Proposal to measure the Migdal effect with Cygno

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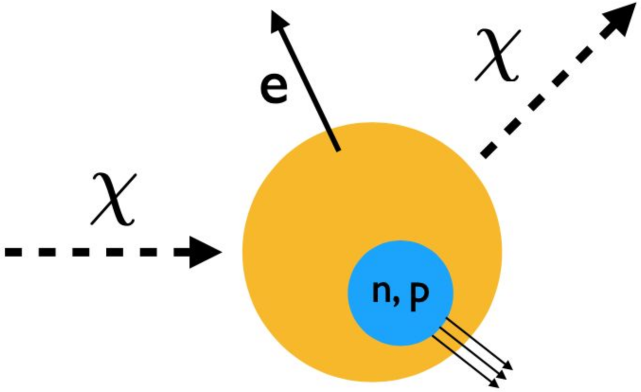
Outline

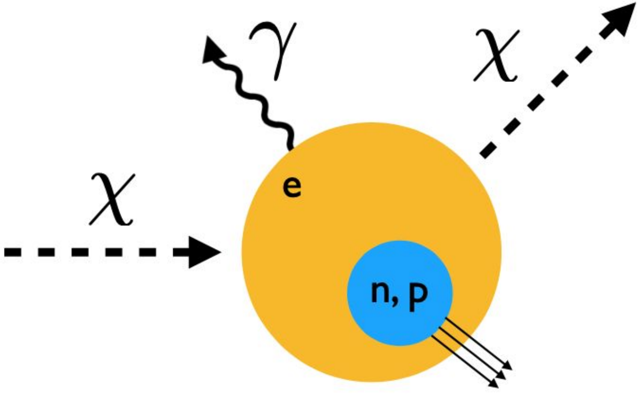
- Migdal effect
- How it can be measured
- Can we measure it with a Cygno prototype

The Migdal and Bremstrahlung effects



The atom emits an electron (Migdal effect).

[Ibe, Nakano, Shoji, Suzuki - arXiv:1707.07258,
Dolan, Kalhoefer, McCabe - arXiv:1711.09906]



The polarised atom emits a photon.

[Kouvaris, Pradler - arXiv:1607.01789]

The Migdal and Bremstrahlung effects

$$\frac{d^2R}{dE_R dv} = \overbrace{\boxed{\frac{d^2R_{NR}}{dE_R dv}}}^{\text{Usual nuclear recoil rate}} \boxed{|Z|^2}$$

$$\boxed{|Z|^2 \simeq \overset{\text{NR}}{1} + \overset{\text{de-excitation: negligible}}{|Z_{\rm de}|^2} + \underset{\text{Ionization rate}}{|Z_{\rm ion}|^2}}$$

$$\boxed{|Z_{\rm ion}(E_R, E_e)|^2 = \frac{1}{2\pi}\sum_{n,\ell}\int dE_e \frac{dp^c_{q_e}(n\ell \to E_e)}{dE_e}}$$

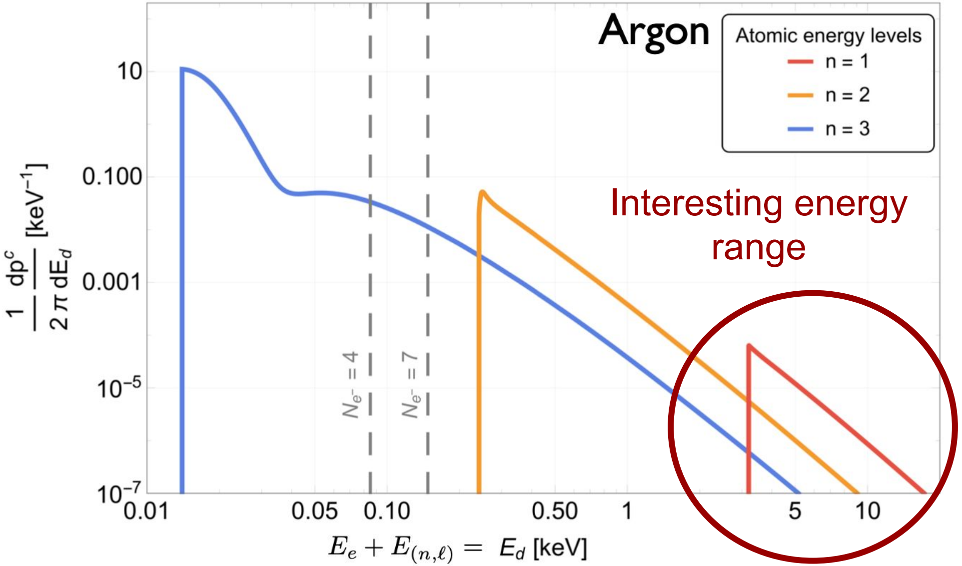
Computed in
[Ibe, Nakano, Shoji, Suzuki - arXiv:1707.07258]

The Migdal effect in Argon

ArXiv:2006.02453[hep-ph]

There is O(1keV) of energy release in the electron channel associated to a nuclear recoil interaction. The probability of this emission is few percent [7.3 10^{-5} (for 1s only)]

Migdal effect



Interesting energy range

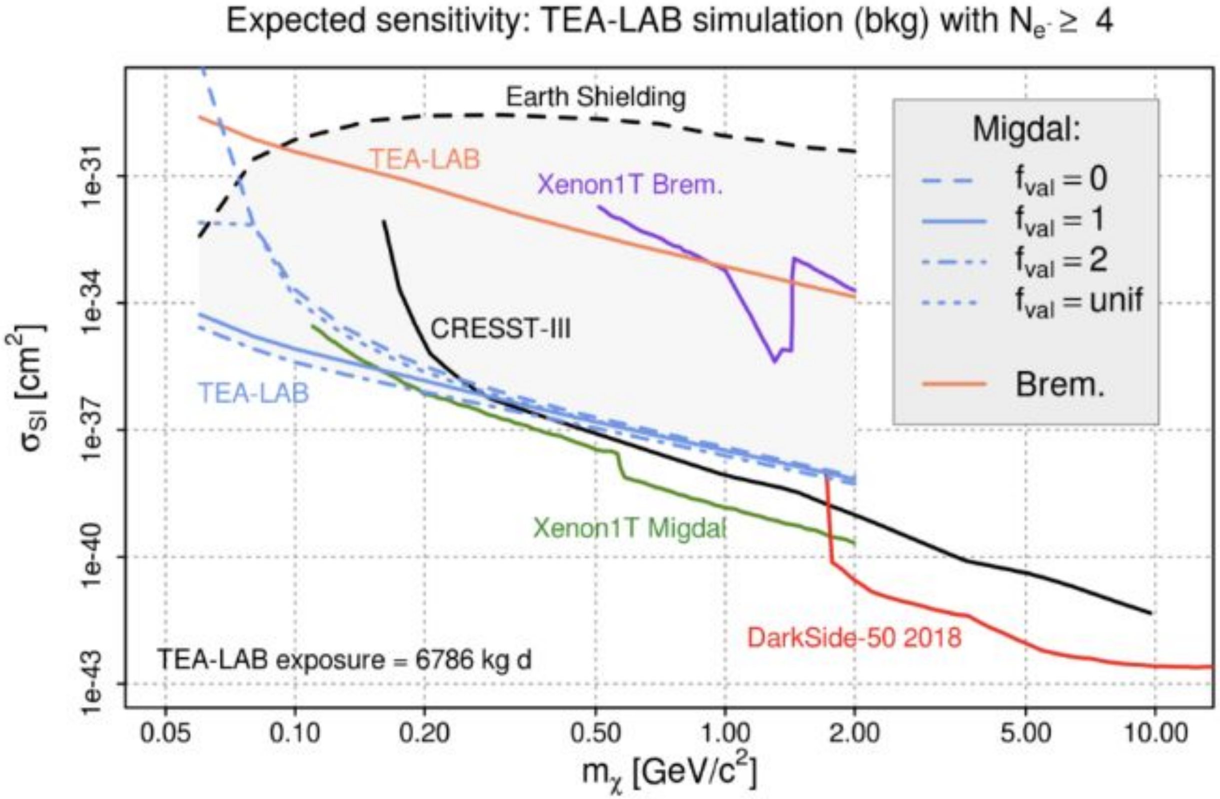
Figure 1: Differential ionization probabilities as a function of the detected energy E_d for isolated argon and different principal quantum number n. We show also the 4 and 7 electron thresholds for DarkSide-50.

Important contribution of Migdal to low mass search

$$E_{R,\mathrm{max}} = \frac{2\mu_N^2 v_{\mathrm{max}}^2}{m_N}$$

$$\delta_{\mathrm{max}} = \frac{\mu_N v_{\mathrm{max}}^2}{2}$$

$\delta_{\mathrm{max}} > E_{R,\mathrm{max}}$ for $m_\chi \ll m_N$ (suppression factor $\frac{\mu_N}{m_N}$);


Expected sensitivity: TEA-LAB simulation (bkg) with $N_{e^-} \geq 4$

How the Migdal effect can be measured

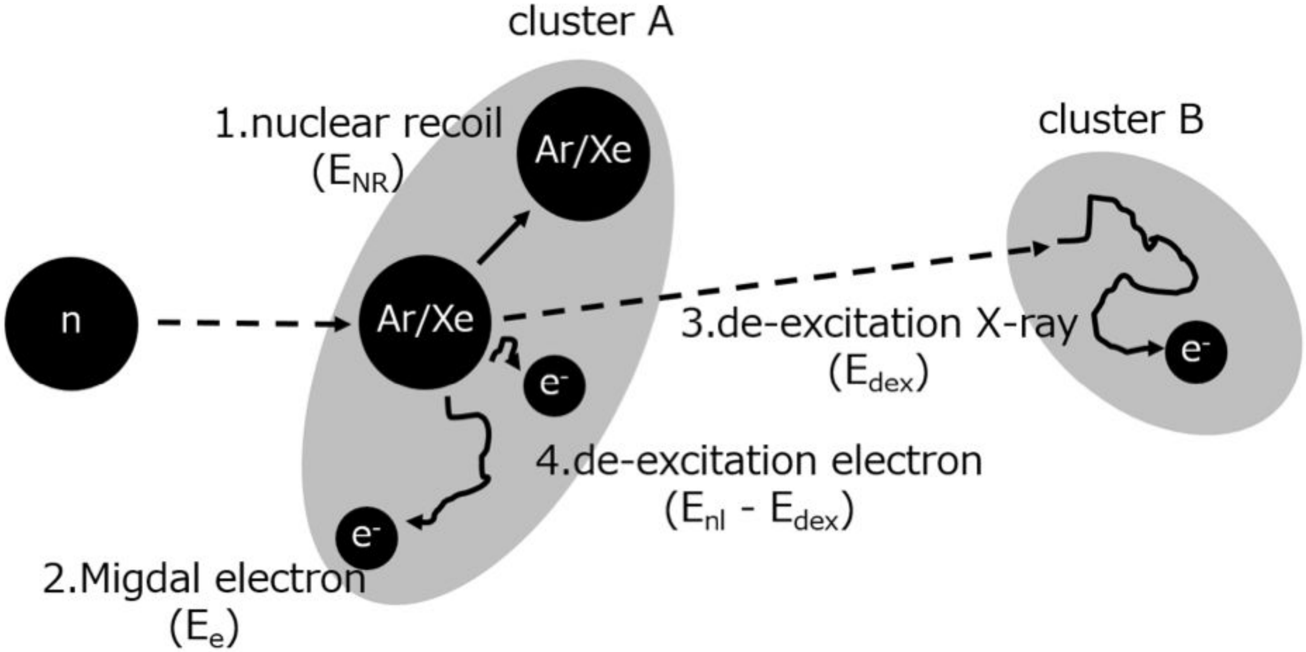
Nakamura et al. ArXiv:2009.05939

Detector: argon gas (1atm) TPC $(30\text{cm})^3$ with a O(mm) spatial resolution and an energy resolution of 30% FWHM @ 5.9 keV

Neutron source: continuous neutron beam 565 keV with a flux of 1000 / cm^2 / sec @ 1 m. Produced with $^7\text{Li}(p, n)^7\text{Be}$ (similar as the LNS tandem). (the neutron energy is kept low to contain the gamma rate)

Signal: use the (1s, K shell) x-ray de-excitation line @ 3 keV as an event tag. The signature is a NR with an ER separated by O(cm)

How the Migdal effect can be measured



How the Migdal effect can be measured

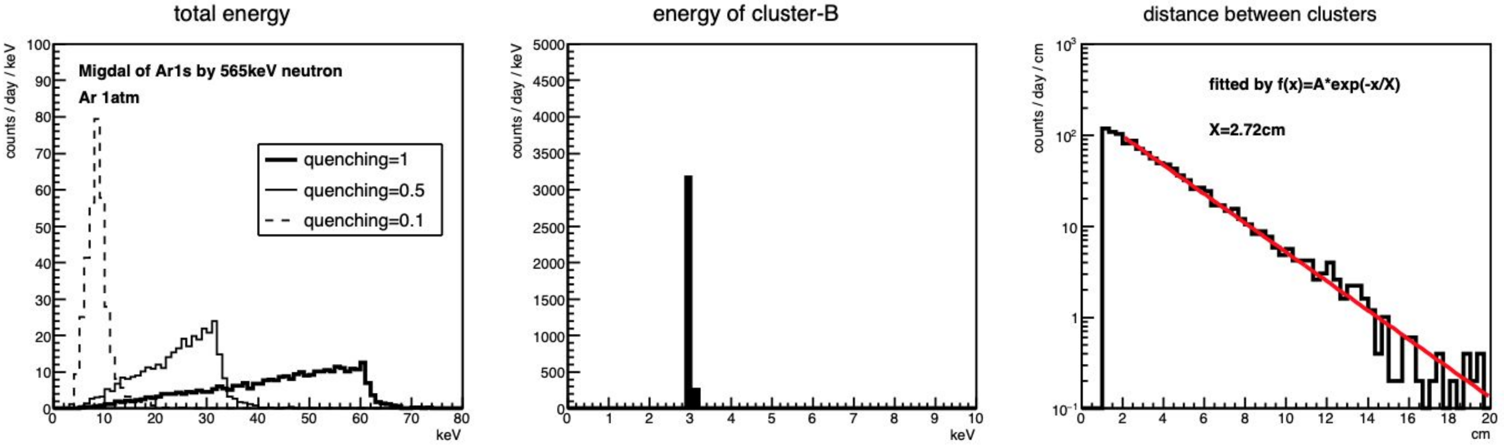
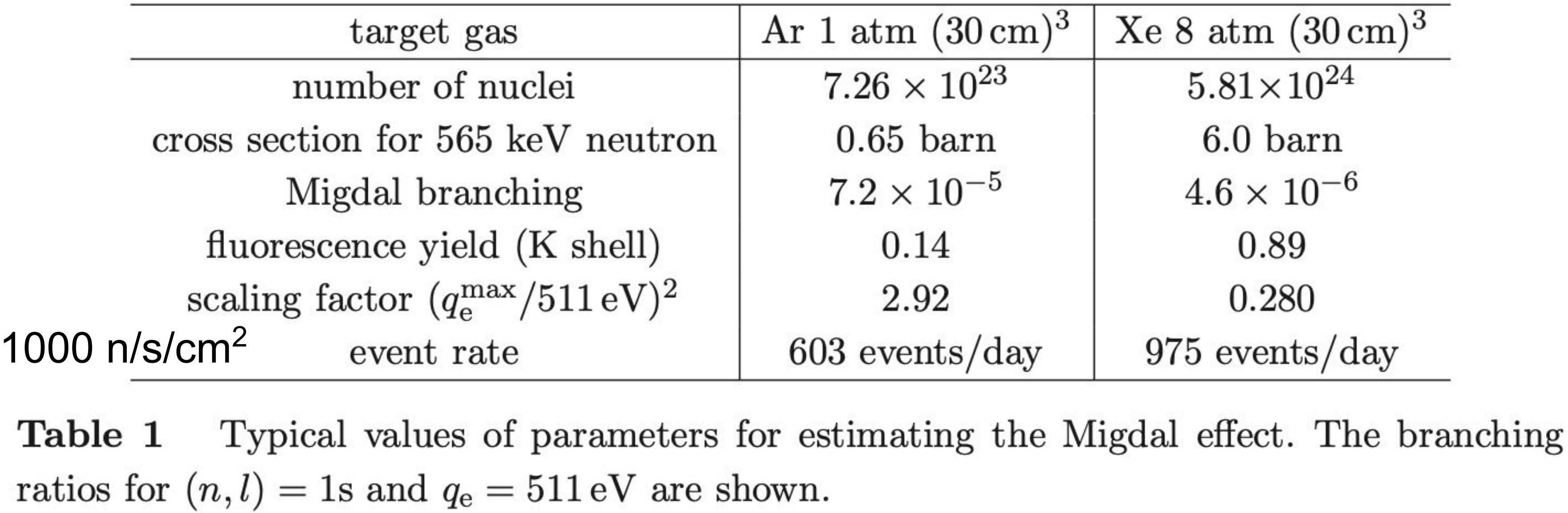


Fig. 2 Signal MC simulation results with argon gas. The spectra of the total energy, energy spectra of cluster B, and the distributions of the distance between the two clusters are shown in the left, center, and right, respectively.

How the Migdal effect can be measured



target gas	Ar 1 atm $(30\,\mathrm{cm})^3$	Xe 8 atm $(30\,\mathrm{cm})^3$
number of nuclei	7.26×10^{23}	5.81×10^{24}
cross section for 565 keV neutron	0.65 barn	6.0 barn
Migdal branching	7.2×10^{-5}	4.6×10^{-6}
fluorescence yield (K shell)	0.14	0.89
scaling factor $(q_e^{\mathrm{max}}/511\,\mathrm{eV})^2$	2.92	0.280
event rate	603 events/day	975 events/day

1000 $\mathrm{n/s/cm^2}$

Table 1 Typical values of parameters for estimating the Migdal effect. The branching ratios for $(n, l) = 1\mathrm{s}$ and $q_e = 511\,\mathrm{eV}$ are shown.

How the Migdal effect can be measured

1. Cut0: no cuts :)
2. Cut1: fiducial volume
3. Cut2: 2 clusters
4. Cut3: E_{ER} = 3.2 +- 2 keV

Then fit the separation between NR and ER

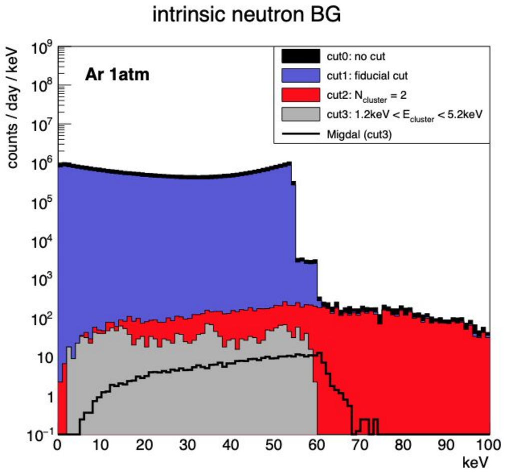


Fig. 4 Simulated total energy spectra of the intrinsic neutron background events for the argon target. Black-filled histogram is the raw energy spectrum. Blue, red, and gray ones are those after cut 1, 2, and 3, respectively. The black-solid line is the energy spectrum of the Migdal effect.

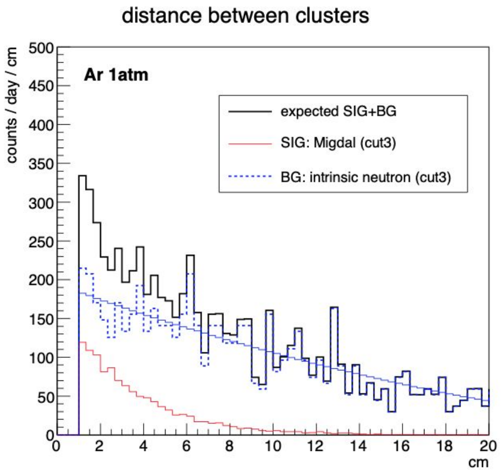


Fig. 5 MC simulation results on the distance between two clusters for the argon target. Red, blue, and black histogram show the intrinsic neutron background events, signal events and sum of these two components.

Can we measure it with a Cygno prototype?

YES, WE CAN

and it is quite a interesting measurement opportunity

- Need to use Ar instead of He. He does not have any keV emission line.
    - This, I believe, is possible and it is a quite interesting detector characterization test
- Energy and position resolution more than enough
- What is not straight forward is the neutron source
    - Depending on the n-source we need to estimate the background rates

What can be done

- Investigate the possibility to have a run with Lemon/Lime with Ar/CF_4
- As preliminary step use the AmBe source to qualify the detector performance
- Setup a simulation for such a run including a simulation of the AmBe (or other neutron) source to characterize energy and geometric acceptance of signal and background
- Explore other possible neutron sources as the Tandem at LNS, ENEA neutron beam, or the DS(Naples) neutron gun

Further considerations (1.10.2020)

- Time integration of the camera ~ 1 sec, is it a problem?
    - The spatial correlation between NR and x-ray should mitigate the pileup. Need to investigate more
- Geant simulation of the neutron interactions in the detector
    - Geometrical acceptance
    - Induced background (essentially gamma)
    - Study the energy spectrum and the energy deposit position

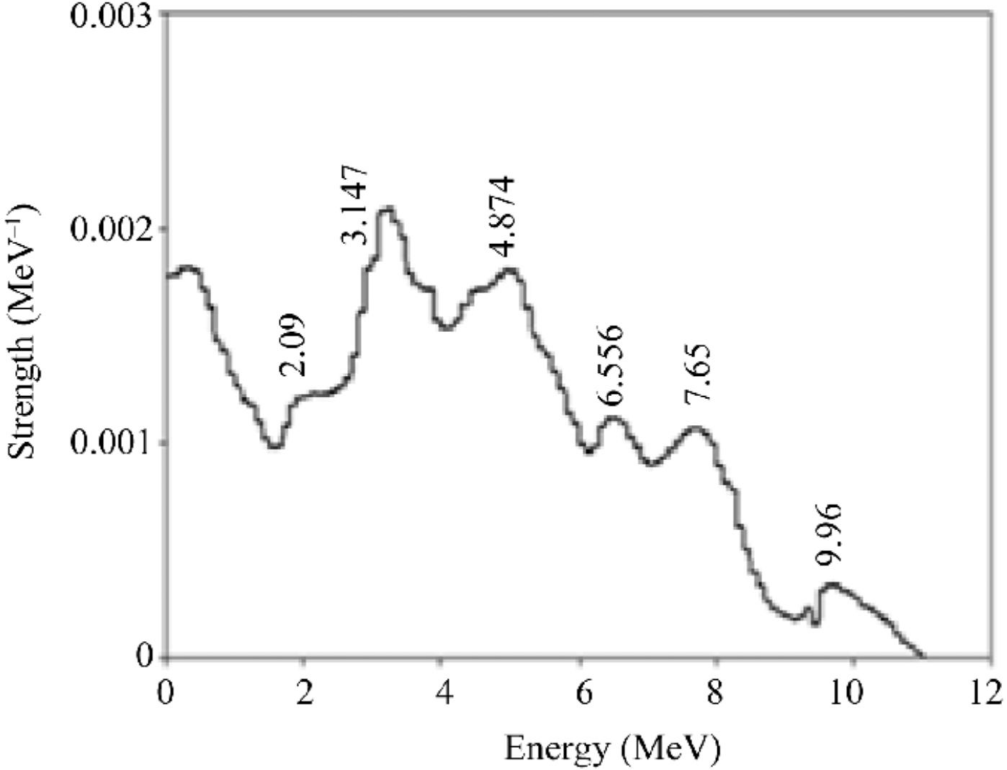
Additional material

AmBe source neutron Spectrum

AmBe activity(alpha) 3.5 GBq

- n per alpha ~70 10^{-6} (Knoll)
- ~ 20 10^3 n/s/rad
- ~ 7 n/s/cm^2 @ 50 cm
- ~ 3 10^3 n/s dentro Lemon

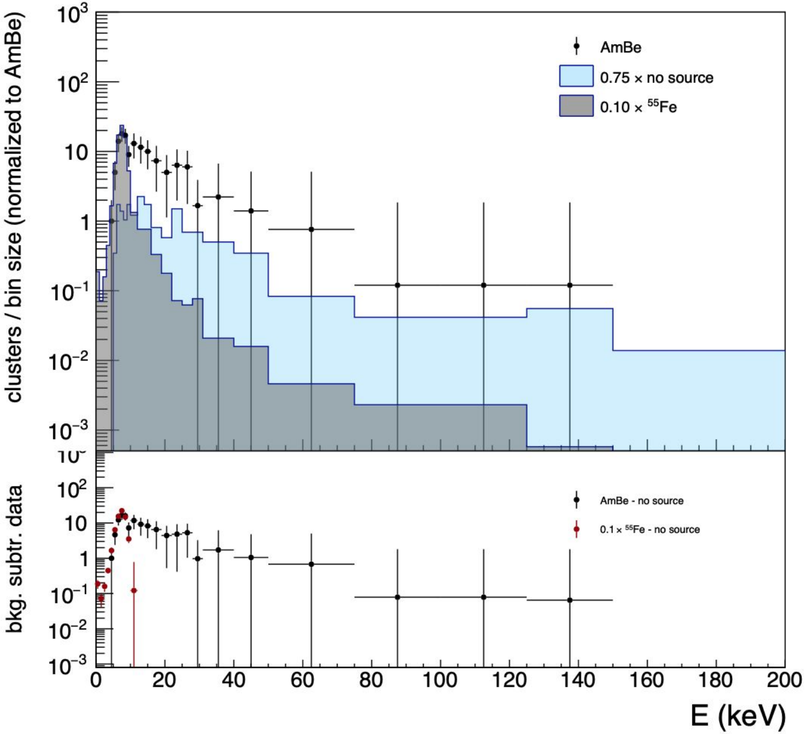
Missing the effect of collimators and lead-shielding



Lemon nuclear recoil events

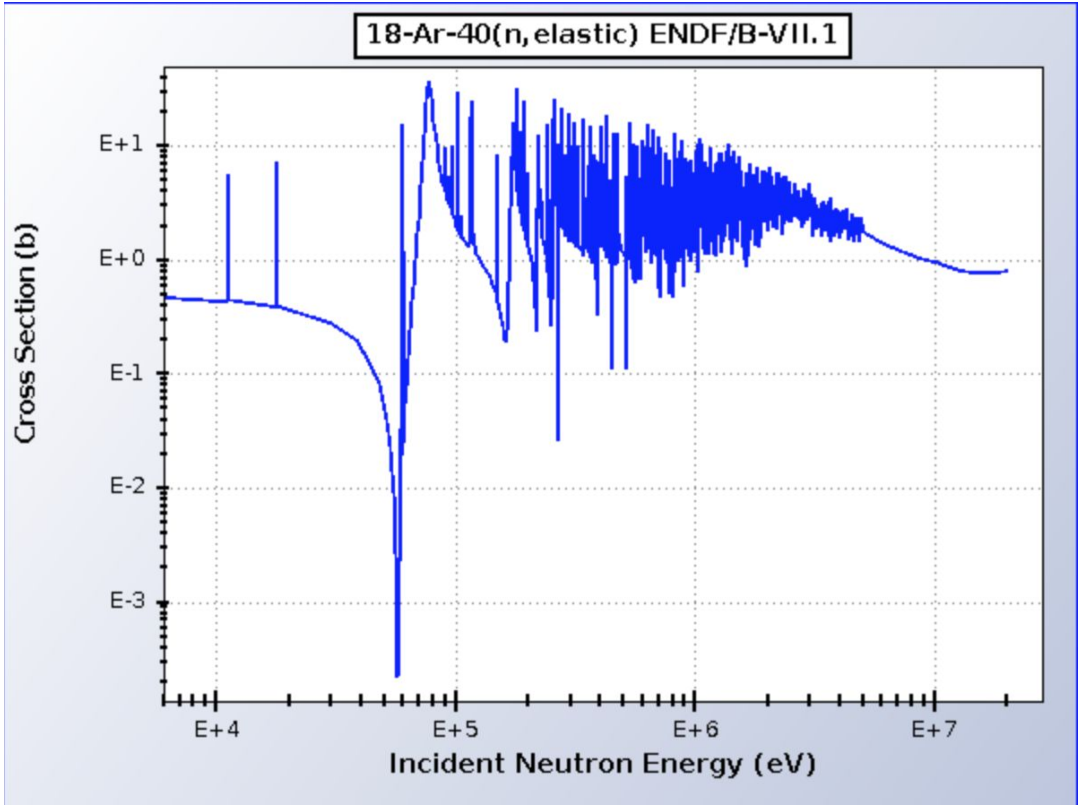
ArXiv:2007.12508[physics.ins-det]

- ~ 1h of data taking with AmBe -> 100 reconstructed NR candidates
- Then have to pay a factor
  - 10^{-5} to have a migdal electron
  - 0.1 to have a X-ray
- Additional inefficiency for the analysis selection



Neutron-Ar elastic cross section

National Nuclear Data Center

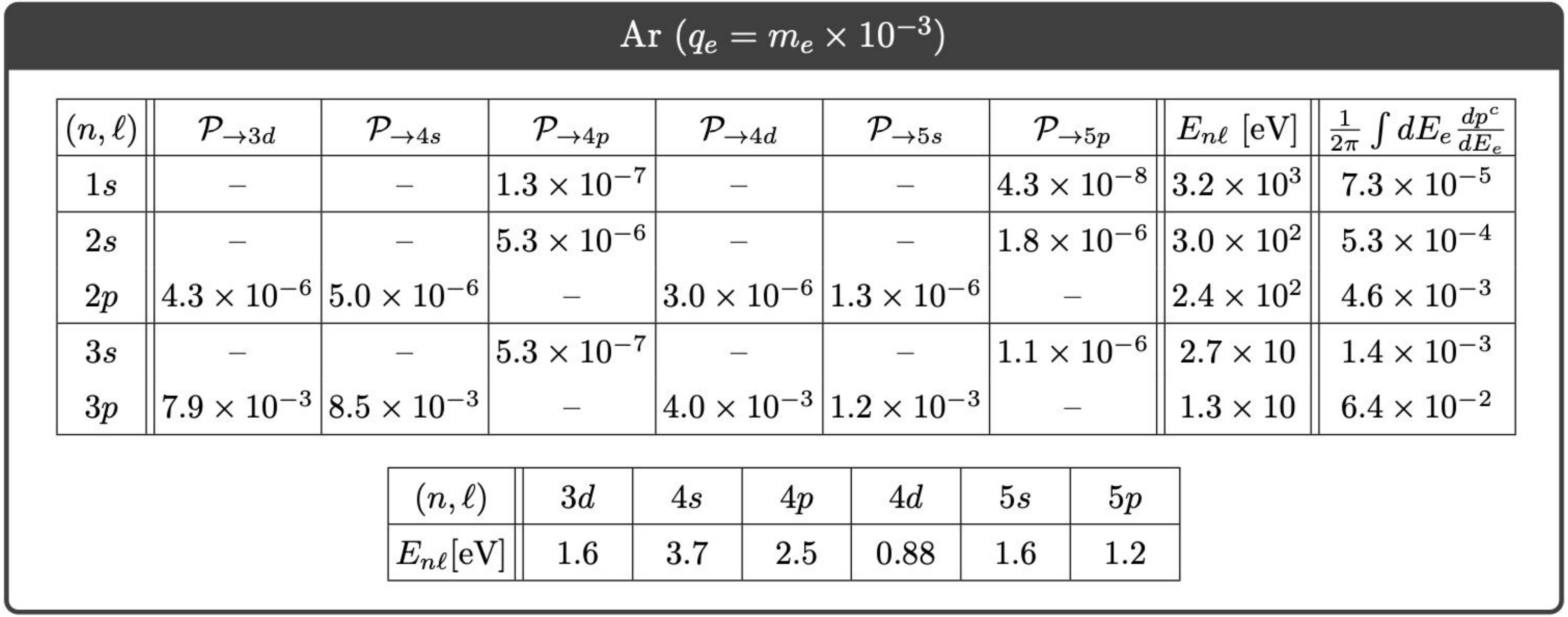


Fluorescence lines

https://onlinelibrary.wiley.com/doi/full/10.1002/xrs.3056

https://www.bruker.com/fileadmin/user_upload/8-PDF-Docs/X-rayDiffraction_ElementalAnalysis/HH-XRF/Misc/Periodic_Table_and_X-ray_Energies.pdf

Migdal probabilities



Ar ($q_e = m_e \times 10^{-3}$)

(n, ℓ)	$\mathcal{P}_{\to 3d}$	$\mathcal{P}_{\to 4s}$	$\mathcal{P}_{\to 4p}$	$\mathcal{P}_{\to 4d}$	$\mathcal{P}_{\to 5s}$	$\mathcal{P}_{\to 5p}$	$E_{n\ell}$ [eV]	$\frac{1}{2\pi}\int dE_e \frac{dp^c}{dE_e}$
$1s$	–	–	1.3×10^{-7}	–	–	4.3×10^{-8}	3.2×10^{3}	7.3×10^{-5}
$2s$	–	–	5.3×10^{-6}	–	–	1.8×10^{-6}	3.0×10^{2}	5.3×10^{-4}
$2p$	4.3×10^{-6}	5.0×10^{-6}	–	3.0×10^{-6}	1.3×10^{-6}	–	2.4×10^{2}	4.6×10^{-3}
$3s$	–	–	5.3×10^{-7}	–	–	1.1×10^{-6}	2.7×10	1.4×10^{-3}
$3p$	7.9×10^{-3}	8.5×10^{-3}	–	4.0×10^{-3}	1.2×10^{-3}	–	1.3×10	6.4×10^{-2}

(n, ℓ)	$3d$	$4s$	$4p$	$4d$	$5s$	$5p$
$E_{n\ell}$[eV]	1.6	3.7	2.5	0.88	1.6	1.2