Resonance Photoproduction of Pionic Atoms
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Victor V. Flambaum

Based on: V. V. Flambaum, J. Jin, and D. Budker, **arXiv:2010.06912**

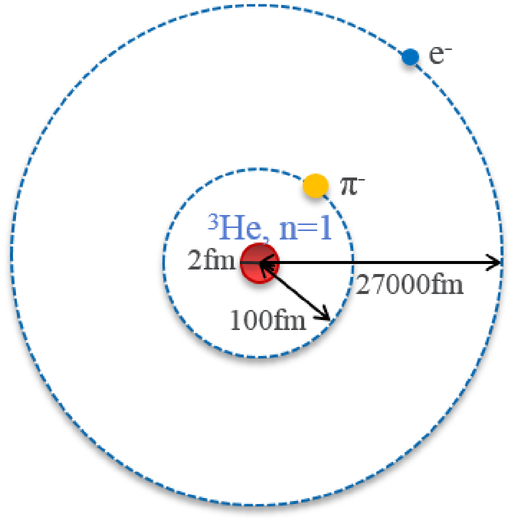
Outline

- Pionic atoms
- Photoproduction cross-sections
- Production rates expected at GF

Pionic atoms

➢ A negative pion orbiting the nucleus

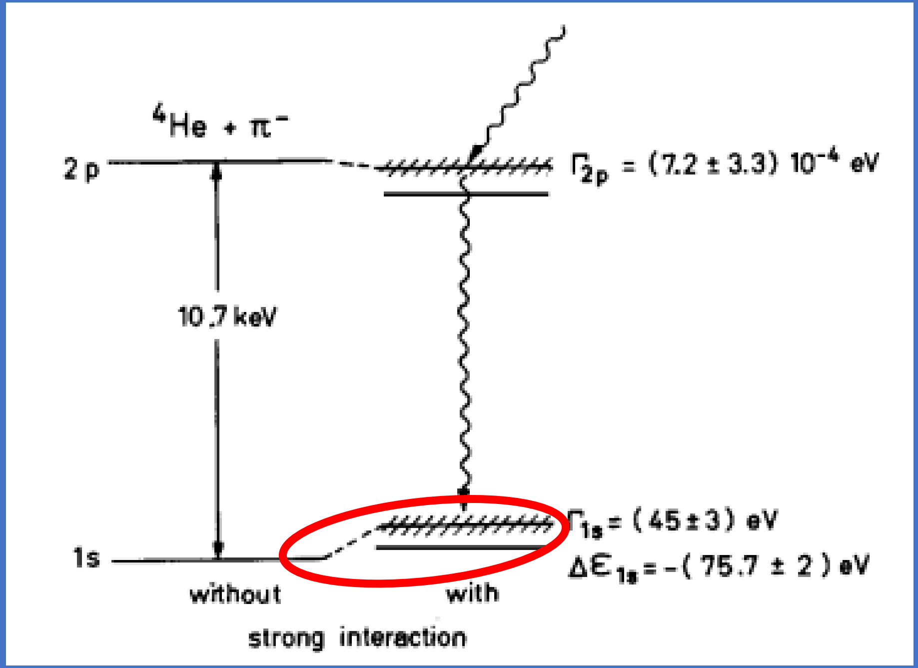
- hydrogen-like system
- $m_\pi c^2 \approx 140$ MeV$\approx 270\ m_e c^2$



Spin =0. Critical charge for point nucleus Z=68!
1s orbital radius is close to nuclear radius for Z=40

➢ Strong interaction effects

- pion absorption → width broadening
- energy shift *vs.* Coulomb



J. Hüfner, Pions interact with nuclei, Physics Reports 21, 1 (1975)

Pionic atoms

➢ Physics Motivation

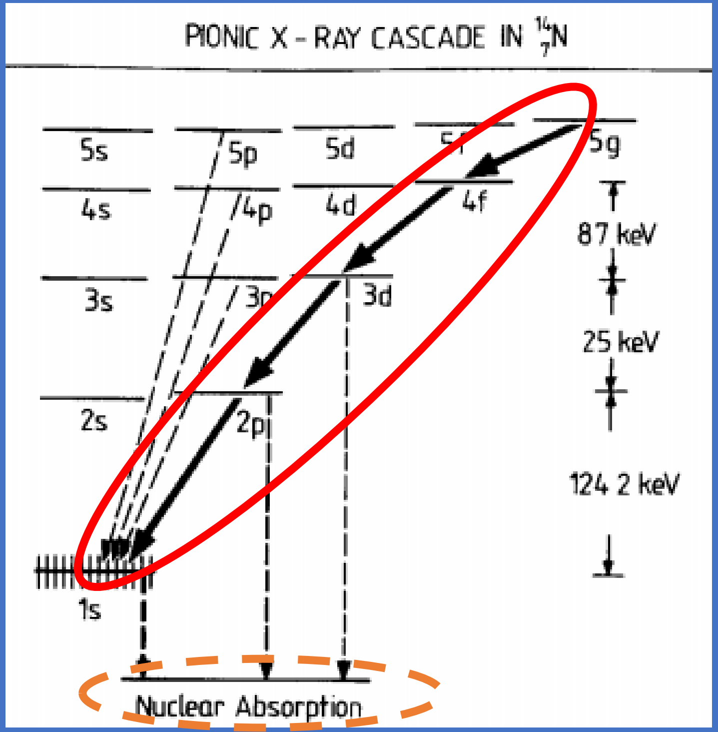
- GF photons → bound pions

  E_{γ}, Γ_{ph} vs. Γ_{tot}, flux (tunable energy, narrow band, high flux)
- deeply bound pionic atoms
- strong interaction, nuclear structure, nuclear forces forming the structure…

Methods for producing pionic atoms

➢ **Stopping free π^- in a pion beam**

- produce ~10^5 pionic atoms per sec
- X-ray cascade between “circular” states
- deeply bound states cannot be produced
- population of higher *ns* states is suppressed



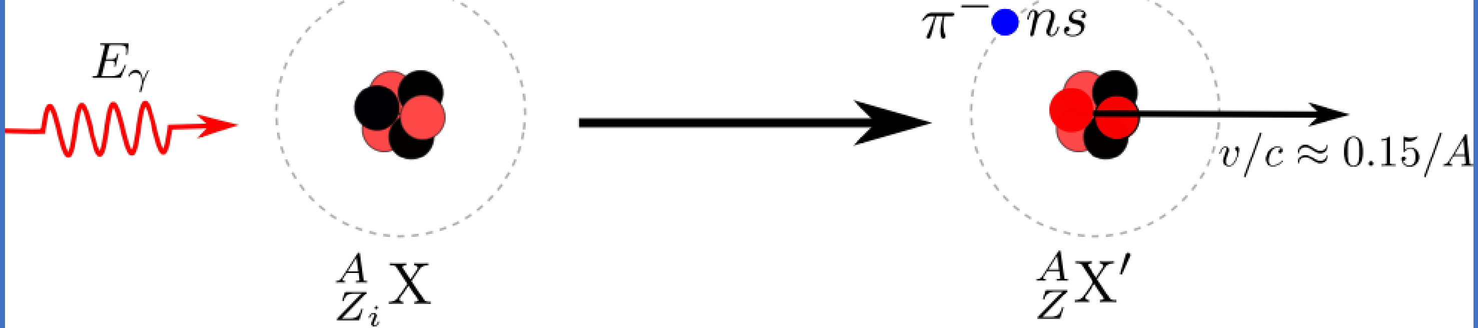
M. Hori, *et al*, Nature 581, 37 (2020); T. Ericson and W. Weise, Pions and Nuclei (Clarendon Press, 1988)

Methods for producing pionic atoms

➢ Our proposal

- resonance photoproduction of bound pions from the nucleus

$\gamma + n \rightarrow p + \pi^-,\ \gamma + {}^{A}_{Z_i}X \rightarrow ({}^{A}_{Z}X' + \pi^-)_{nl}\,,\ Z = Z_i + 1$

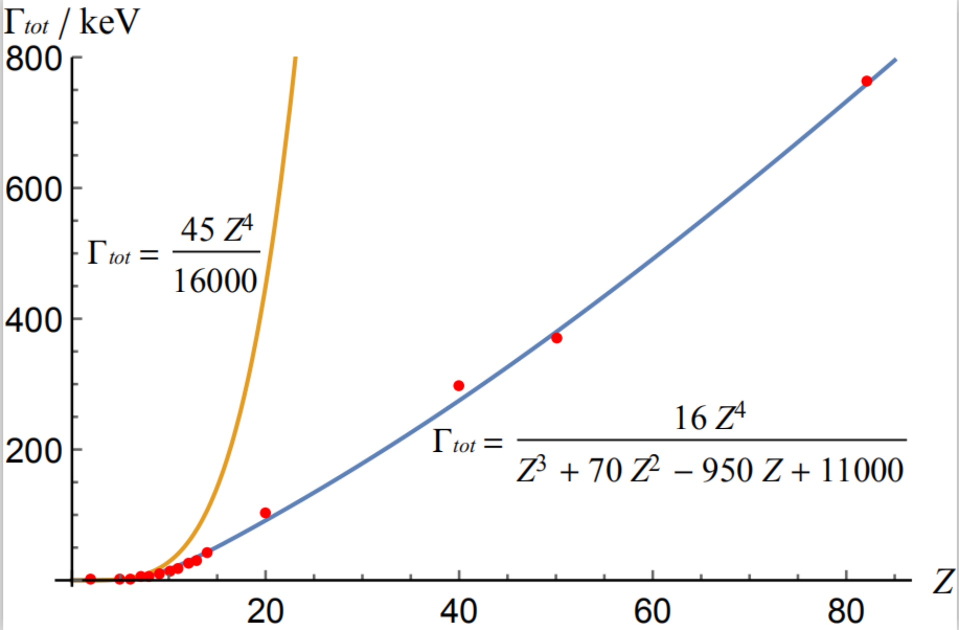


- $E_\gamma \approx 140$ MeV (final nucleus in its ground state)
- Γ_{ph} *vs.* Γ_{tot}

Methods for producing pionic atoms

➢ Total width of *ns* pionic states

- width: pion absorption, X-ray radiation, Auger electron emission
- fitting 1*s* width data



$$\Gamma_{tot}(Z,1)$$

$$\Gamma_{tot}(Z,n) \approx \Gamma_{tot}(Z,1)\frac{1}{n^3}$$

for pionic atoms with 1*s* orbital radius larger than nuclear radius

E. Friedman and A. Gal, Physics Reports 452, 89 (2007); J. Konijn, *et al*, Nuclear Physics A 519, 773 (1990)

Photoproduction cross-sections

➢ Cross-section for monochromatic photons

- $\sigma_0 = 2\pi \frac{2I_f+1}{2I_i+1}\left(\frac{\hbar c}{E_\gamma}\right)^2 \frac{\Gamma_\gamma}{\Gamma_{tot}}$
- $E_\gamma \approx 140$ MeV
- Γ_{tot}: dominated by pion absorption
- Γ_γ : radiative capture of the pion by nuclei, with final nuclei in the ground state
- $\frac{\Gamma_\gamma}{\Gamma_{tot}}$: α (σ_0 ~ 1mb, valid for light nuclei)

  2% (radiative capture probability, upper estimate of $\frac{\Gamma_\gamma}{\Gamma_{tot}}$)

J. Delorme and T. Ericson, Physics Letters 21, 98 (1966)

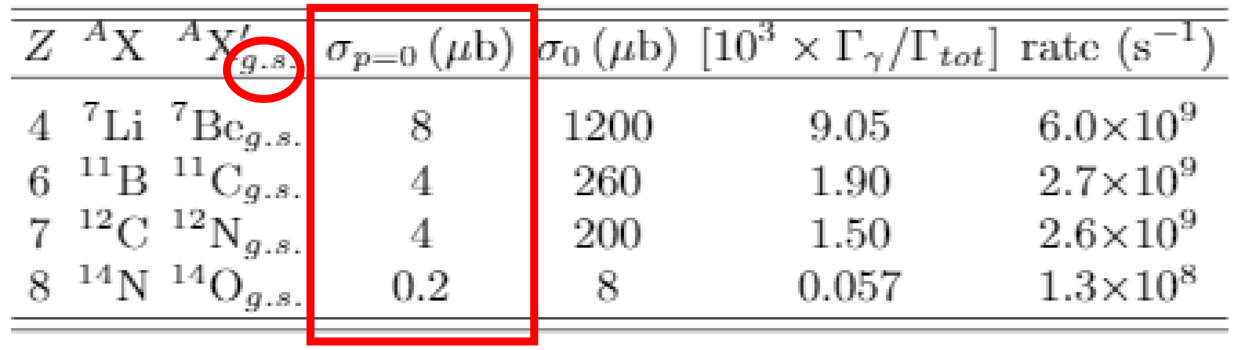
Photoproduction cross-sections

➢ **bound pion *vs.* free pion**

- Integrated cross-section: $\int \sigma(E)dE = \frac{\pi}{2}\,\sigma_0\,\Gamma_{tot}$ (bound pion)
- $\int \sigma(E)dE = (Z\alpha)^2 mc^2 K\sigma_p,\ K = 1 - \exp(-2\pi Z\alpha mc/p)$ (near threshold)

➢ $\sigma_{p=0}$

- measurements of $\sigma_{p=0}$ (using quasi-monochromatic photons) are limited.
- light nuclei:



Z	^{A}X	$^{A}X'_{g.s.}$	$\sigma_{p=0}$ (μb)	σ_0 (μb)	$[10^3 \times \Gamma_\gamma/\Gamma_{tot}]$	rate (s^{-1})
4	^{7}Li	^{7}Be$_{g.s.}$	8	1200	9.05	6.0×10^{9}
6	^{11}B	^{11}C$_{g.s.}$	4	260	1.90	2.7×10^{9}
7	^{12}C	^{12}N$_{g.s.}$	4	200	1.50	2.6×10^{9}
8	^{14}N	^{14}O$_{g.s.}$	0.2	8	0.057	1.3×10^{8}

- heavy nuclei: $\sigma_{p=0} \sim 1\mu$b

C. Tzara, Nuclear Physics B 18, 246 (1970); M. Singham and F. Tabakin, Annals of Physics 135, 71 (1981)

Photoproduction cross-sections

- $\boldsymbol{\sigma_{p=0}}$

- yields for (γ, π^-) are A-independent for targets with $A \geq 40$ $(A \approx 2Z)$
- $\gamma + {}^{197}\mathrm{Au} \rightarrow {}^{197}\mathrm{Hg}_{g.s.} + \pi^-$, $\sigma_{p=0} \sim 1\mu\mathrm{b}$

➡ $\sigma_{p=0} \sim 1\mu\mathrm{b}$ for nuclei with $9 \leq Z \leq 92$ (rough estimate)

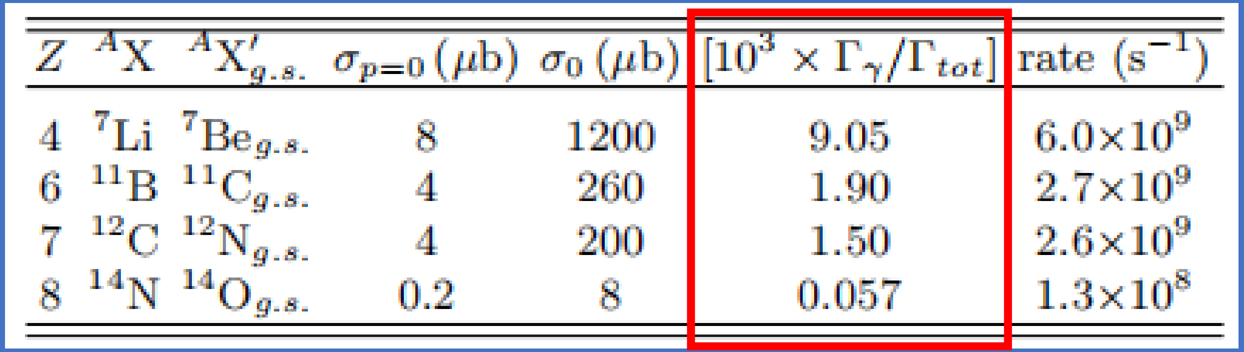
K. Sakamoto, *et al*, Phys. Rev. C 59, 1497 (1999); I. Blomqvist, *et al*, Z Physik A 288, 313 (1978)

Photoproduction cross-sections

- **bound pion *vs.* free pion**

$\sigma_p \rightarrow \Gamma_\gamma/\Gamma_{tot}$, σ_0 , production rates

light nuclei:



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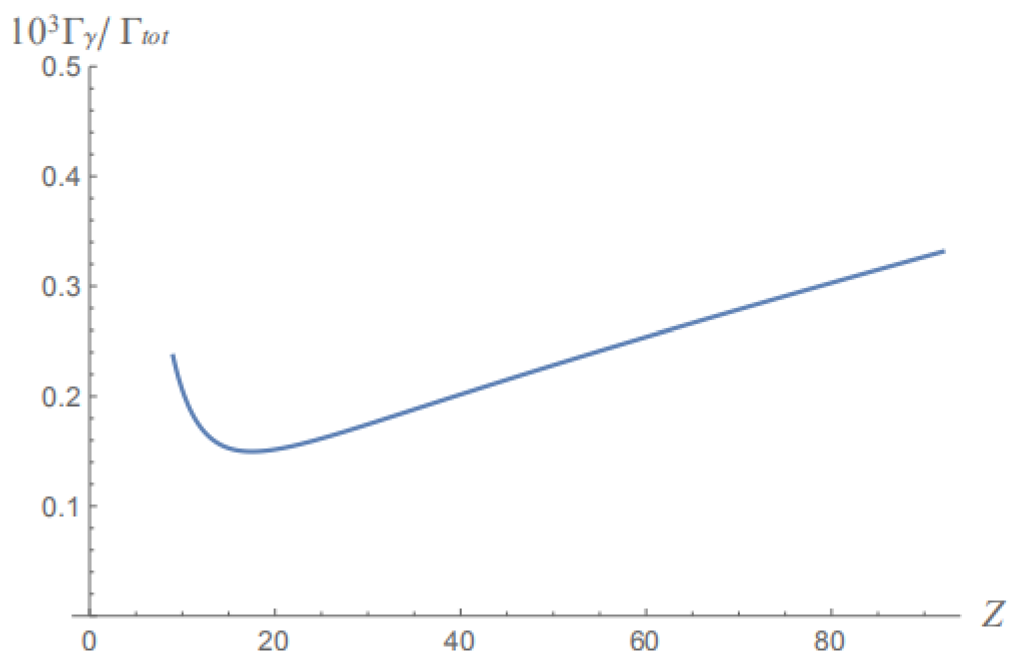
$Z \geq 9: \sigma_p \approx 1\mu\text{b} \rightarrow \Gamma_\gamma/\Gamma_{tot} \approx 0.25 \times 10^{-3}$



Photoproduction cross-sections

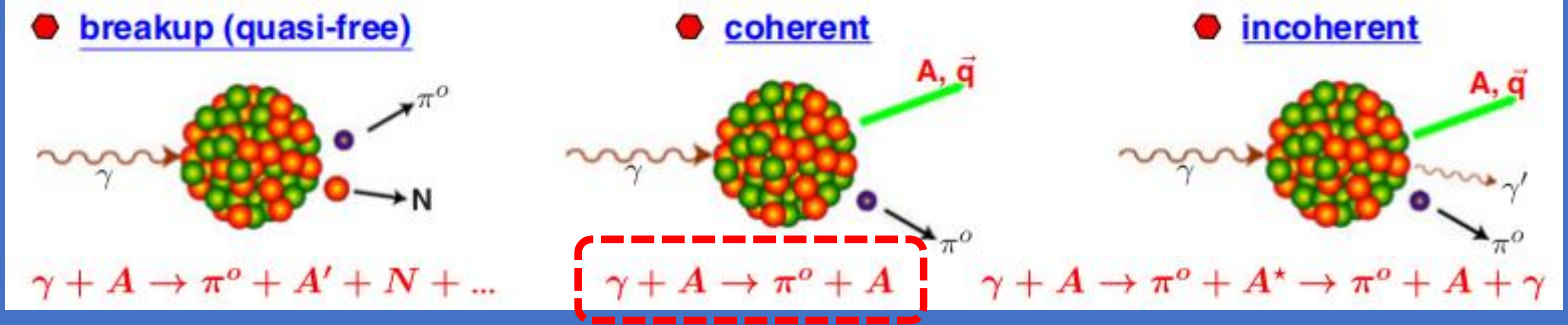
- **Free π^- *vs.* π^0**

- Coulomb interaction → Sommerfeld factor

$$\sigma_p(\pi^-)/\sigma_p(\pi^0) \sim \frac{2\pi f}{1-\exp(-2\pi f)},\ f = Z\alpha mc/p$$

- Coherent production of π^0

$$\sigma_p(\pi^-)/\sigma_p(\pi^0) \approx \frac{A-Z}{A^2}\frac{2\pi f}{1-\exp(-2\pi f)} \approx \frac{1}{4Z}\frac{2\pi f}{1-\exp(-2\pi f)}$$



B. Krusche, *et al*, Physics Letters B 526, 287 (2002); B. Krusche, Eur. Phys. J. Special Topics 198, 199 (2011)

Photoproduction cross-sections

➢ Background photon attenuation

- For 140 MeV photon:

  pair production & Compton scattering
- $\sigma_{tot}(Z_i) \approx \sigma_{pp} + \sigma_{scat} \approx 0.6 \times 10^{-26}(Z_i^2 + Z_i)\ \mathrm{cm}^2 >> \sigma_0$

Particle Data Group, Progress of Theoretical and Experimental Physics 2020, 083C01 (2020)

Production rates at the GF

- GF photons: nearly uniformly distributed up to the maximal energy

- Proper collimation: suppress the background

$$j = 10^{17}\,\text{ph/s} \xrightarrow{\text{collimation}} j_{eff} = j\,\frac{\Gamma_{ph}}{E_\gamma}$$

- Γ_{ph}: $\Gamma_{ph} = \Gamma_{tot}$ or $\Gamma_{ph} = E_{1s}$ (1*s* binding energy)

- $\sigma_{eff}(Z,n)$, $\sigma(E) = \sigma_0 \frac{(\Gamma_{tot}/2)^2}{\left(E-E_\gamma\right)^2+(\Gamma_{tot}/2)^2}$

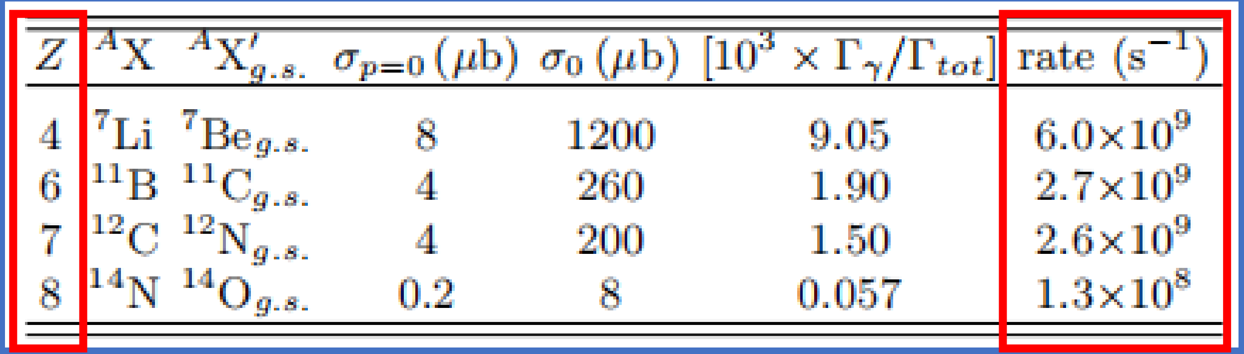
$$\sigma_{eff}(Z,n) \approx \sigma_0\,\frac{\Gamma_{tot}}{\Gamma_{ph}}$$

Production rates at the GF

➢ Maximal production rates

$$p(Z,n) = j_{eff}\,\frac{\sigma_{eff}(Z,n)}{\sigma_{tot}(Z_i)} = 5.6\times 10^{8}\,\frac{\sigma_{p=0}(Z)/1\mu b}{n^{3}}\ \mathrm{s}^{-1}$$

- light nuclei:



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- $Z \geq 9: \sigma_p \approx 1\mu\mathrm{b} \Rightarrow p(Z,1) \approx 5.6\times 10^{8}\mathrm{s}^{-1}$

Kaonic atoms

- Strangeness conservation

  ➡ $\gamma + n \to p + K^-$ ✖

  (K^-: $\bar{u}s$. Require $\bar{s}$.)

- **Possible methods**
  - $\gamma \to K^- + K^+$ ➡ $\gamma + {}^{A}_{Z}X \to ({}^{A}_{Z}X' + K^-)_{nl} + K^+$

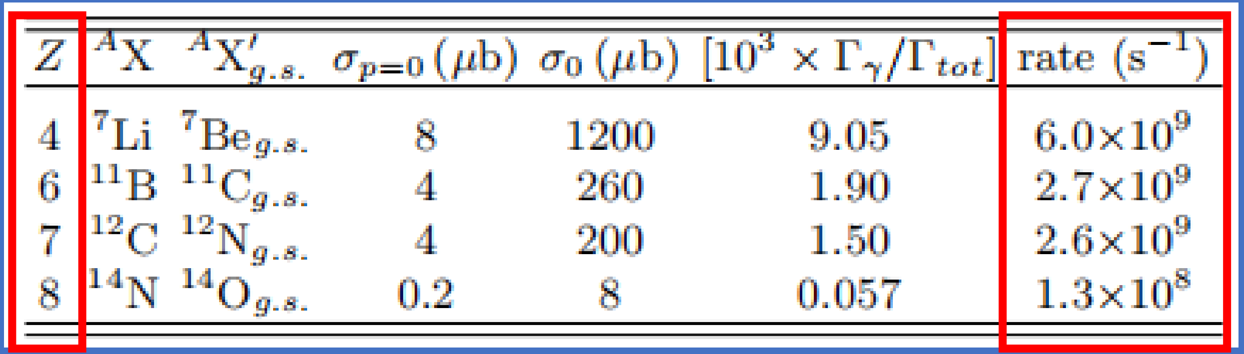
    threshold energy, $E_\gamma \approx 1\text{GeV}$, beyond current scope of the GF

    nonresonance (free K^+)

Summary

- **High production rates**

- light nuclei:



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- $Z \geq 9: \sigma_p \approx 1\mu\mathrm{b} \Rightarrow p(Z,1) \approx 5.6 \times 10^{8}\mathrm{s}^{-1}$

- **Deeply bound states** ✓

- **Higher *ns* states and *nl* states** ✓

Thank you!