Exploring the Migdal Effect in CEνNS searches at low energies

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In collaboration with

M. Cadeddu, N. Cargioli, F. Dordei, C. Giunti

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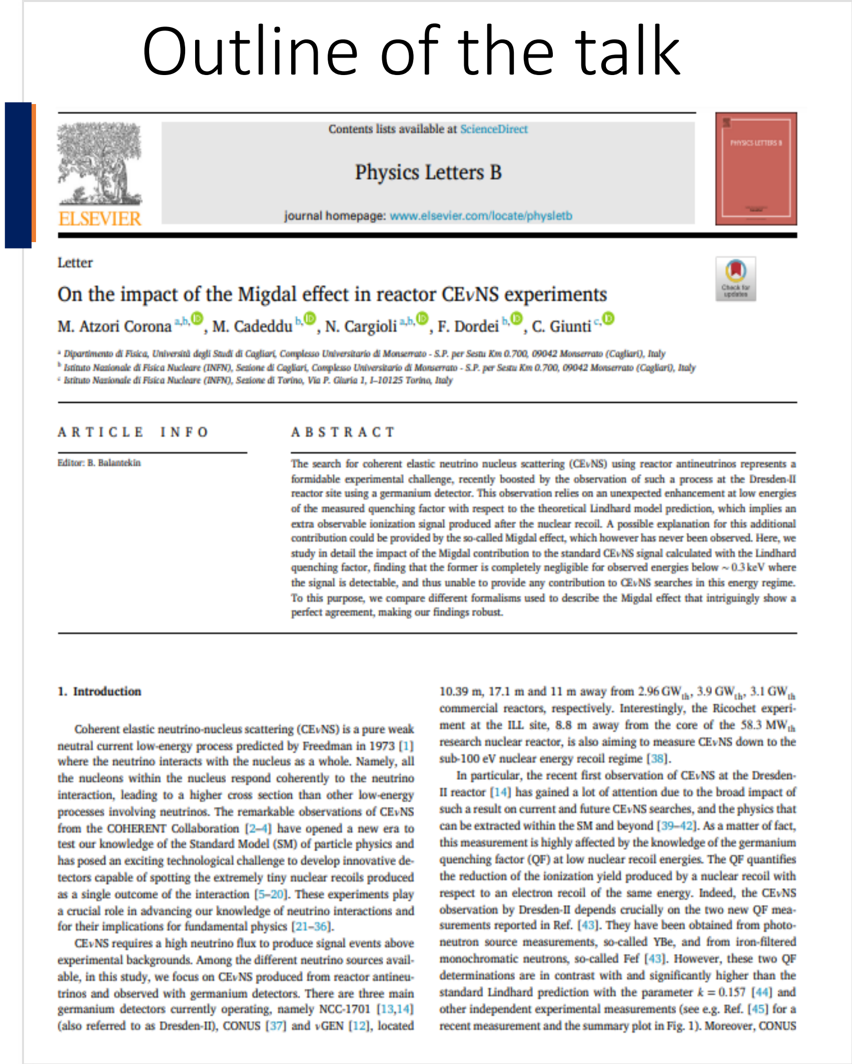
Outline of the talk



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Letter

On the impact of the Migdal effect in reactor CEνNS experiments

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ABSTRACT

The search for coherent elastic neutrino nucleus scattering (CEνNS) using reactor antineutrinos represents a formidable experimental challenge, recently boosted by the observation of such a process at the Dresden-II reactor site using a germanium detector. This observation relies on an unexpected enhancement at low energies of the measured quenching factor with respect to the theoretical Lindhard model prediction, which implies an extra observable ionization signal produced after the nuclear recoil. A possible explanation for this additional contribution could be provided by the so-called Migdal effect, which however has never been observed. Here, we study in detail the impact of the Migdal contribution to the standard CEνNS signal calculated with the Lindhard quenching factor, finding that the former is completely negligible for observed energies below ~ 0.3 keV where the signal is detectable, and thus unable to provide any contribution to CEνNS searches in this energy regime. To this purpose, we compare different formalisms used to describe the Migdal effect that intriguingly show a perfect agreement, making our findings robust.

1. Introduction

Coherent elastic neutrino-nucleus scattering (CEνNS) is a pure weak neutral current low-energy process predicted by Freedman in 1973 [1] where the neutrino interacts with the nucleus as a whole. Namely, all the nucleons within the nucleus respond coherently to the neutrino interaction, leading to a higher cross section than other low-energy processes involving neutrinos. The remarkable observations of CEνNS from the COHERENT Collaboration [2–4] have opened a new era to test our knowledge of the Standard Model (SM) of particle physics and has posed an exciting technological challenge to develop innovative detectors capable of spotting the extremely tiny nuclear recoils produced as a single outcome of the interaction [5–20]. These experiments play a crucial role in advancing our knowledge of neutrino interactions and for their implications for fundamental physics [21–36].

CEνNS requires a high neutrino flux to produce signal events above experimental backgrounds. Among the different neutrino sources available, in this study, we focus on CEνNS produced from reactor antineutrinos and observed with germanium detectors. There are three main germanium detectors currently operating, namely NCC-1701 [13,14] (also referred to as Dresden-II), CONUS [37] and νGEN [12], located 10.39 m, 17.1 m and 11 m away from 2.96 $\mathrm{GW_{th}}$, 3.9 $\mathrm{GW_{th}}$, 3.1 $\mathrm{GW_{th}}$ commercial reactors, respectively. Interestingly, the Ricochet experiment at the ILL site, 8.8 m away from the core of the 58.3 $\mathrm{MW_{th}}$ research nuclear reactor, is also aiming to measure CEνNS down to the sub-100 eV nuclear energy recoil regime [38].

In particular, the recent first observation of CEνNS at the Dresden-II reactor [14] has gained a lot of attention due to the broad impact of such a result on current and future CEνNS searches, and the physics that can be extracted within the SM and beyond [39–42]. As a matter of fact, this measurement is highly affected by the knowledge of the germanium quenching factor (QF) at low nuclear recoil energies. The QF quantifies the reduction of the ionization yield produced by a nuclear recoil with respect to an electron recoil of the same energy. Indeed, the CEνNS observation by Dresden-II depends crucially on the two new QF measurements reported in Ref. [43]. They have been obtained from photoneutron source measurements, so-called YBe, and from iron-filtered monochromatic neutrons, so-called Fef [43]. However, these two QF determinations are in contrast with and significantly higher than the standard Lindhard prediction with the parameter $k = 0.157$ [44] and other independent experimental measurements (see e.g. Ref. [45] for a recent measurement and the summary plot in Fig. 1). Moreover, CONUS

1. The hunt for CEνNS from reactor $\bar{\nu}_e$

2. The quenching factor puzzle on Ge

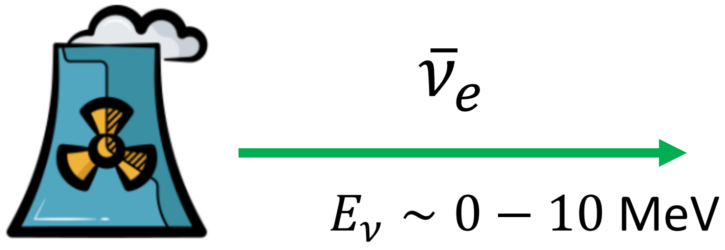
3. The Migdal Effect

4. Impact of the Migdal Effect in the Dresden-II observation

Phys.Lett.B 852 (2024) 138627

The Hunt for CEνNS from reactor $\bar{\nu}_e$

Reactor antineutrinos



$\bar{\nu}_e$

$E_\nu \sim 0 - 10$ MeV

World-wide effort to spot this tiny interaction

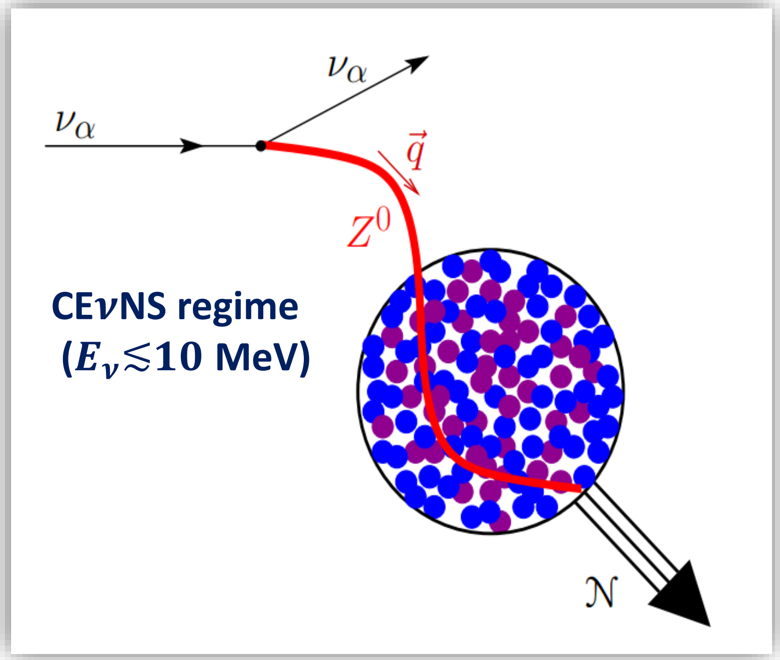
Neutrinos are produced through β-decay at a reactor power plant. These low energetic neutrinos produce small nuclear recoils.

Coherent elastic neutrino nucleus scattering (CEνNS) is pure weak neutral current process when the De-Broglie wavelength fo the Z^0 boson is bigger than the size of the nucleus.

$$\lambda_{Z^0} \simeq \frac{h}{|q|} \geq 2R$$

$|q| \sim E_\nu$

To fully exploit the coherency in the interaction, it is beneficial to consider low-energy neutrinos



CEνNS regime
($E_\nu \lesssim 10$ MeV)

The Hunt for CEνNS from reactor $\bar{\nu}_e$

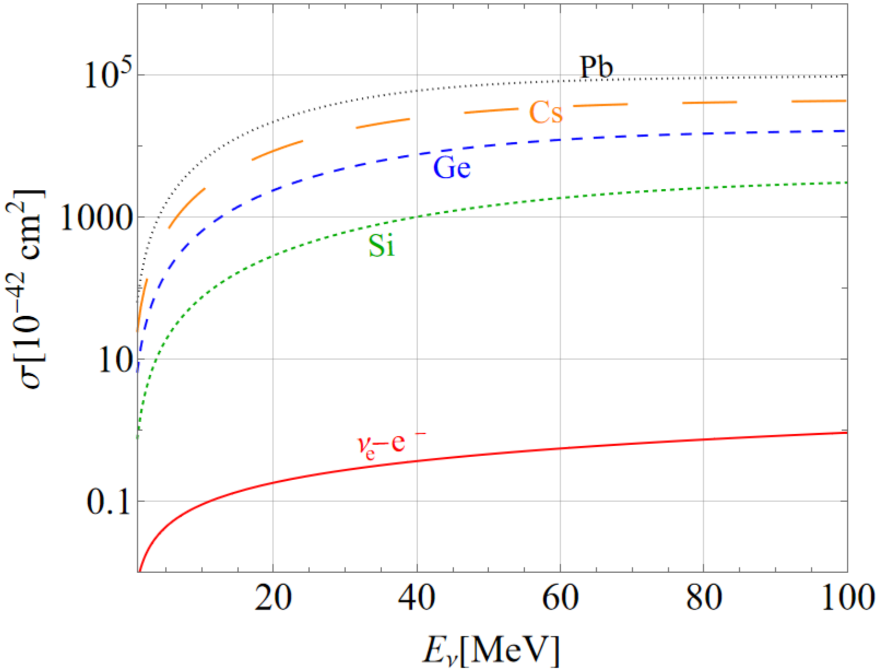
Pro of CEνNS serarch from using reactor anti-neutrinos:

- ✓ Full Coherency
- ? No dependence on the nuclear structure
- ✓ Very high neutrino flux
- ✓ Extract weak mixing angle and neutrino charge radius at unprobed energy regime

See **M. Cadeddu**, **F. Dordei** and ***O. Miranda*** talks!

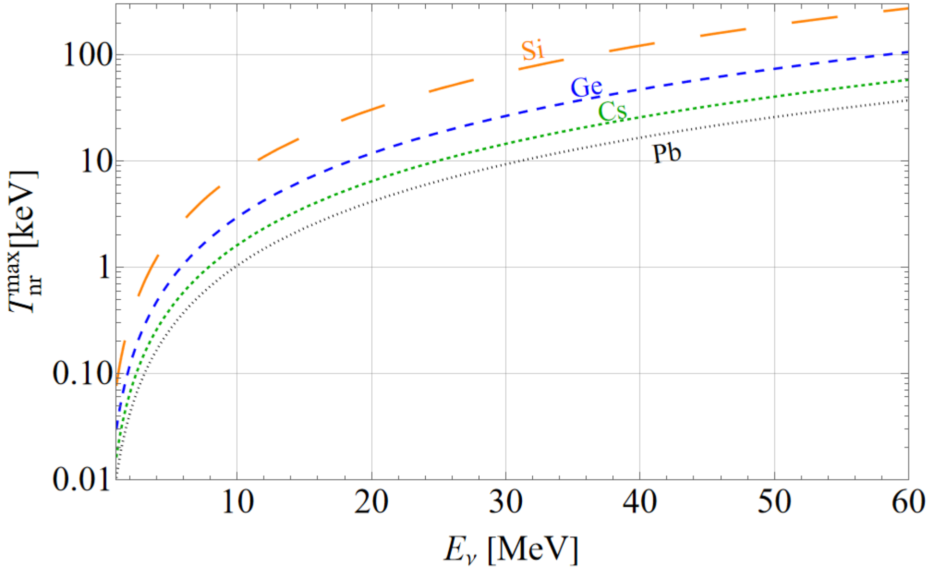
- ✓ Light mediatos and νEM properties 'explode' at low energies

See **C. A. Ternes** and ***Y. Li*** *talks*



Cons

- ✗ CEνNS cross section is smaller for lower neutrino energy
- ✗ Very low threshold is required
- ✗ Pioneering low energy physics (new effects might occurs)



The world-wide hunt

νBDX-DRIFT

Dresden-II

GanESS/COLINA

Coherent CAPTAIN-Mills (CCM)

CSNS

***ν*IOLETA**

+Bullkid

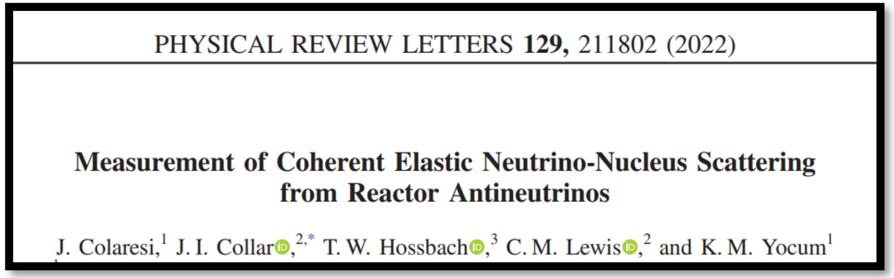
● Reactor

○ Stopped Pion Source

Created with mapchart.net

The NCC-1701 detector at the Dresden-II reactor

- 96.4 day (**Rx-ON**) exposure of a 3 kg ultra-low noise germanium detector.
- 10.39 m away from the Dresden-II boiling water reactor ($P = 2.96\ \mathrm{GW_{th}}$).
- **Strong preference** ($p < 1.2 \times 10^{-3}$) for the presence of CEνNS.
- This observation was under debate within the CEνNS Community.



PHYSICAL REVIEW LETTERS **129,** 211802 (2022)

Measurement of Coherent Elastic Neutrino-Nucleus Scattering from Reactor Antineutrinos

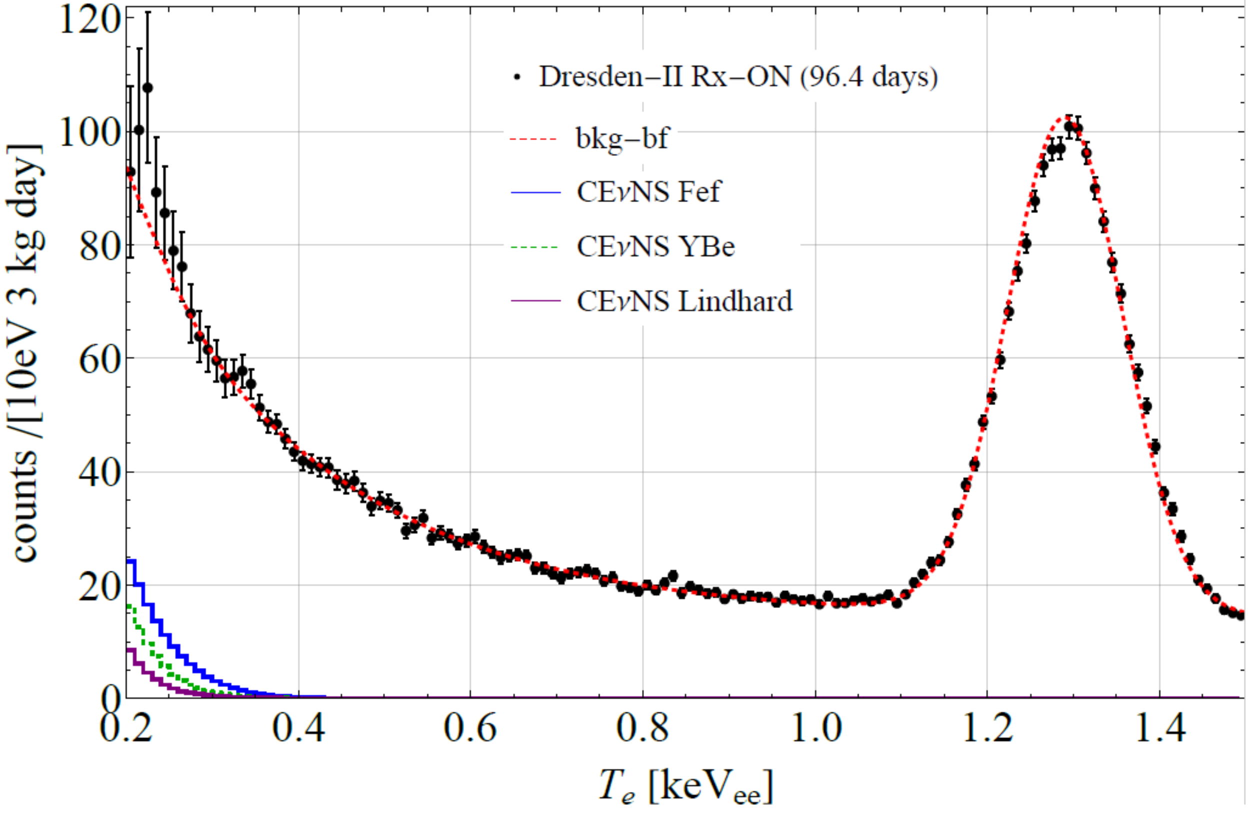
J. Colaresi,[1] J. I. Collar,[2,*] T. W. Hossbach,[3] C. M. Lewis,[2] and K. M. Yocum[1]

It relies on two main hypotheses:

1. Deep understanding of the **background model**.

$$\frac{dN^{\mathrm{bkg}}}{dT_{\mathrm{e}}} = N_{\mathrm{epith}} + A_{\mathrm{epith}} e^{-T_{\mathrm{e}}/T_{\mathrm{epith}}} + \sum_{i=\mathrm{L1,L2,M}} \frac{A_i}{\sqrt{2\pi}\sigma_i} e^{-\frac{(T_{\mathrm{e}}-T_i)^2}{2\sigma_i^2}}$$

2. Deep understanding of the **predicted CEνNS signal**.



Formation of the CEνNS signal

$$\text{CE}\nu\text{NS}\ Event\ rate = \int dE_\nu \frac{d\sigma}{dT_{\text{nr}}} \times \frac{d\phi}{dE_\nu} \times R$$

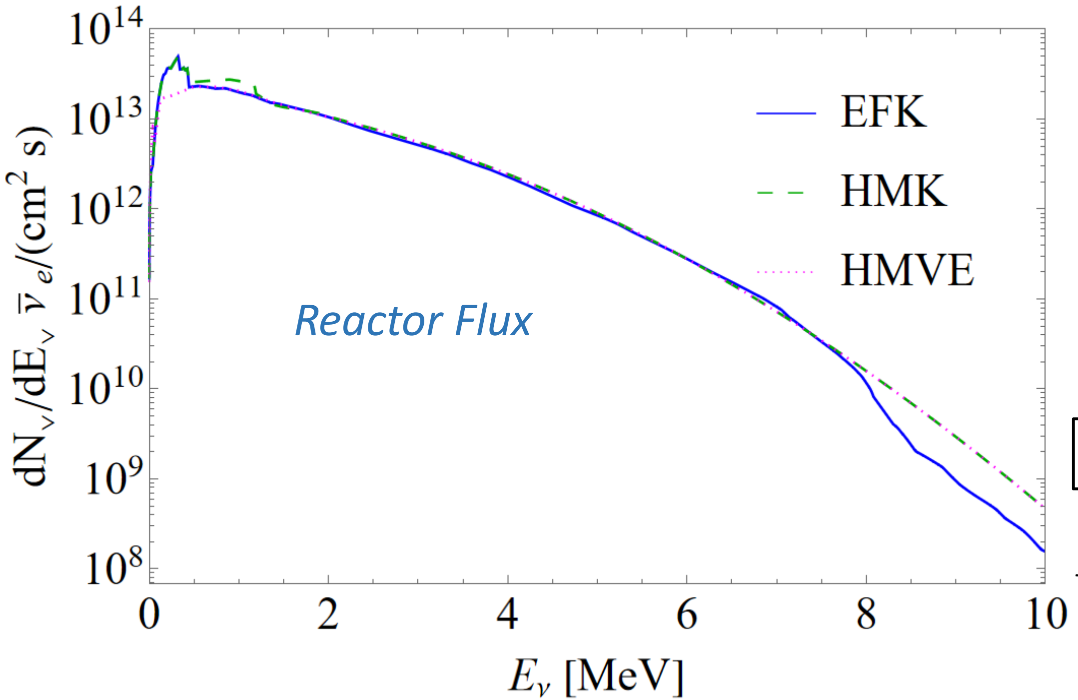
- ✓ CEνNS cross section. Very well known thanks also to the COHERENT measurements.

- ✓ Neutrino Flux is under control.
- ✓ Different parameterizations lead to very similar predictions!

Detector response. Include different effects:

- ❓ Energy efficiency effects
- ❓ Energy smearing effects
- ❓ Quenching factor

} *Beyond our control.*



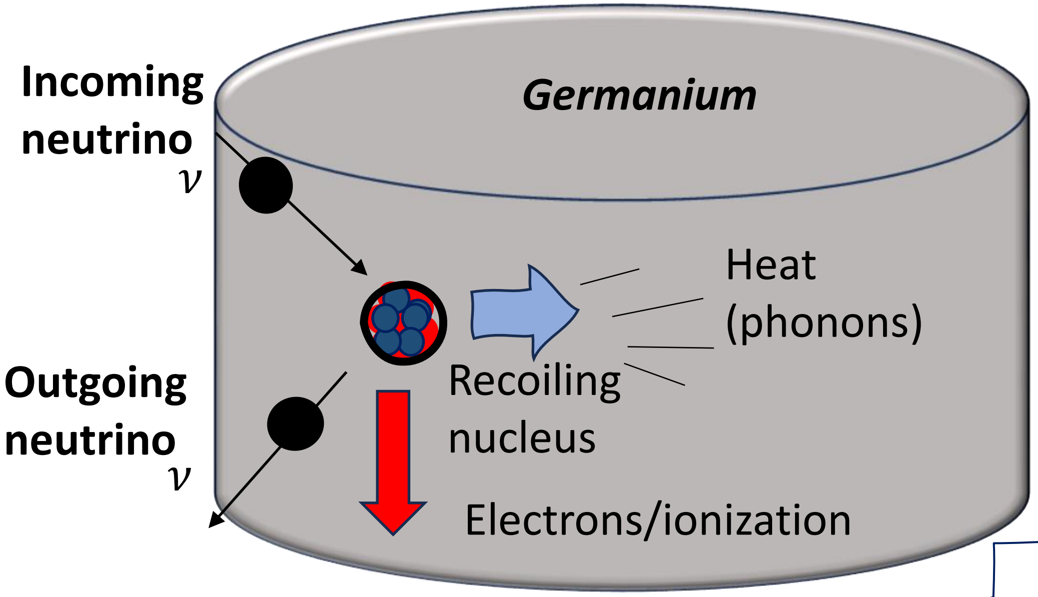
See JHEP 09 (2022) 164 for a description of the reactor fluxes used

Defined as
'the reduction of the ionization yield produced by a nuclear recoil with respect to an electron recoil of the same energy '

The quenching factor

When a neutral particle (neutron, neutrino, dark matter) hits a nucleus, the energy is splitted in two components:

1. ***Heat*** **(does not produce observable signal in the Dresden-II detector)**
2. **Ionization energy $\mathbf{keV_{ee}}$**



We have a theory that predicts this effect → **Lindhard theory**

Quenching factor

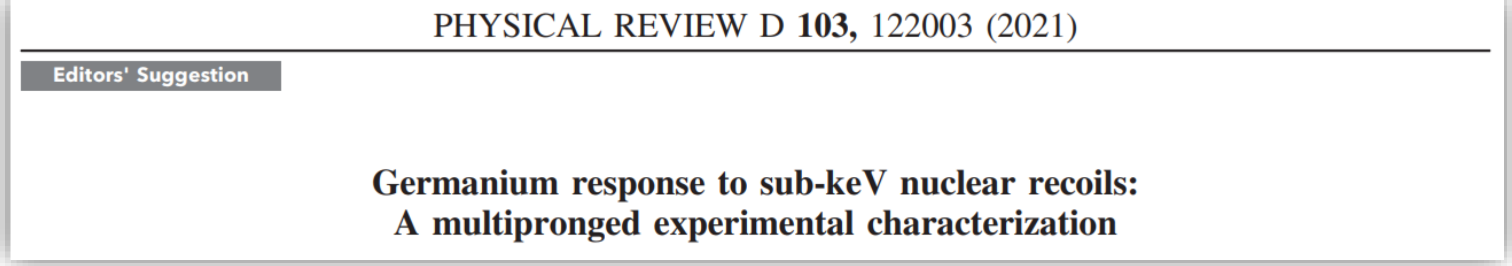
$$f_Q(T_{nr}) = \frac{T_e}{T_{\mathrm{nr}}}$$

Observed energy in the detector

Do we really know its behaviour at low energies?

Total energy deposit due to the nuclear recoil

The quenching factor puzzle


PHYSICAL REVIEW D **103,** 122003 (2021)

Editors' Suggestion

Germanium response to sub-keV nuclear recoils:
A multipronged experimental characterization

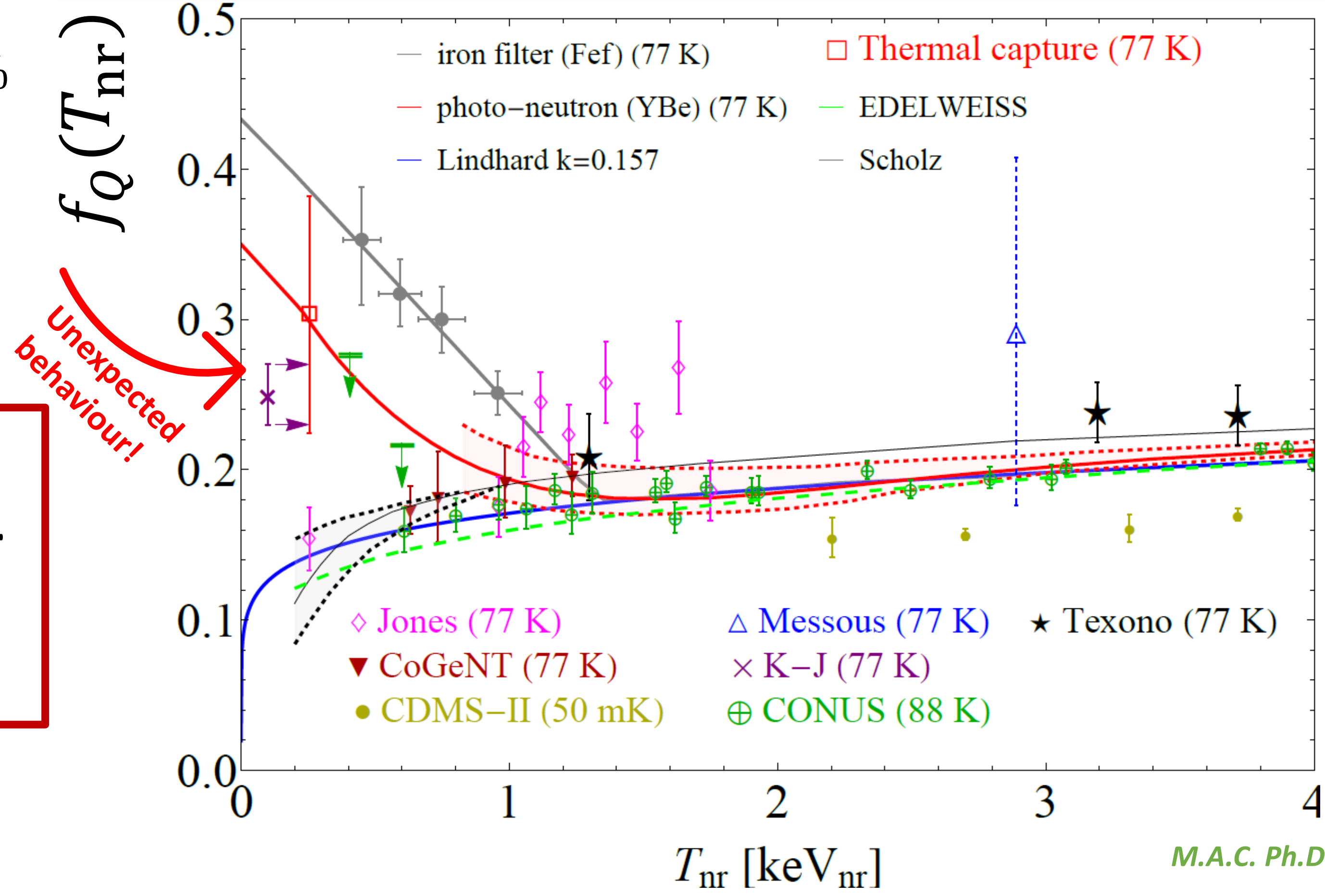
New actor in the game
arXiv: 2405.10405

$f_Q(T_{\mathrm{nr}} = 0.254\ \mathrm{eV}_{nr}) = 25 \pm 2\%$

greater than the 14 % predicted by Lindhard Model!
Pointing to a deviation from the Lindhard theory.

Tension with **CONUS**
recent result **2401.07684**
(No Excess observed compatible with CEνNS)

J. Hakenmüller
Talk

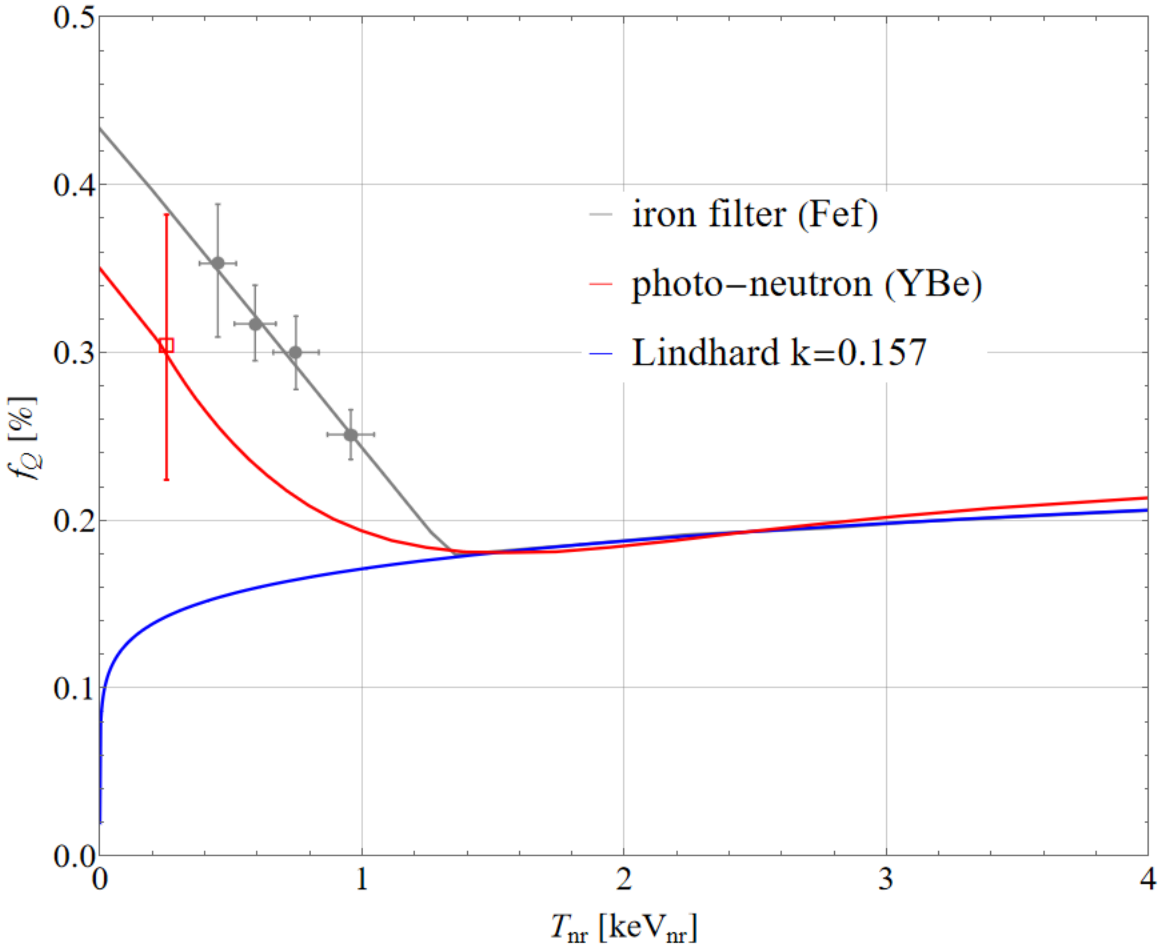


M.A.C. Ph.D. thesis (in preparation)

Key Point

- The new measurements are **much higher** than expected.
- The new quenching results in a **much higher** CEνNS signal.

The quenching factor puzzle

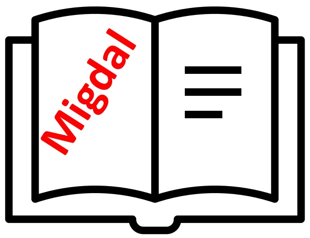


PRD 103, 12003 (2021)

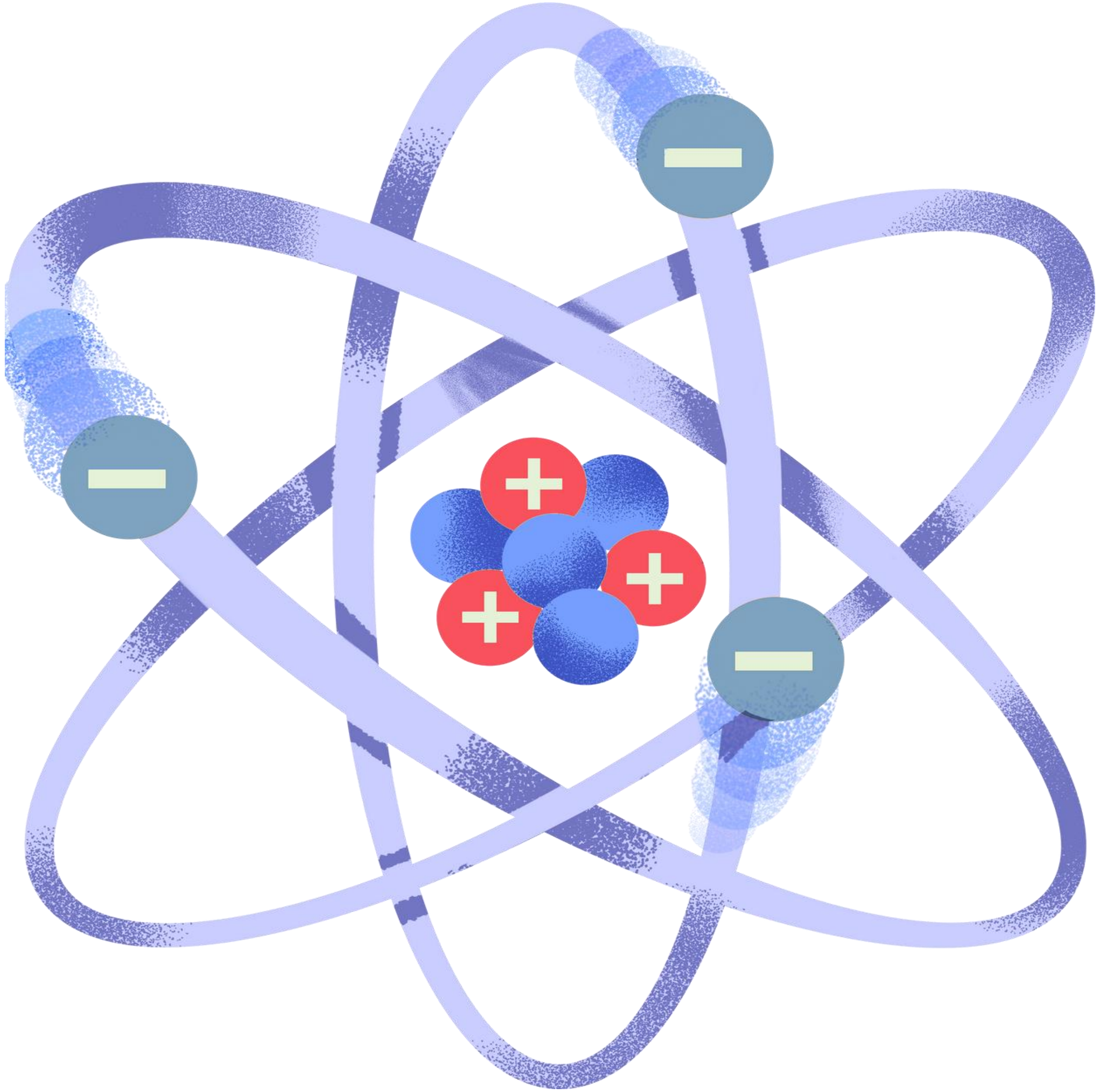
*Our results point to a marked **deviation** from the predictions of the Lindhard model in this mostly unexplored energy range.*

[…]

*We comment on the compatibility of our data with **low-energy processes such as the Migdal effect** [….]*



The Migdal Effect



The ***Migdal effect*** refers to a phenomenon occurring after a nuclear proces:

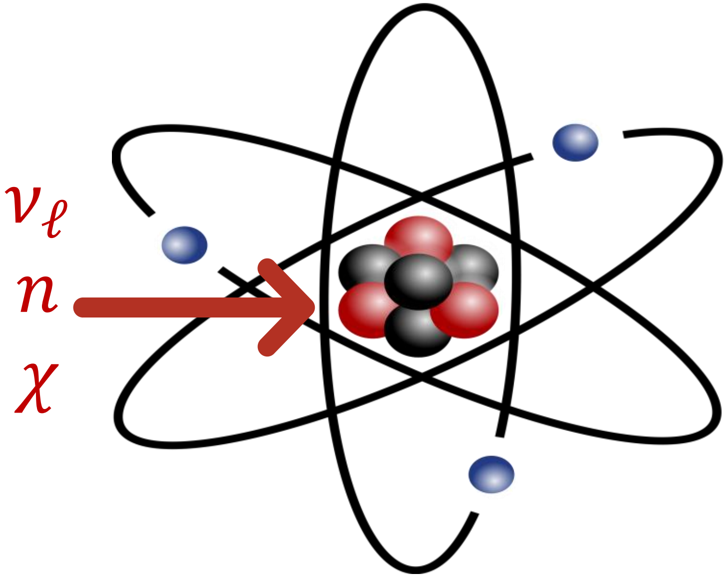
- **α and β decays**
- **Neutral particle scattering**

This results in extra radiation being emitted from the atom.

The Migdal effect induced by NRs

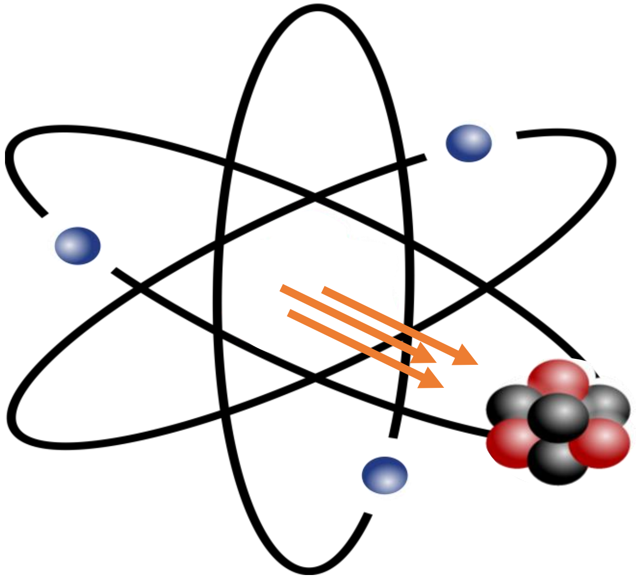
Yet-to-be-observed quantum mechanical effect predicted by A. Migdal in **1939**.

Step 1



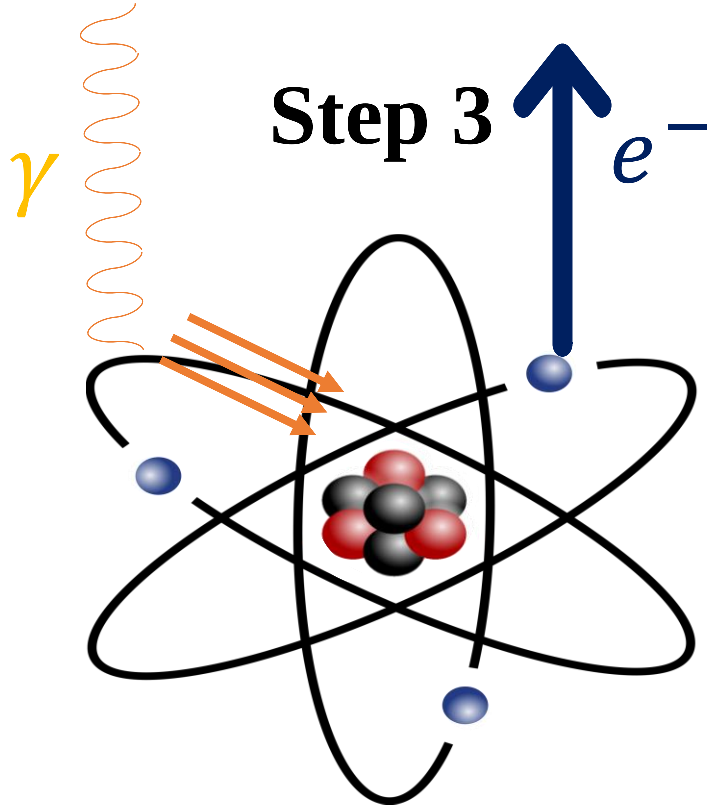
Incoming neutral particle that induces a **nuclear recoil**.

Step 2



The nuclear recoil happens. **The electronic cloud** does not follow **immediately** the recoiling nucleus.

Step 3



The electron cloud follows the nucleus. In this process, **extra ionization can be produced**.

Migdal effect formalisms

Ibe et al. formalism

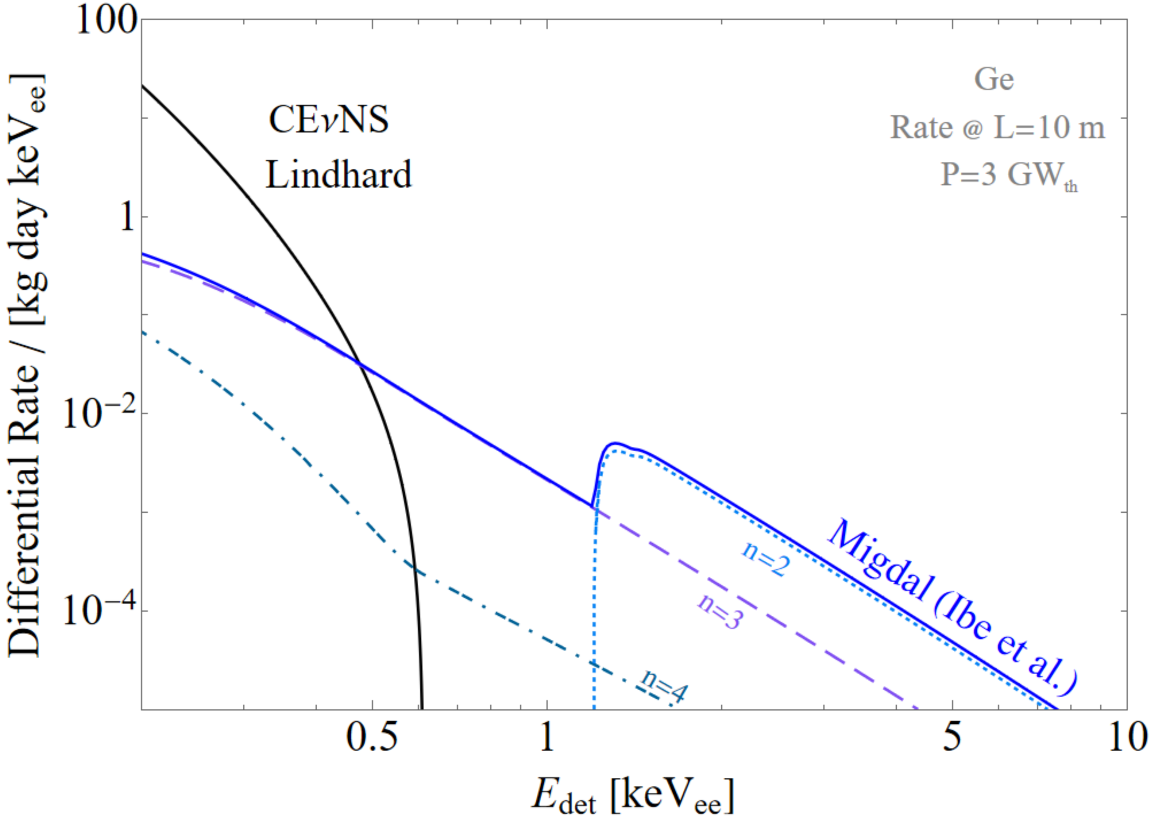
Ibe *et al. JHEP* 03 (2018) 194

- ✓ Evaluate the ionization rate for the electron in the initial quantum state (n, ℓ)
- ✓ Ionization probabilities are evaluated using the Dirac-Hartree-Fock method.

- ✗ Treats the atom as isolated
- ✗ Large theoretical uncertainties
- ✗ Computationally expensive

$$\left(\frac{d^2\sigma_{\bar{\nu}_e\text{-}\mathcal{N}}}{dT_{\rm nr}dT_e}\right)^{\text{Ibe } et\ al.}_{n\ell} = \frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT_{\rm nr}}\,\frac{1}{2\pi}\,\frac{d}{dT_e}p^c_{q_e}(n\ell \to T_e)$$

Ionization probabilities provided in Ibe et al. JHEP 03 (2018) 194



$$E_{\rm det} = f_Q(T_{\rm nr})T_{\rm nr}$$

Migdal effect formalisms

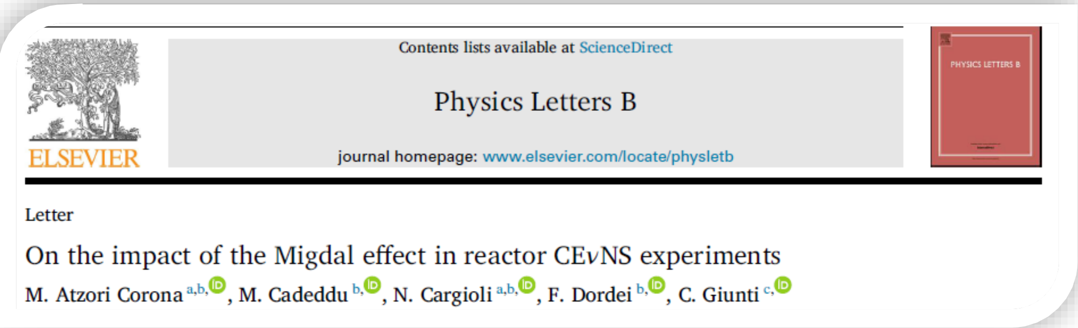
Migdal Photo Absorption (MPA)

Liu *et al. Phys.Rev.D* 102 (2020) 12, 121303

- ✓ Relates the Migdal ionization rate to the experimentally well-known **photoabsorption cross section**.
- ✓ Data-driven approach
- ✓ Accounts for many-body effects
- ✓ Computationally easy
- ✗ It is not possible to evaluate the single atomic state (n, ℓ) contribution

$$\left(\frac{d^2\sigma_{\bar{\nu}_e\text{-}\mathcal{N}}}{dT_{\mathrm{nr}}dE_r}\right)^{\mathrm{MPA}}_{\mathrm{Migdal}} = \frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT_{\mathrm{nr}}}\frac{1}{2\pi^2\alpha_{\mathrm{EM}}}\frac{m_e^2}{M}\frac{T_{\mathrm{nr}}}{E_r}\sigma_\gamma^{\mathrm{Ge}}(E_r)$$

Surprisingly, the two approaches lead to very consistent results



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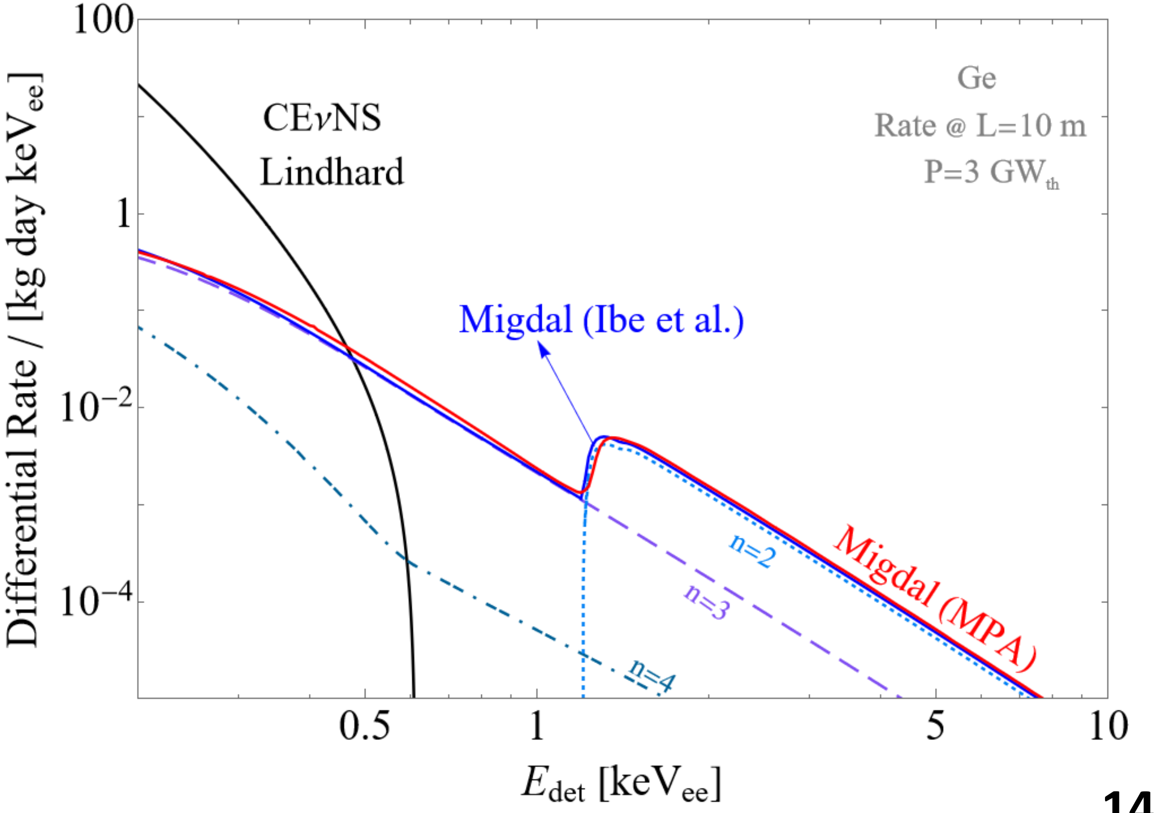
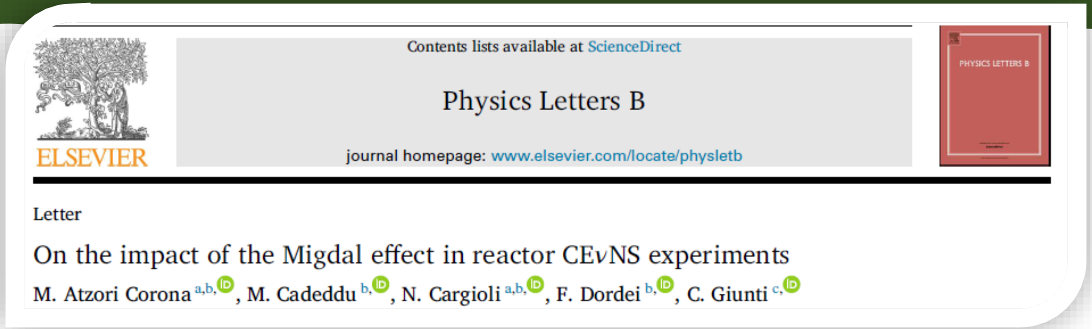


Dresden-II and the Migdal effect



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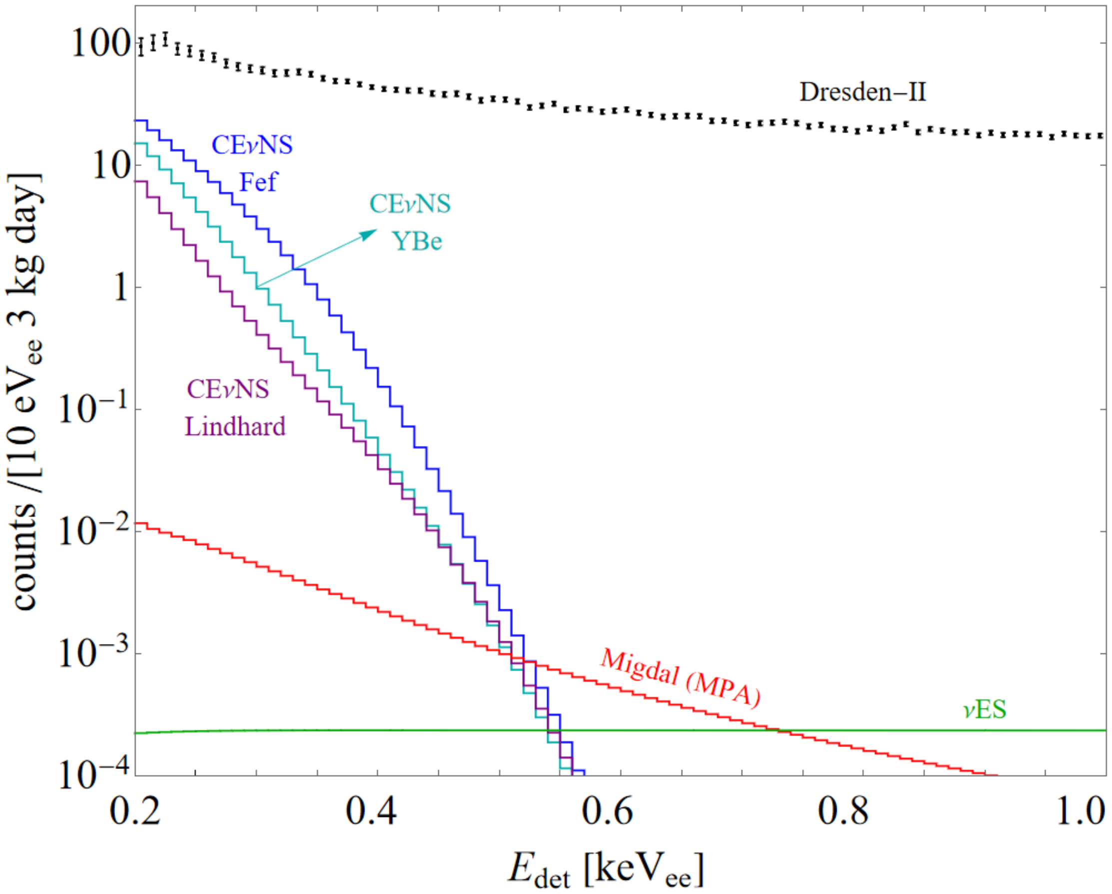


✓ The Migdal contribution **adds** to the standard Lindhard prediction.

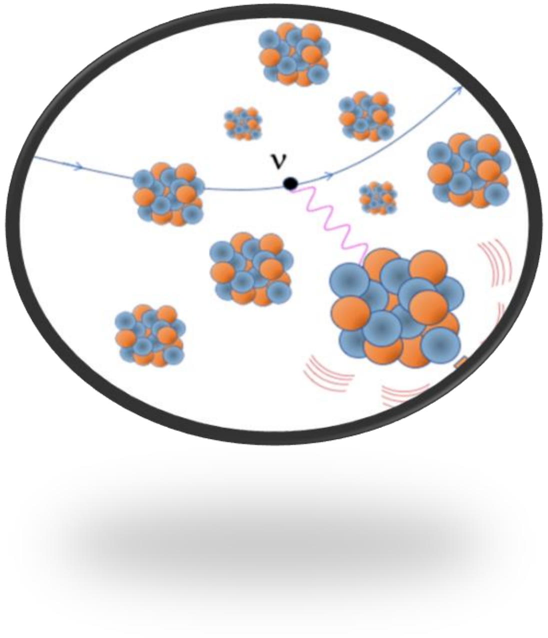
! If the enhanced signal (Fef or YBe) is due to Migdal, it should have been retrieved as: **Migdal + CEνNS Lindhard**.

! The Migdal contribution is **completely subdominant wrt CEνNS!**

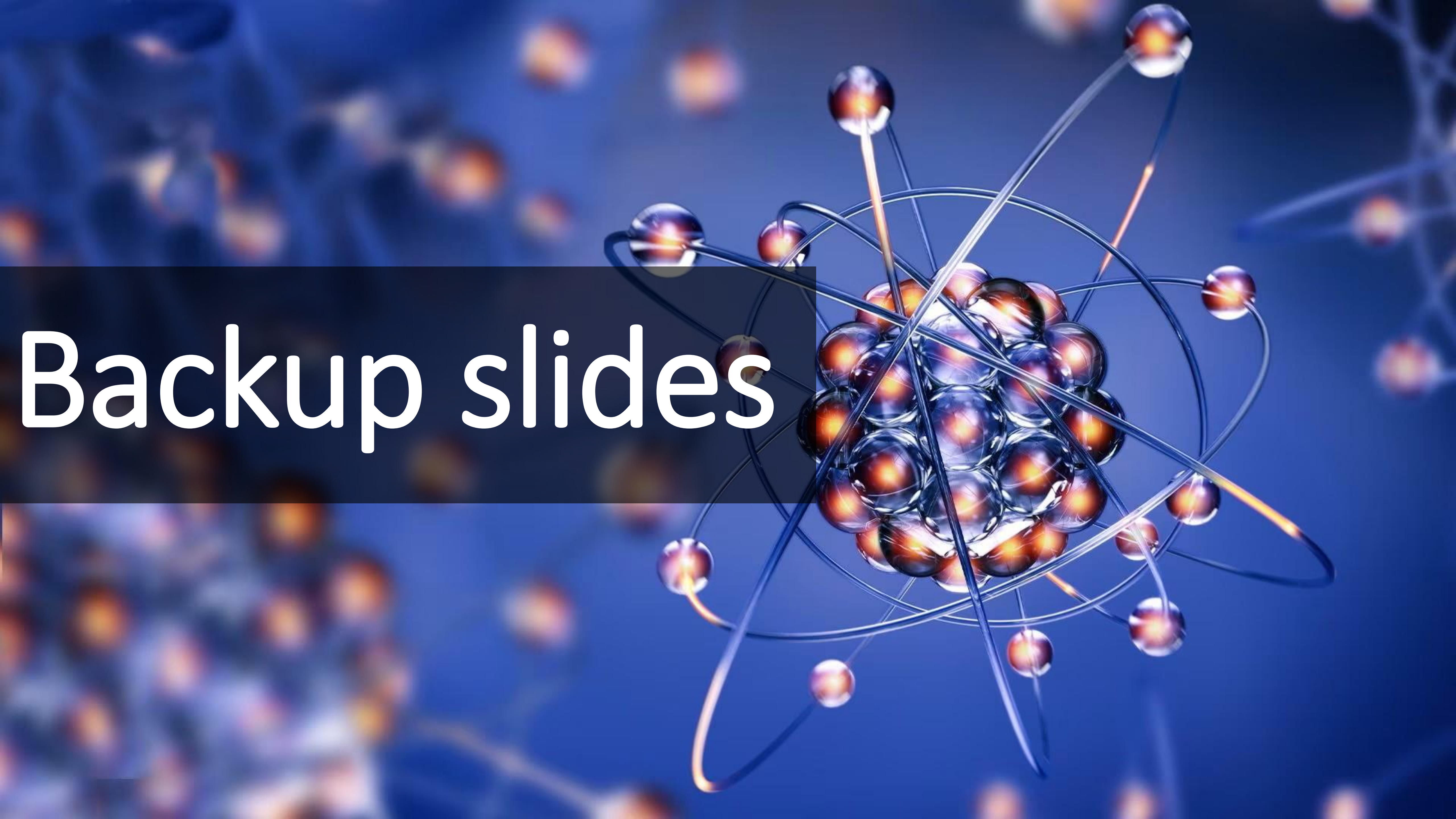
✗ The standard Migdal effect induced by neutrinos cannot be the source of the **enhancement** at low energies of the **new quenching factor measured for Germanium!**

Conclusions

- The search for CEνNS from reactor $\bar{\nu}_e$ remains a **formidable experimental challenge**.
- The recent results from the **NCC-1701 germanium detector** boosted experimental and theoretical investigations
- The higher quenching factor at low energy is crucial to interpret the Dresden-II excess in terms of a CEνNS signal (different experimental campaign are underway to explore this poorly known energy regime)
- We discussed the **Migdal effect** following the NR in the neutrino scattering
- Using different formalisms, we showed that the amount of ionization provided by the Migdal effect is **negligible compared to CEνNS assuming the Lindhard theory**. The Fef or YBe QF cannot by explained by the standard Migdal effect.

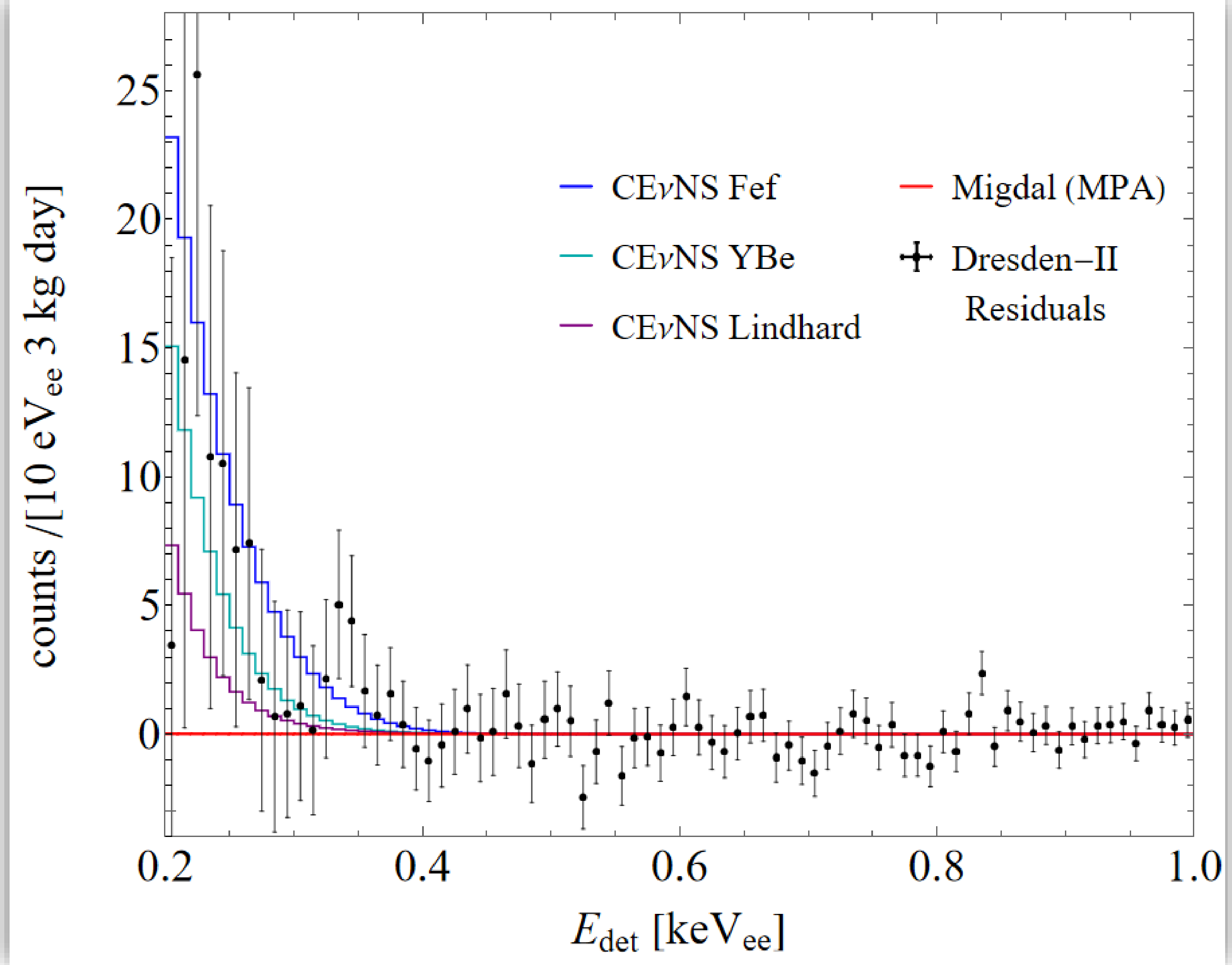


Thanks
for your attention!



Backup slides

Migdal vs CEνNS rate

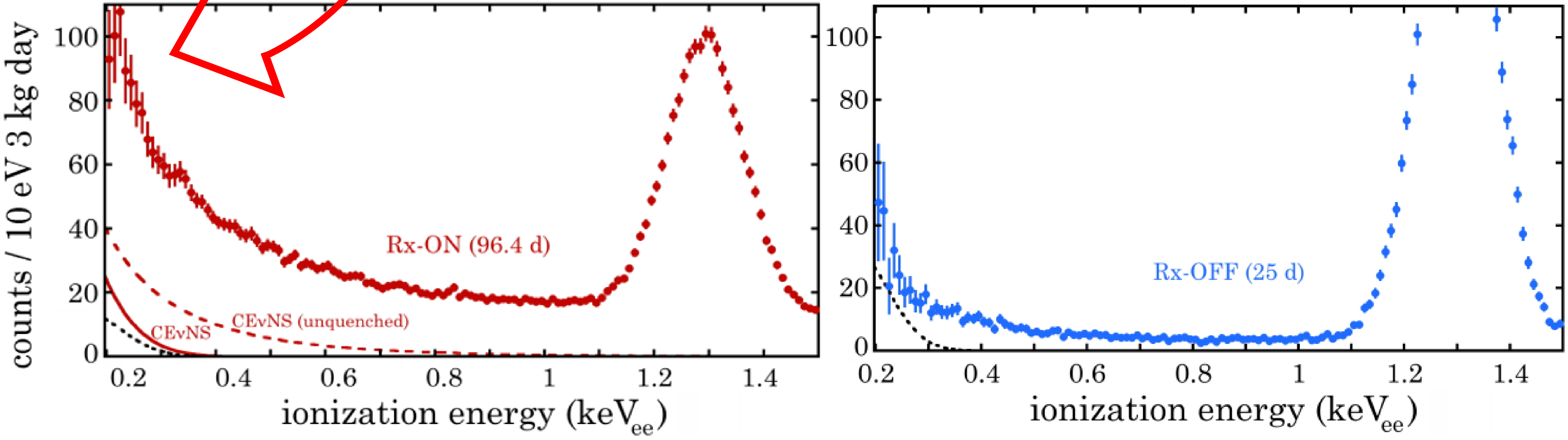


Background for Dresden-II

$$\frac{dN^{\text{bkg}}}{dT_{\text{e}}} = \underbrace{N_{\text{epith}} + A_{\text{epith}} e^{-T_{\text{e}}/T_{\text{epith}}}}_{\textit{Reactor related background (mainly slow neutrons)}} + \underbrace{\sum_{i=\text{L1,L2,M}} \frac{A_i}{\sqrt{2\pi}\sigma_i} e^{-\frac{(T_{\text{e}}-T_i)^2}{2\sigma_i^2}}}_{\textit{Detector related background}}$$

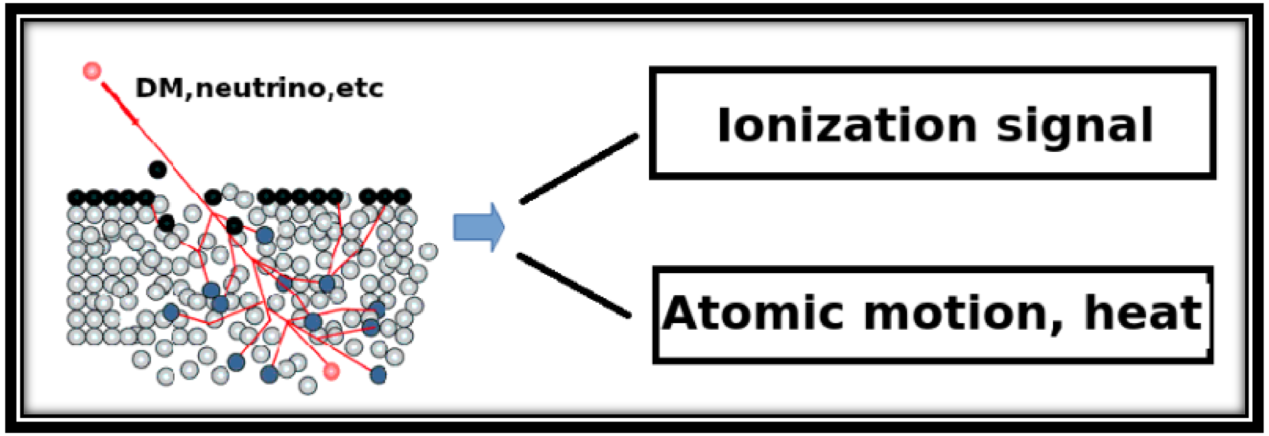
L1-shell Electron Capture peak of 1.297 keV of ^{71}Ge
(https://atom.kaeri.re.kr/cgi-bin/decay?Ge-71%20EC)

$$^{71}_{32}\text{Ge} + {}^{0}_{-1}\text{e} \rightarrow {}^{71}_{31}\text{Ga}^{*} + \nu_e$$



The standard Lindhard Theory for the Quenching Factor

The moving ion sets off a cascade of slowing-down processes that dissipate the energy E throughout the medium.



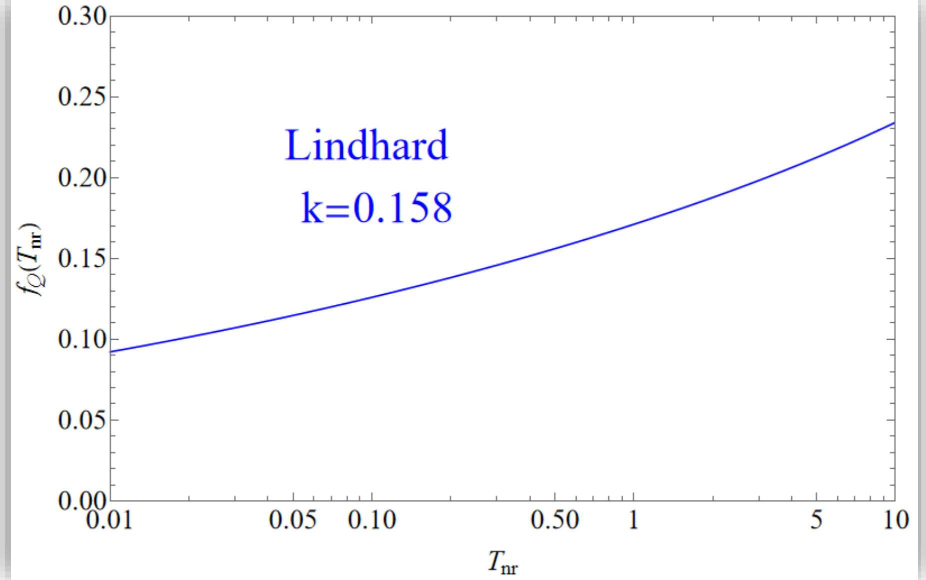
Underlying assumptions within this formalism:

i. The contribution of the moving electrons is negligible
ii. The electronic cloud follow immediately the nucleus
iii. The energy transferred to ionized electrons is small compared to that transferred to recoiling ions.
iv. The effects of electronic and atomic collisions can be treated separately.
v. $T_{\rm nr} < E_{inc}$

The Lindhard QF is defined as

$$f_Q(T_{\rm nr}) = \frac{k\ g(\epsilon)}{1 + k\ g(\epsilon)}$$

where $g(\epsilon) = 3\epsilon^{0.15} + 0.7\epsilon^{0.6} + \epsilon$
with $\epsilon = 11.5\ Z^{-7/3} T_{\rm nr}$.
k is found to be $k = 0.133\ Z^{2/3} A^{-1/3} \sim 0.158$ for Ge



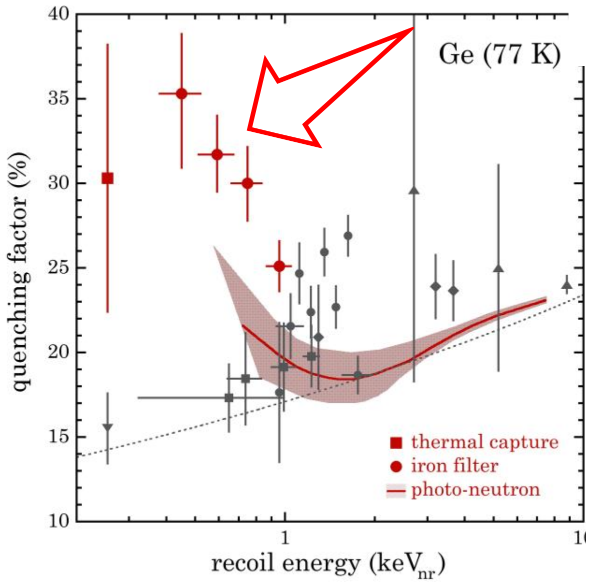
New measurements of the Quenching factor

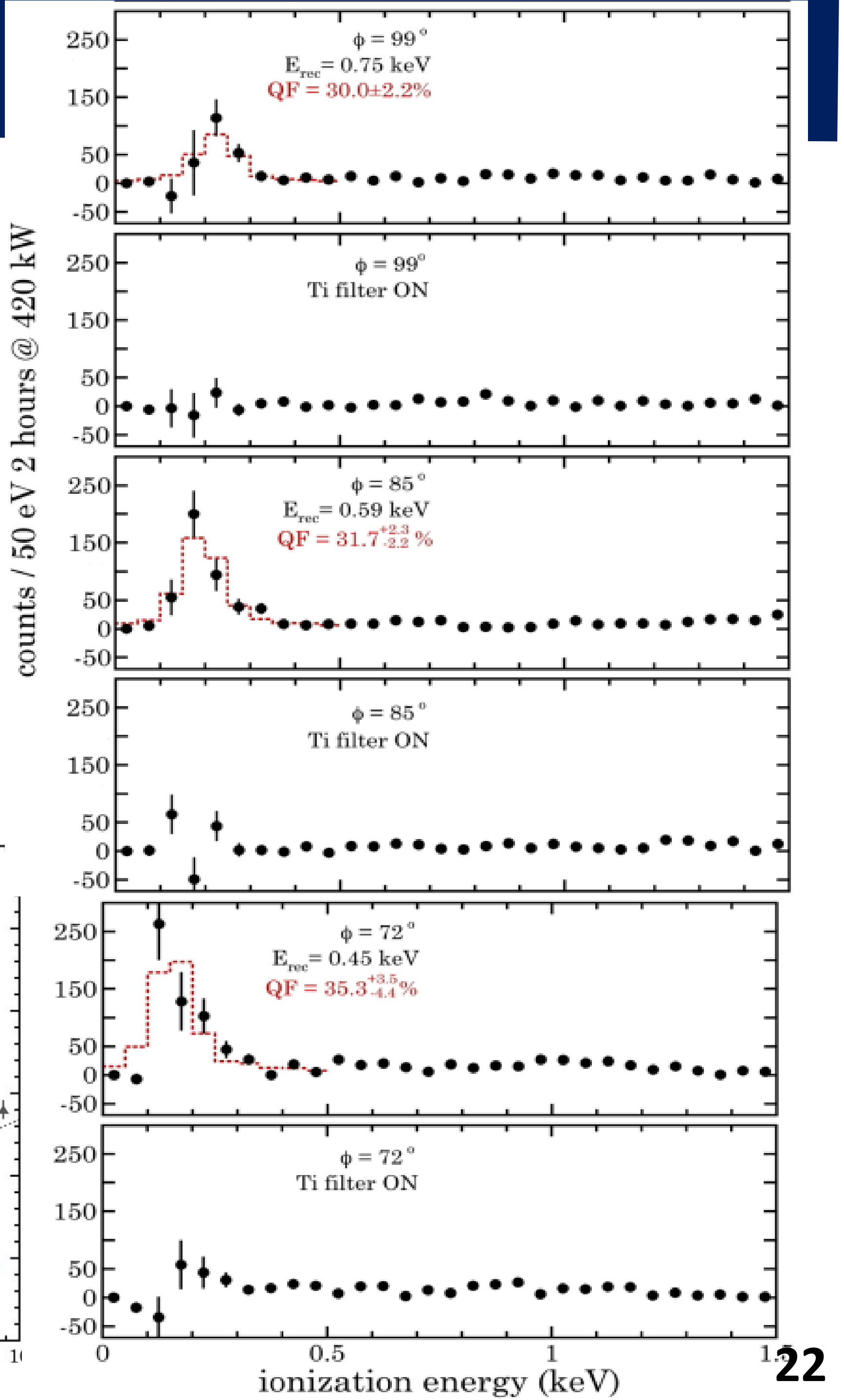
Calibration QF measurements are performed with neutrons.
Three techniques have been exploited:

1. **Iron filter (Fef)**
2. Photo-neutron source (YBe)
3. Neutron capture

Iron filter (Fef)

- The germanium detector was exposed to a monochromatic (~24 keV) iron-filtered neutron bean produced at the Kansas State University (KSU) experimental reactor.
- This technique exploits a dip in the elastic scattering neutron cross-section for iron at 24 keV, where it is reduced by three orders of magnitude over a narrow energy region. For ultra-pure iron filters ~1 m in length, designed to reduce capture gamma backgrounds, a high beam purity is achievable.
- By changing the scattering angle it is possible to obtain measurements for different $T_{\rm nr}$, fixed by the kinematics.





New QF measurements of the Quenching factor

Calibration QF measurements are performed with neutrons.
Three techniques have been exploited:

1. Iron filter (Fef)
2. **Photo-neutron source (YBe)**
3. Neutron capture

Photo-disintegration process with the production of neutrons.

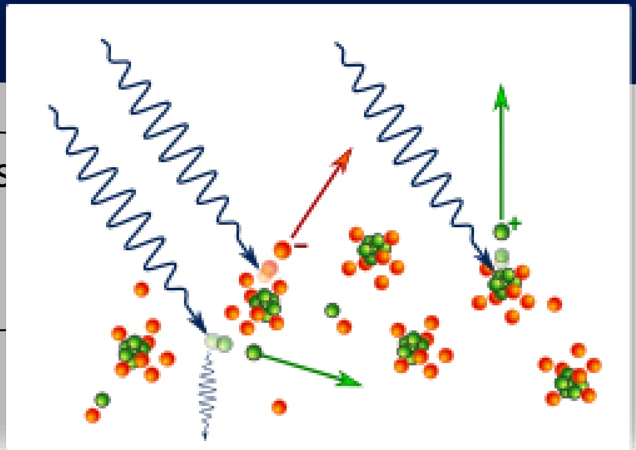
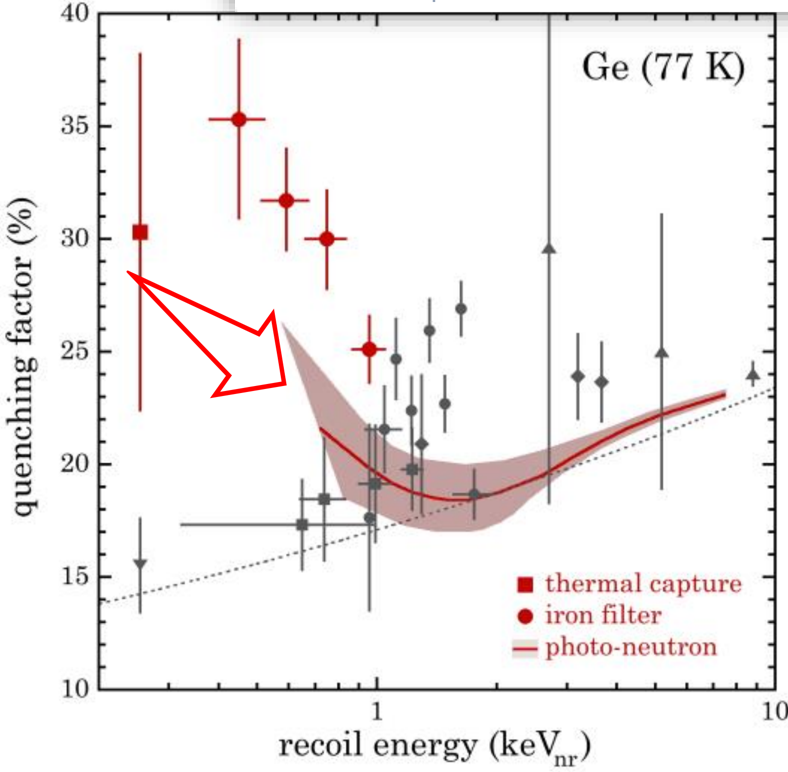


Photo-neutron source (YBe)

- Photo-disintegration is a nuclear process where a nucleus absorbs a high-energy photon, enters an excited state, and immediately decays emitting subatomic particles, including **neutrons**.
- A photo-neutron YBe source generates monochromatic **152 keV** neutrons from beryllium photo-disintegration.
- The intense high-energy gamma emission is stopped by 15 cm of lead.
- Average neutron yield 848 n/s.



$$E_{nr}^{max} = (4MmE_n)/(M+m)^2 = 8.5\ \mathrm{keV_{nr}}$$

New QF measurements of the Quenching factor

Calibration QF measurements are performed with neutrons.
Three techniques have been exploited:

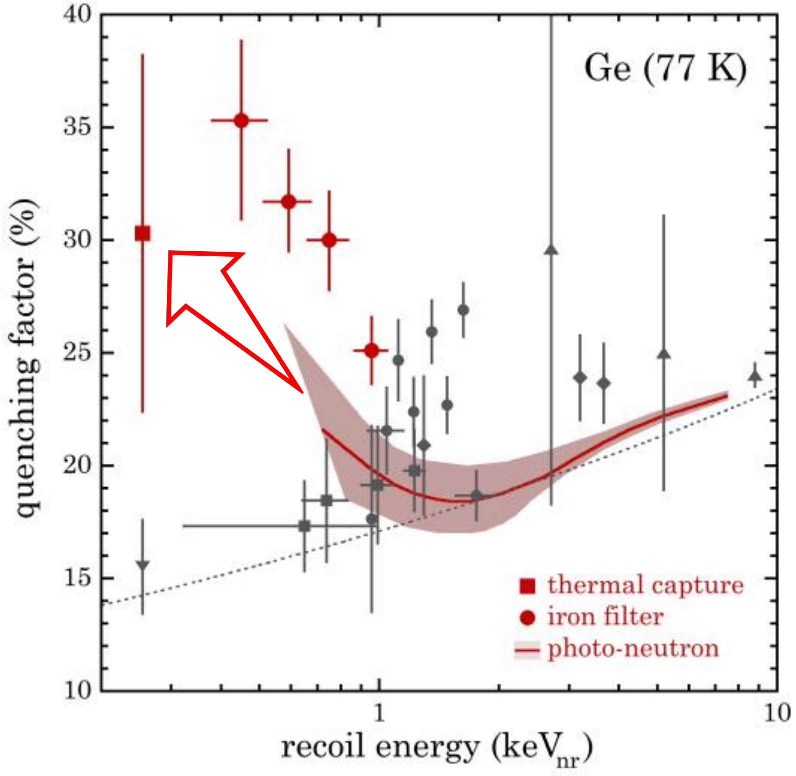
1. Iron filter (Fef)
2. Photo-neutron source (YBe)
3. **Neutron capture**

Neutron Capture

- The third technique exploits recoils from gamma emission following thermal neutron capture.
- This techniques (that backs to 1975!) is able to produce fixed-energy germanium recoils carrying a mere $0.254 \pm 0.001\ \mathrm{keV_{nr}}$.
- $^{72}\mathrm{Ge} + \mathrm{n} \rightarrow\ ^{73}\mathrm{Ge} + \gamma$

The γ is observed with a SiPM.

$$E_R = E_\gamma^2 / 2Mc^2$$



Migdal formalism

The Migdal ionization rate is determined by the matrix element for the transition of the electron in the initial state ψ_i into the final state ψ_f.

$$M_{fi} = \langle \psi_f | e^{-i m_e \vec{v} \cdot \sum_{i=1}^{Z} \vec{r}_i} | \psi_i \rangle \simeq$$

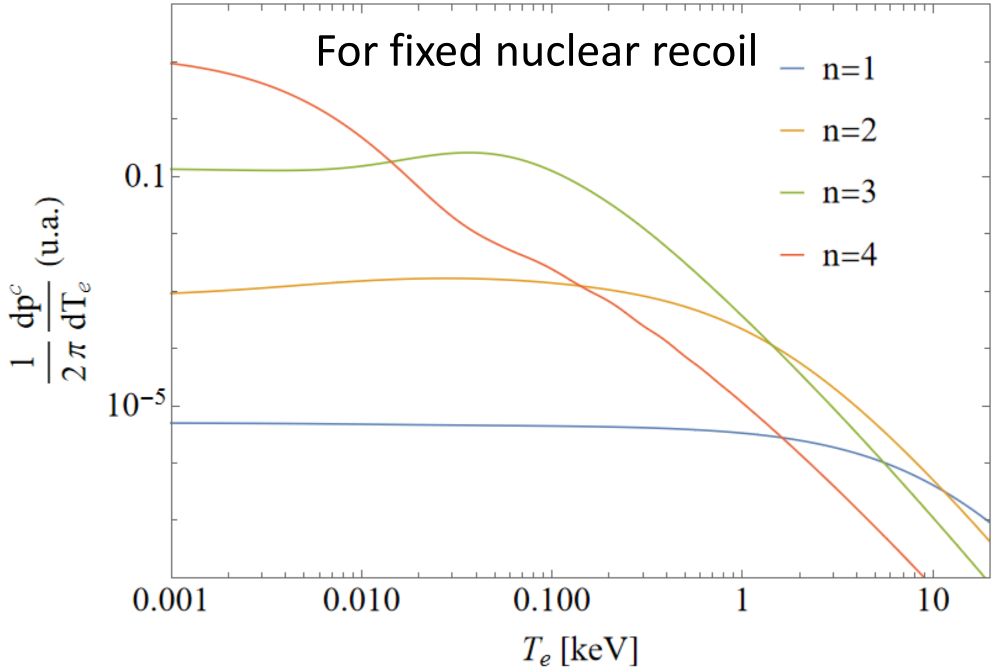
$$\simeq -i m_e \vec{v} \cdot \langle \psi_f | \sum_{i=1}^{Z} \vec{r}_i | \psi_i \rangle$$

Ibe at. al. **approach**

$$\equiv -i m_e \vec{v} \cdot \boxed{\vec{D}_{fi},}$$

Dipole matrix element

- The final state wavefunctions are boosted to the rest frame of the recoiling nucleus by a Galilean transformation and are computed using the Dirac-Hartree-Fock method in order to compute $\vec{\boldsymbol{D}}_{\boldsymbol{fi}}$.
- The ionization rate is espressed in terms of $p^c(n\ell \rightarrow T_e)$, which gives the probabilities for an atomic electron, with quantum numbers *n* and *ℓ, to be* ionized with a final energy T_e.



The total energy absorbed in the detector is
$E_{\text{det}} = f_Q T_{nr} + E_{n\ell} + T_e$

Migdal Photo Absorption Formalism

It is based on the relation between the dipole matrix element and the photoabsorption cross section.

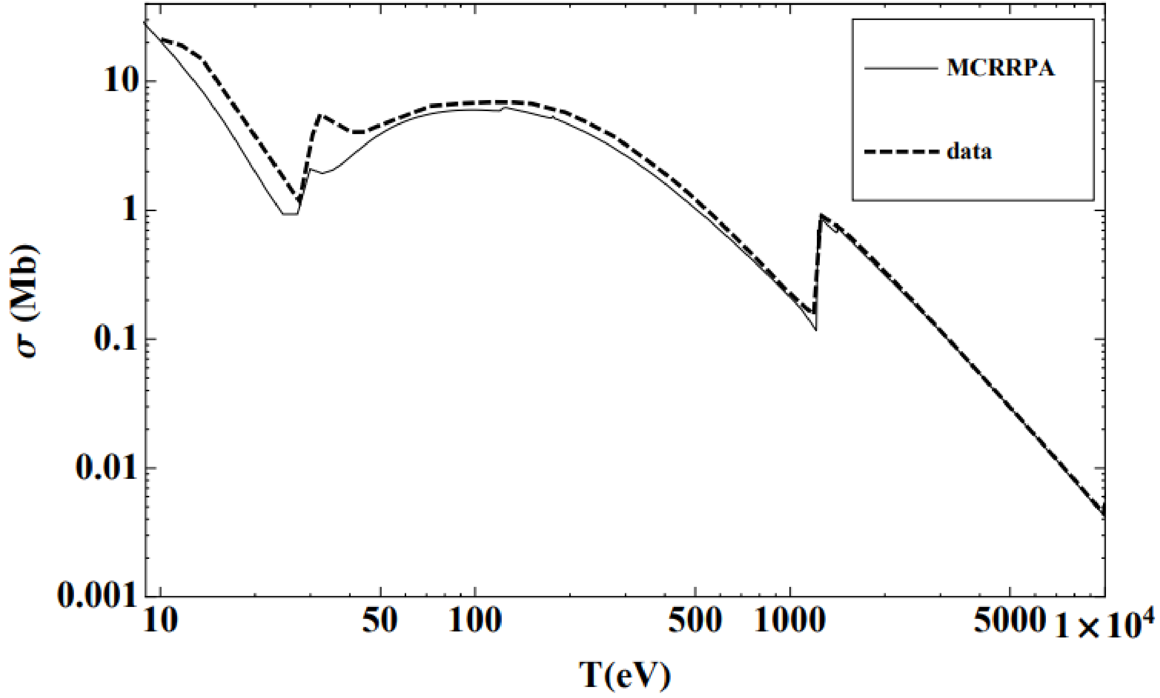
- $\vec{D}_{fi} = \frac{1}{4\pi^2 \alpha_{EM} E_r} \sigma(E_r)$

$\boldsymbol{E_r}$ is the total energy deposit due to ionisation or excitation.

$$E_{det} = f_Q T_{nr} + E_r$$

$$\left(\frac{d^2\sigma_{\bar{\nu}_e\text{-}\mathcal{N}}}{dT_{\rm nr}\,dE_r}\right)^{\rm MPA}_{\rm Migdal} = \frac{G_{\rm F}^2 M}{\pi}\left(1-\frac{MT_{\rm nr}}{2E_\nu^2}\right)Q_W^2 \times \frac{1}{2\pi^2\alpha_{\rm EM}}\frac{m_e^2}{M}\frac{T_{\rm nr}}{E_r}\sigma_\gamma^{\rm Ge}(E_r), \quad (11)$$

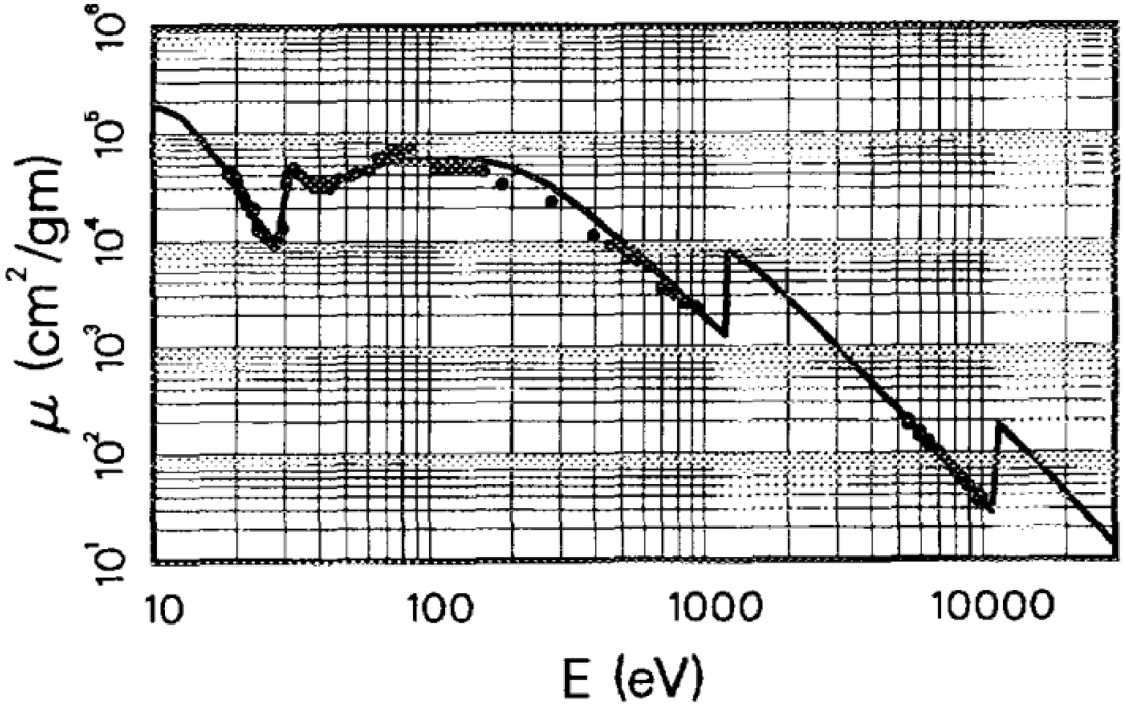
Phys. Rev. D 91, 013005 (2015)

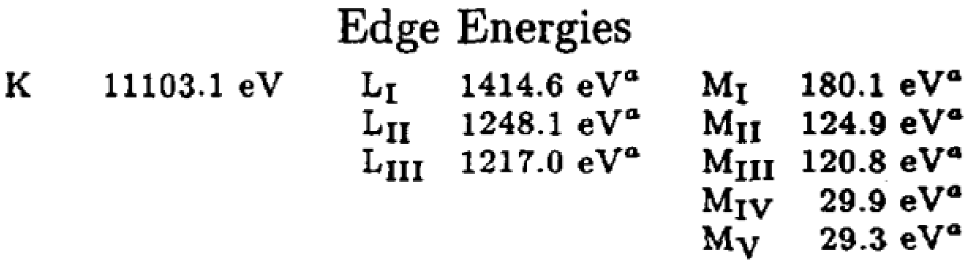


The photoabsoprion cross section reflects the atomic shell structure.

Germanium photoabsorption cross sections

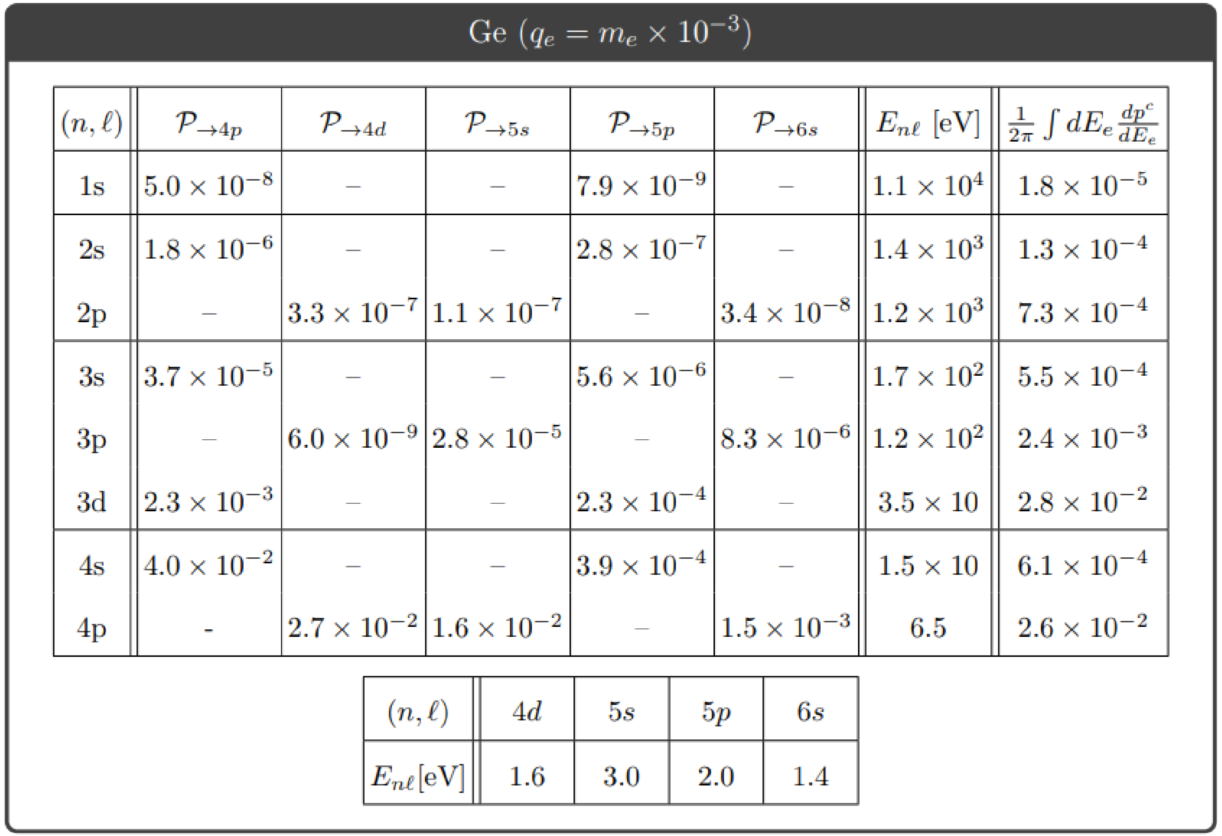
Atomic Data and Nuclear Data Tables Volume 54, Issue 2, July 1993, Pages 181-342





Edge Energies

K	11103.1 eV	L_I	1414.6 eV^a	M_I	180.1 eV^a
		L_{II}	1248.1 eV^a	M_{II}	124.9 eV^a
		L_{III}	1217.0 eV^a	M_{III}	120.8 eV^a
				M_{IV}	29.9 eV^a
				M_V	29.3 eV^a



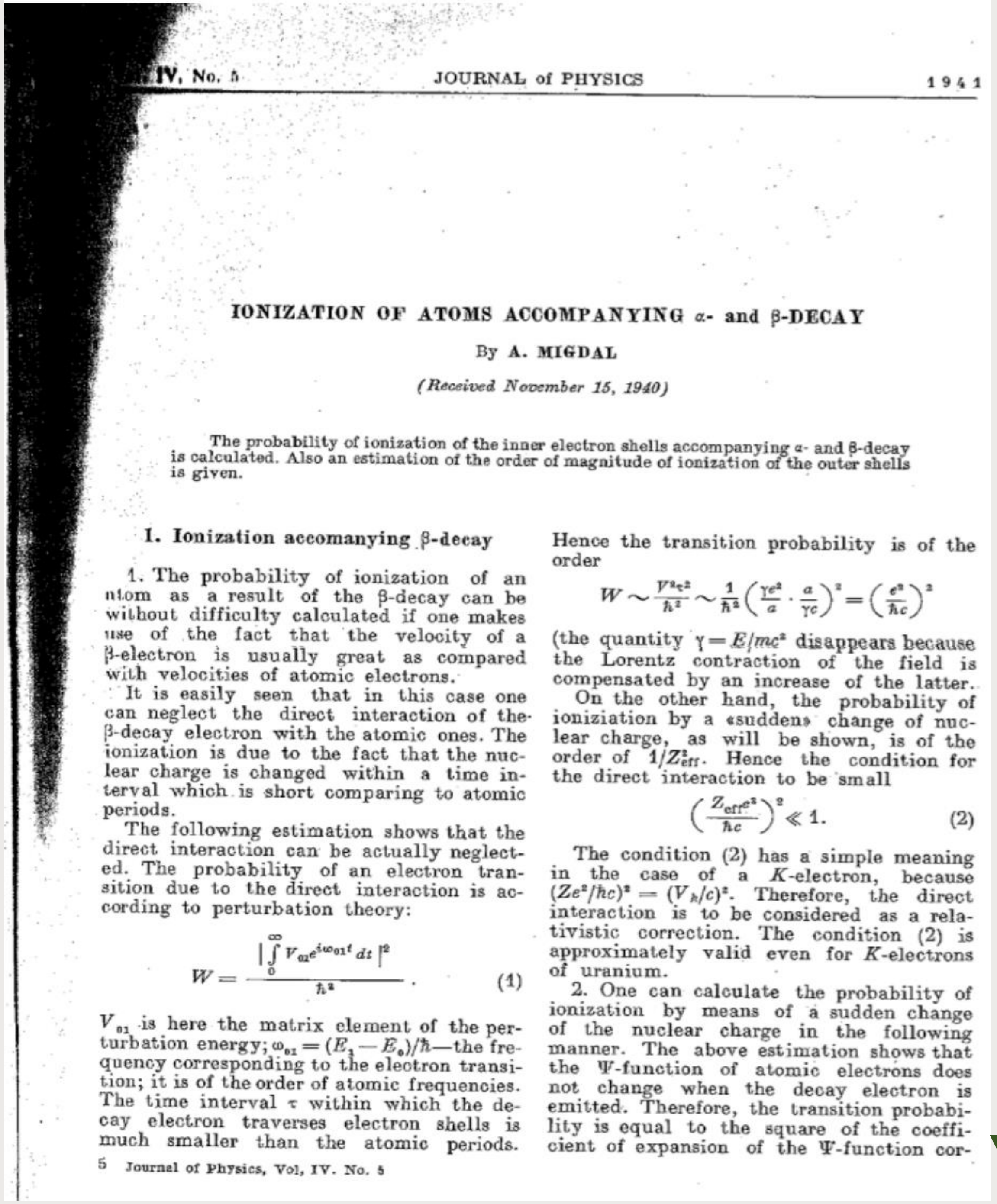
Ge ($q_e = m_e \times 10^{-3}$)

(n,ℓ)	$\mathcal{P}_{\to 4p}$	$\mathcal{P}_{\to 4d}$	$\mathcal{P}_{\to 5s}$	$\mathcal{P}_{\to 5p}$	$\mathcal{P}_{\to 6s}$	$E_{n\ell}$ [eV]	$\frac{1}{2\pi}\int dE_e \frac{dp^c}{dE_e}$
1s	5.0×10^{-8}	–	–	7.9×10^{-9}	–	1.1×10^4	1.8×10^{-5}
2s	1.8×10^{-6}	–	–	2.8×10^{-7}	–	1.4×10^3	1.3×10^{-4}
2p	–	3.3×10^{-7}	1.1×10^{-7}	–	3.4×10^{-8}	1.2×10^3	7.3×10^{-4}
3s	3.7×10^{-5}	–	–	5.6×10^{-6}	–	1.7×10^2	5.5×10^{-4}
3p	–	6.0×10^{-9}	2.8×10^{-5}	–	8.3×10^{-6}	1.2×10^2	2.4×10^{-3}
3d	2.3×10^{-3}	–	–	2.3×10^{-4}	–	3.5×10	2.8×10^{-2}
4s	4.0×10^{-2}	–	–	3.9×10^{-4}	–	1.5×10	6.1×10^{-4}
4p	-	2.7×10^{-2}	1.6×10^{-2}	–	1.5×10^{-3}	6.5	2.6×10^{-2}

(n,ℓ)	$4d$	$5s$	$5p$	$6s$
$E_{n\ell}$[eV]	1.6	3.0	2.0	1.4

See also
https://xdb.lbl.gov/Section1/Table_1-1.pdf

Migdal effect storyline



IV, No. 5 JOURNAL of PHYSICS 1941

IONIZATION OF ATOMS ACCOMPANYING α- and β-DECAY

By A. MIGDAL

(Received November 15, 1940)

The probability of ionization of the inner electron shells accompanying α- and β-decay is calculated. Also an estimation of the order of magnitude of ionization of the outer shells is given.

1. Ionization accomanying β-decay

1. The probability of ionization of an atom as a result of the β-decay can be without difficulty calculated if one makes use of the fact that the velocity of a β-electron is usually great as compared with velocities of atomic electrons.

It is easily seen that in this case one can neglect the direct interaction of the β-decay electron with the atomic ones. The ionization is due to the fact that the nuclear charge is changed within a time interval which is short comparing to atomic periods.

The following estimation shows that the direct interaction can be actually neglected. The probability of an electron transition due to the direct interaction is according to perturbation theory:

$$W = \frac{\left|\int\limits_0^\infty V_{01} e^{i\omega_{01}t}\,dt\right|^2}{\hbar^2}. \tag{1}$$

V_{01} is here the matrix element of the perturbation energy; $\omega_{01} = (E_1 - E_0)/\hbar$—the frequency corresponding to the electron transition; it is of the order of atomic frequencies. The time interval τ within which the decay electron traverses electron shells is much smaller than the atomic periods. Hence the transition probability is of the order

$$W \sim \frac{V^2\tau^2}{\hbar^2} \sim \frac{1}{\hbar^2}\left(\frac{\gamma e^2}{a}\cdot\frac{a}{\gamma c}\right)^2 = \left(\frac{e^2}{\hbar c}\right)^2$$

(the quantity $\gamma = E/mc^2$ disappears because the Lorentz contraction of the field is compensated by an increase of the latter.

On the other hand, the probability of ioniziation by a «sudden» change of nuclear charge, as will be shown, is of the order of $1/Z^2_{\text{eff}}$. Hence the condition for the direct interaction to be small

$$\left(\frac{Z_{\text{eff}}e^2}{\hbar c}\right)^2 \ll 1. \tag{2}$$

The condition (2) has a simple meaning in the case of a K-electron, because $(Ze^2/\hbar c)^2 = (V_k/c)^2$. Therefore, the direct interaction is to be considered as a relativistic correction. The condition (2) is approximately valid even for K-electrons of uranium.

2. One can calculate the probability of ionization by means of a sudden change of the nuclear charge in the following manner. The above estimation shows that the Ψ-function of atomic electrons does not change when the decay electron is emitted. Therefore, the transition probability is equal to the square of the coefficient of expansion of the Ψ-function cor-

5 Journal of Physics, Vol, IV. No. 5

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- 1941 Ionization in α and β decays *ZhETF, 11, 207-212 (1941).*
- 1975 First observation of the Migdal effect in α-decay *PRC 11, 1740-1745 (1975), PRC 11, 1746-1754 (1975)*
- 2012 First observation in β-*decay PRL* ***108****, 243201 (2012)*
- 2017 Ibe et at. Paper *JHEP 03 (2018) 194*
- 2018 First observation in β^+-*decay PRA*, ***97****, 023402 (2018)*
- 20XX – first observation in nuclear recoil?