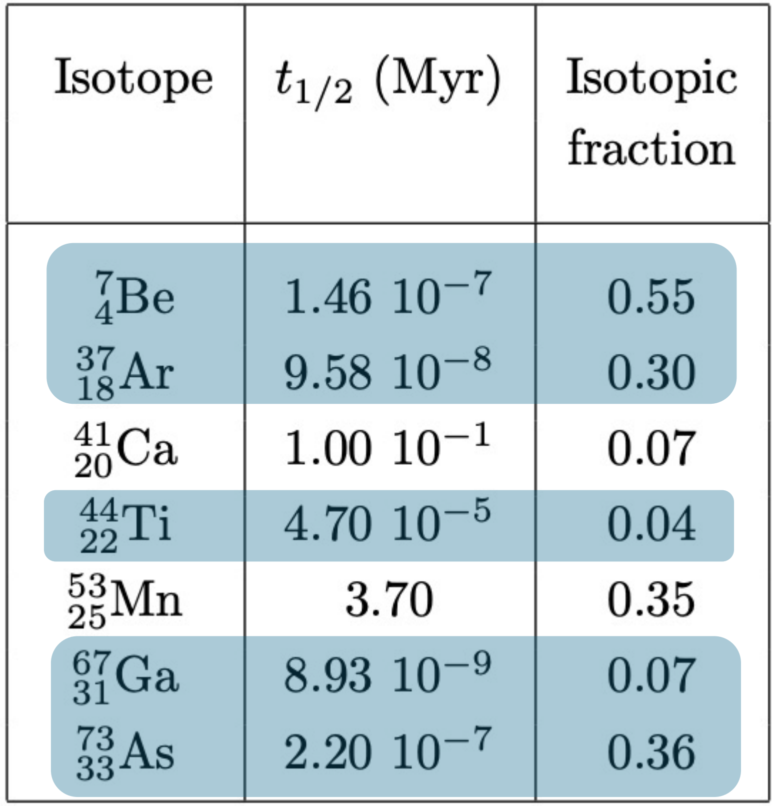

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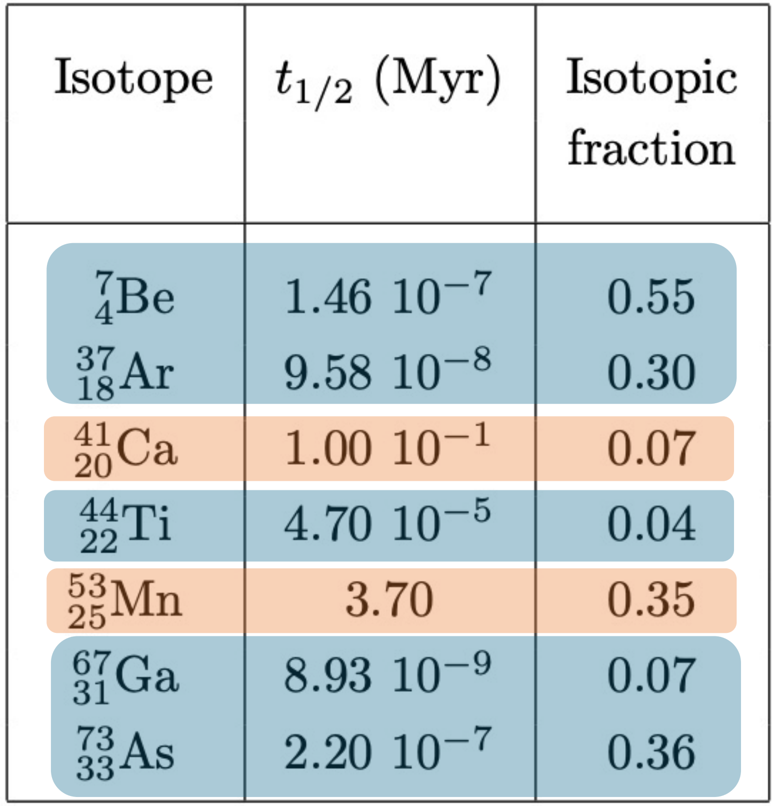
- Short-lived isotopes:

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

- Intermediate-lived isotopes:

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

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



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