STUDY OF THE ENERGY SPECTRUMS OBTAINED BY EXPOSING A CCD TO A ^{252}CF SOURCE

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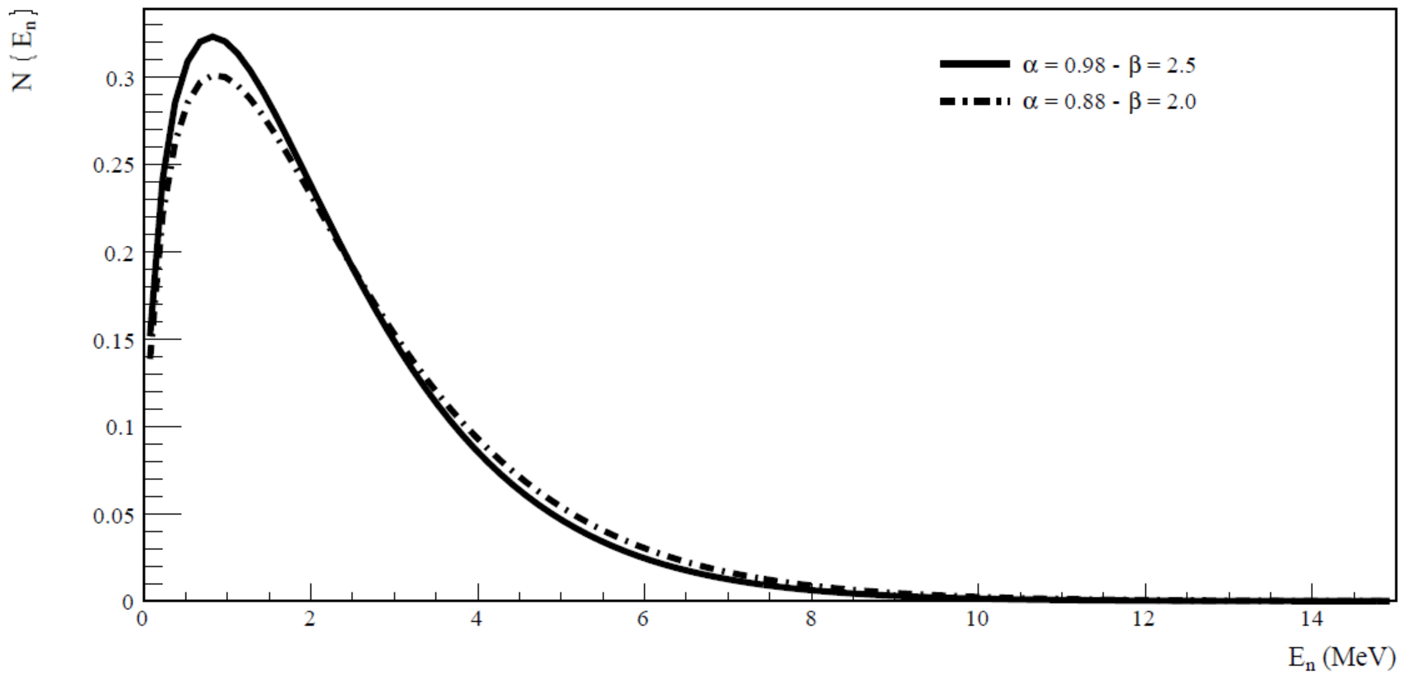
WHY A ^{252}CF SOURCE?

- α decay (96.9 %) → α + ^{248}Cm
- Spontaneous fission (3.1 %) → 3.77 **neutrons** per event and secondary excited nuclei which emit γ rays

Neutron energy spectrum (most probable energy value ~ 0.8 MeV)

$$N\left(E_n\right) = N_0 e^{-\alpha E_n} \sinh\sqrt{\beta E_n}$$

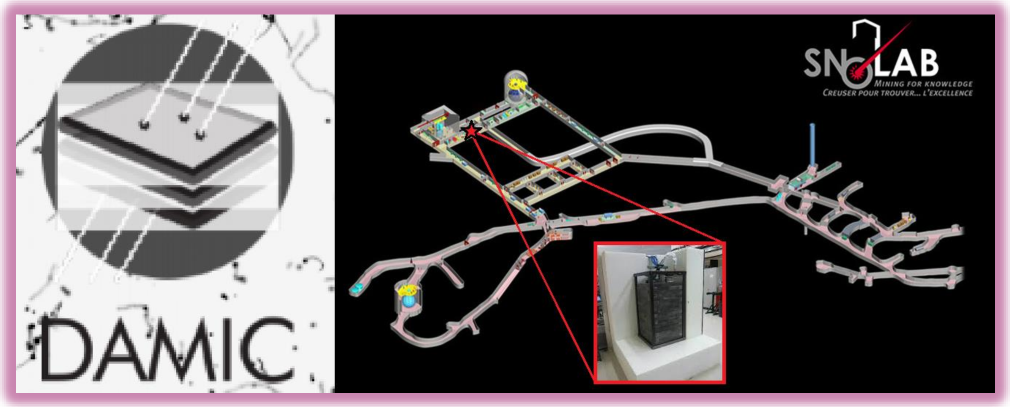


WHY NEUTRONS?

MOTIVATION

International collaborations

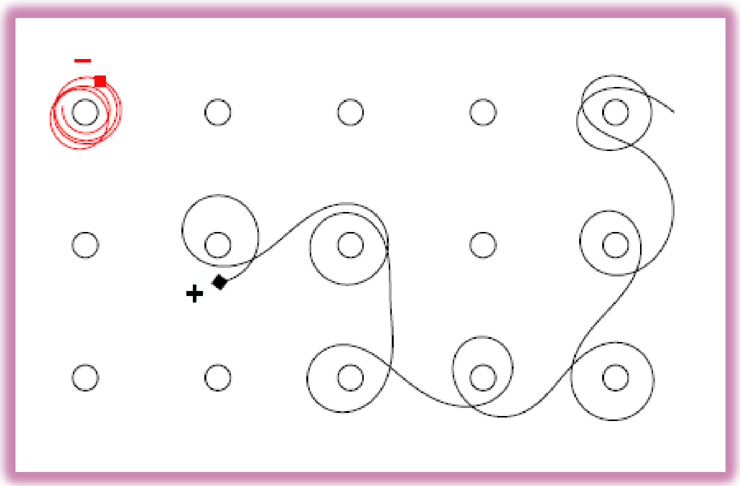
Mexican team leaders (ICN-UNAM): Dr. Juan Carlos D'Olivo and Dr. Alexis Aguilar



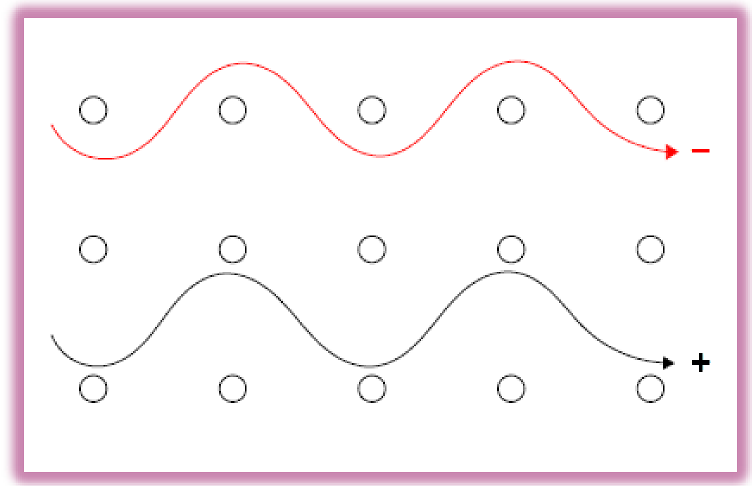
These experiments aim to detect particles that present a elastic-scattering interaction with the detectors (CCDs)

Bozorgnia, Gelmini and Gondolo. Channeling in direct dark matter detection II: channeling fraction in Si and Ge crystals. (DOI 10.1088/1475-7516/2010/11/028)

Energy spectrums depend on the incident particles' direction ?



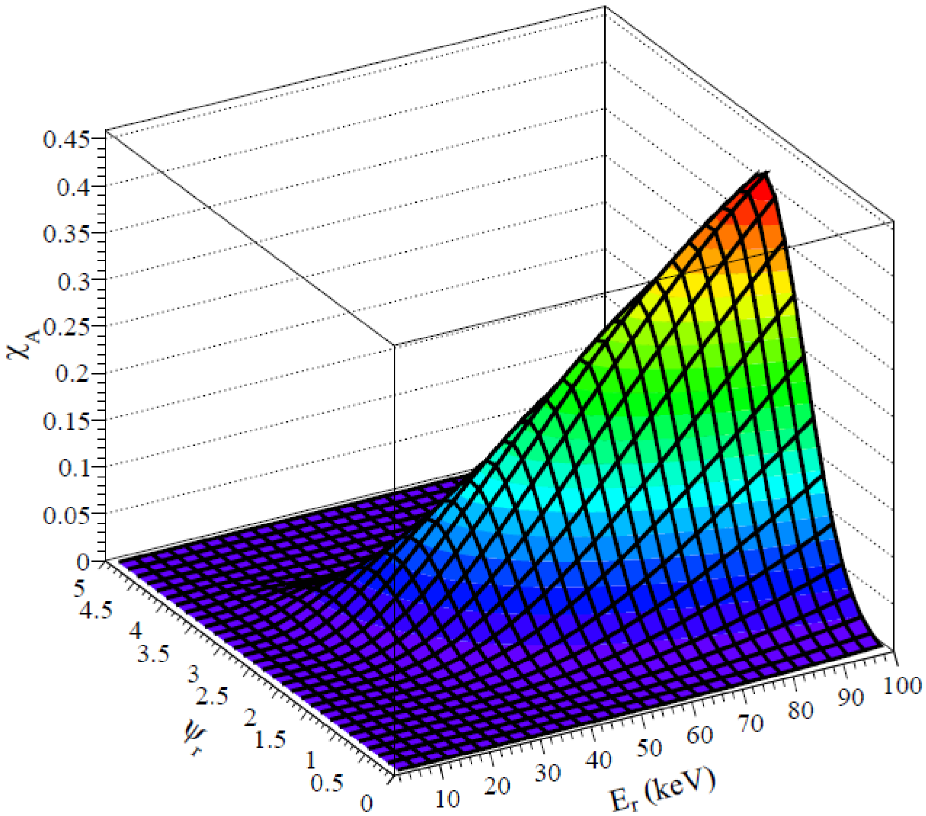
Axial



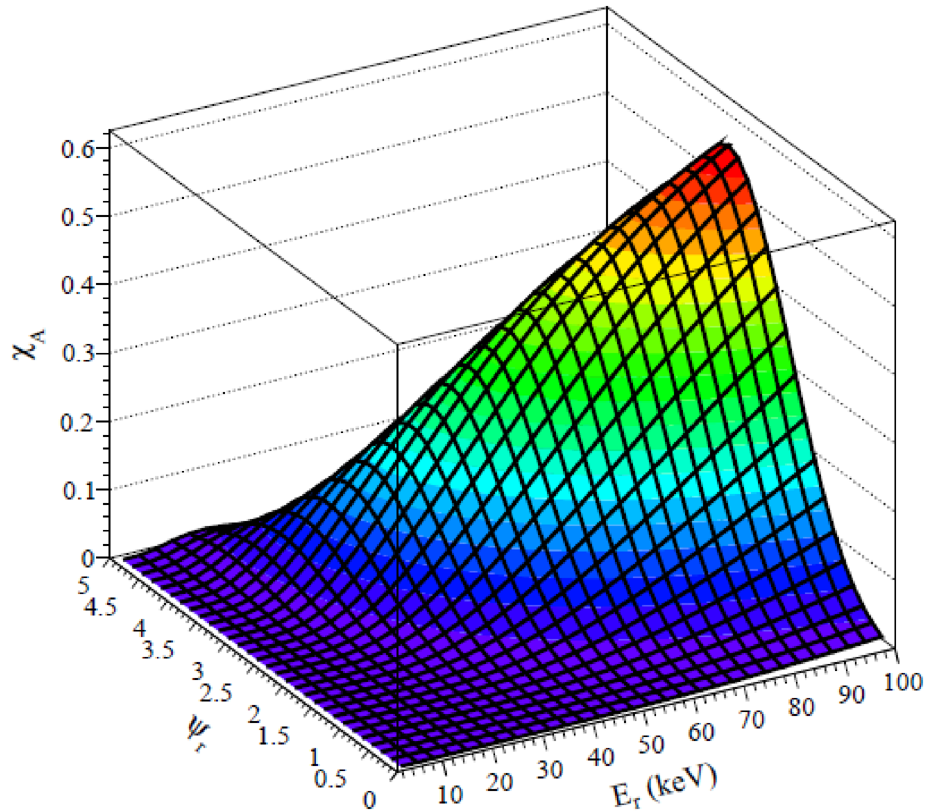
Planar

- Small-angle scattering
- Energy loss mainly due to electric interactions rather than nuclear collisions → Quenching factor ≈ 1
- Studied considering continuous models (See Bozorgnia et al.)

FRACTION OF CHANNELED SI RECOIL NUCLEI IN A SI LATTICE



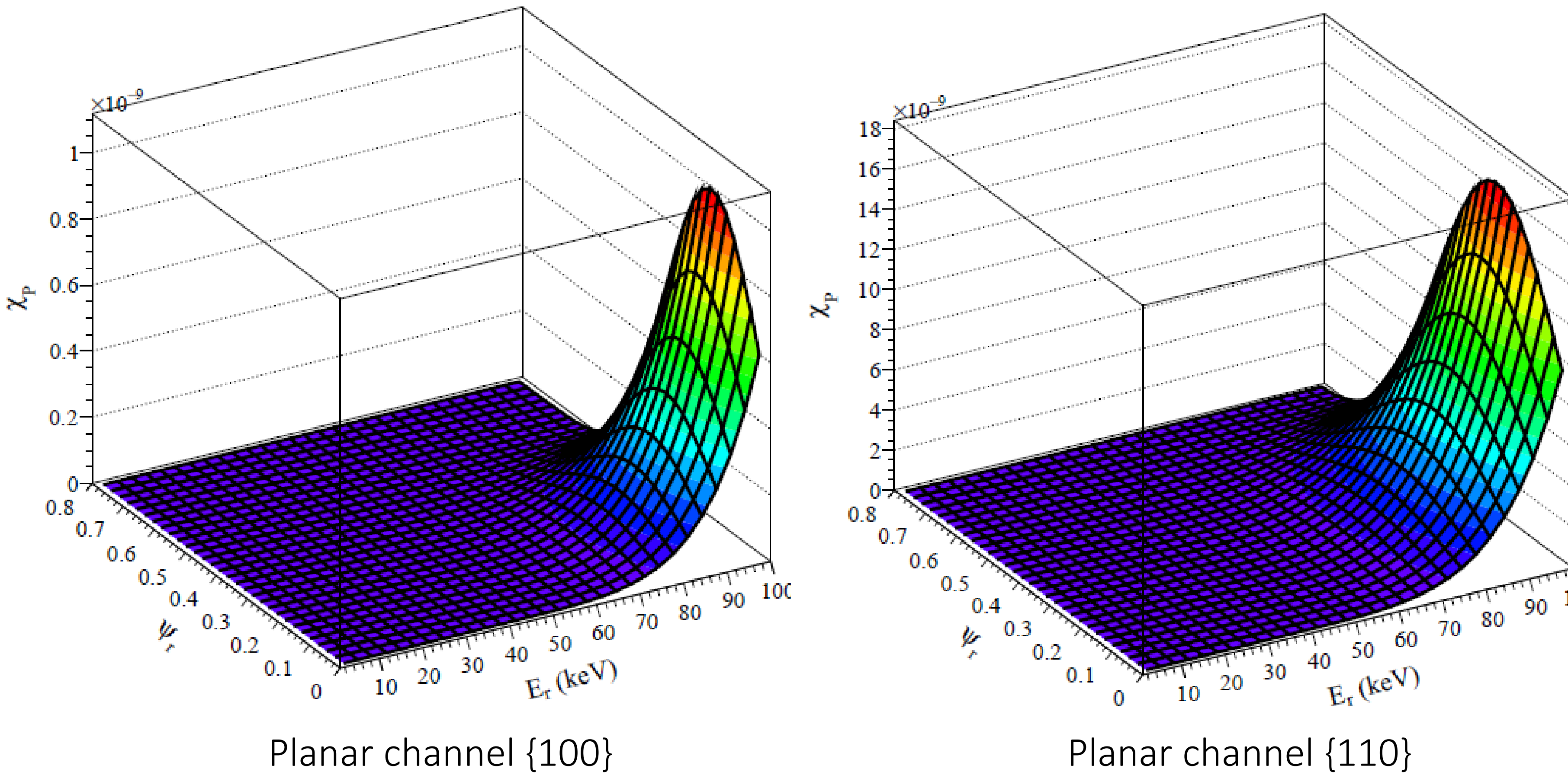
Axial channel <100>



Axial channel <110>

χ_A is found to be maximum at E ~ 100 keV and $2° \leq \Psi_r \leq 3°$

FRACTION OF CHANNELED SI RECOIL NUCLEI IN A SI LATTICE

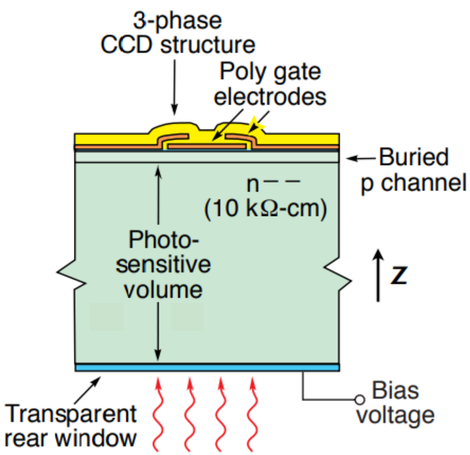


χ_P is found to be maximum at E ~ 100 keV and $0.1° \leq \Psi_r \leq 0.3°$

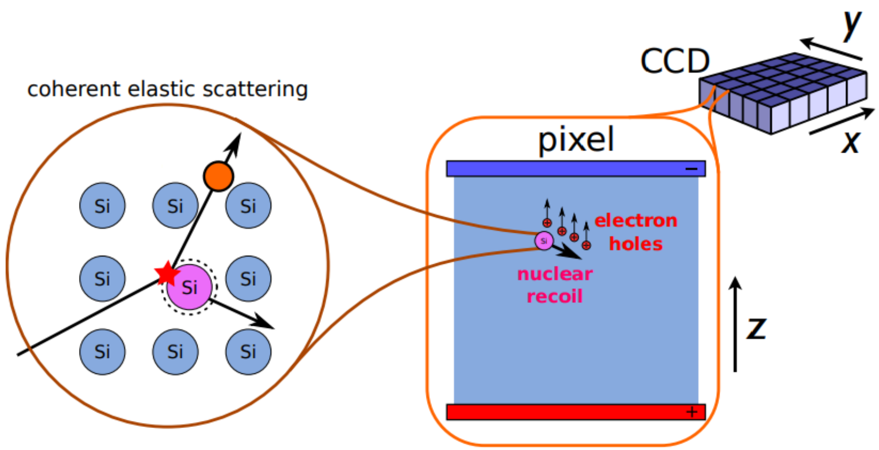
χ_P is, at least, 8 orders of magnitude smaller than χ_A

WHY SI?... THE CCDS

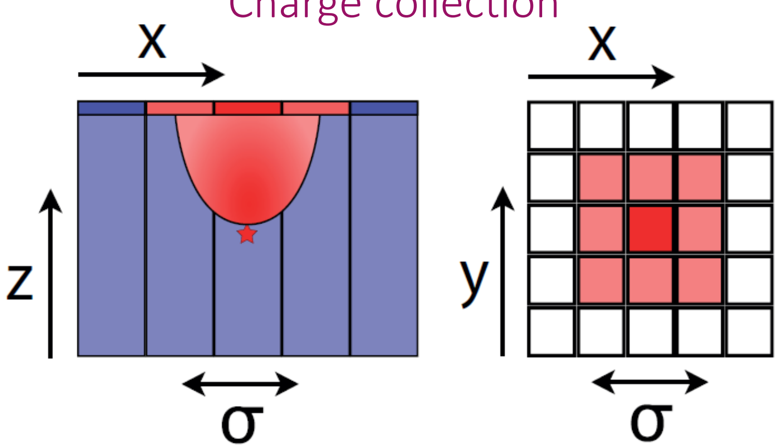
MOS capacitor array

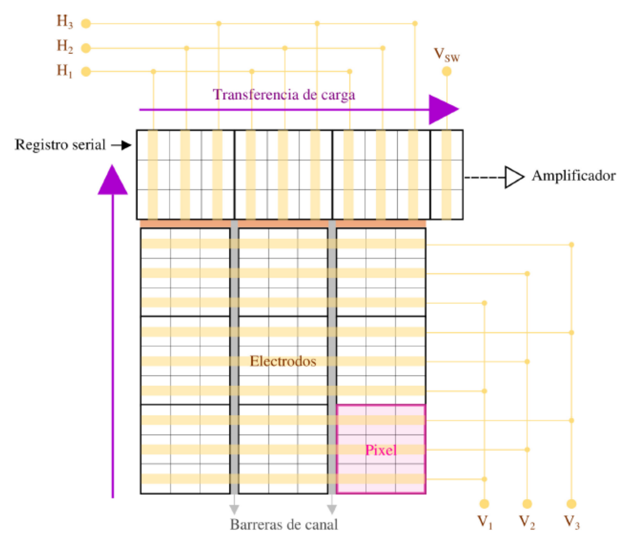


Charge generation (1 e-h pair → ~ 3.6 eV)



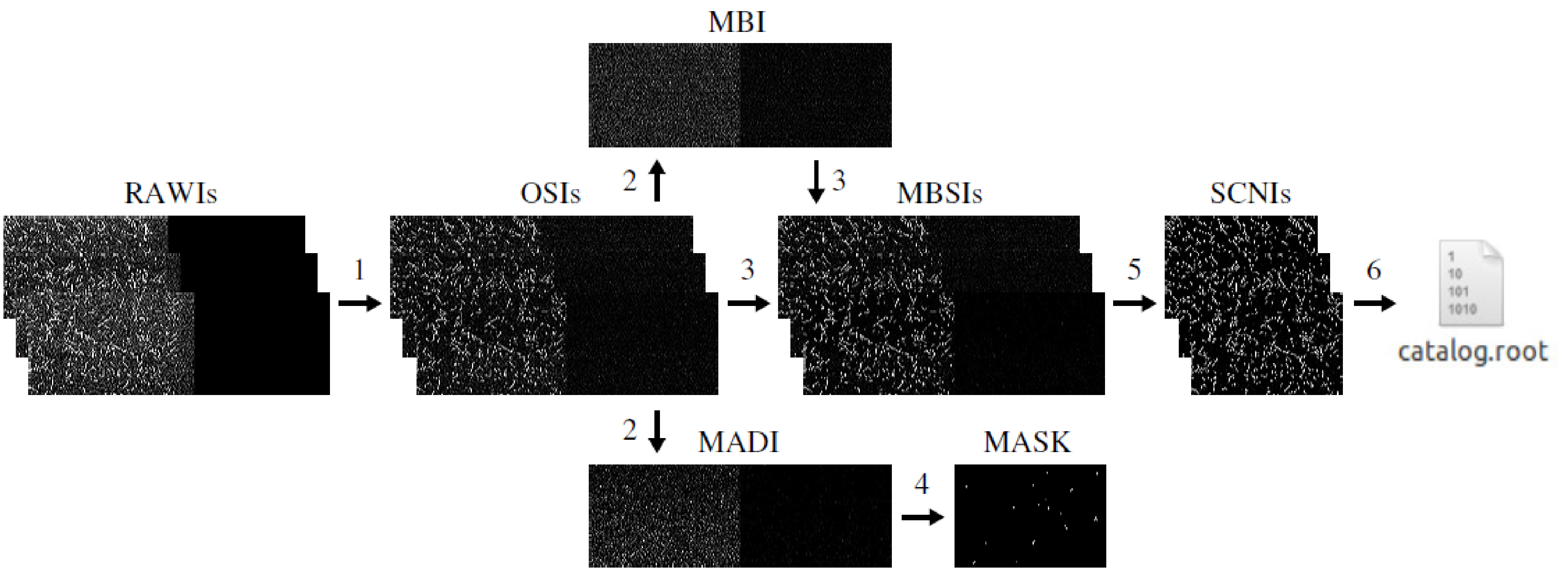
Charge collection





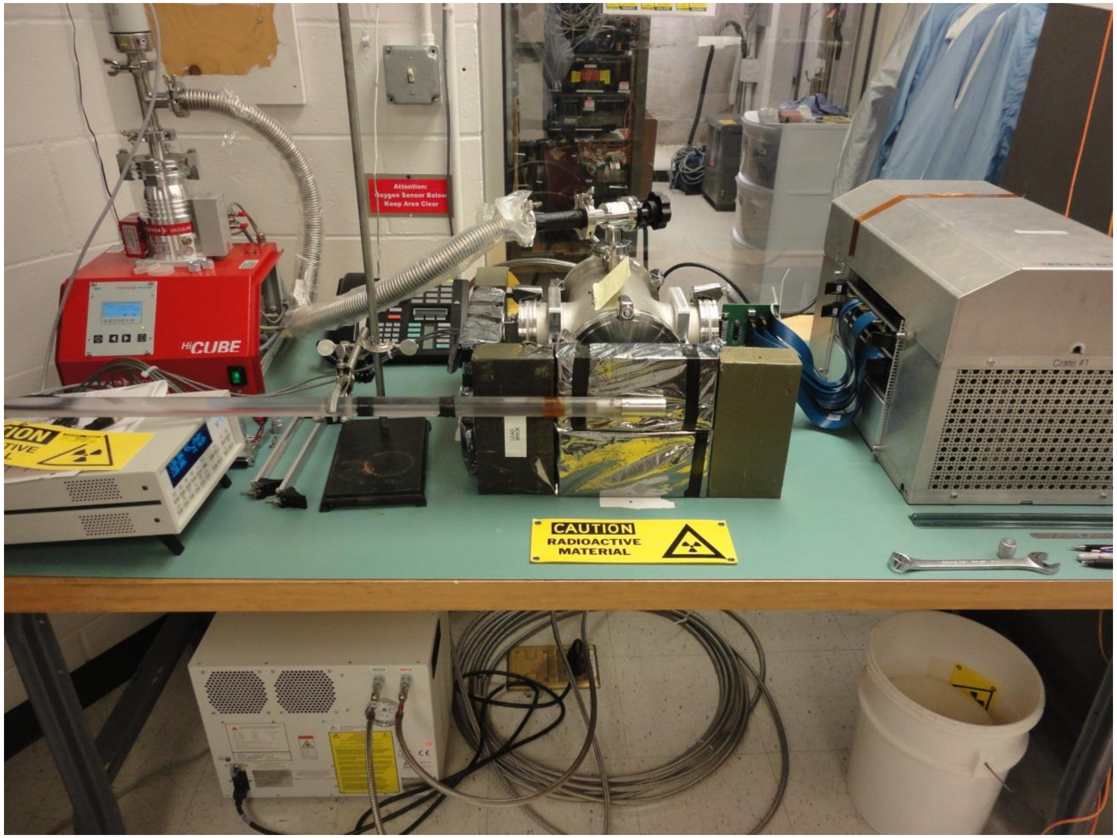
PROCESSING IMAGES

Finally, a *.fits* image is obtained



- RAWI – RAW Image
- OSI – Overscan Subtracted Image
- MBI – Master Bias Image
- MADI – Median Absolute Deviation Image
- MBSI – Master Bias Subtracted Image
- MASK
- SCNI – Subtracted Correlated Noise Image

EXPERIMENTAL SETUP



Fermilab

Vacuum: ~1 x 10^{-7} mbar

Temperature: ~130 K

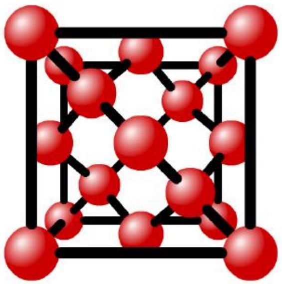
Substrate voltage: ~40 V

CCD USED

Manufactured by the Lawrence Berkeley National Laboratory

2048 x 4096 pixels of 15 x 15 x 250 μm each

<100> is the normal crystallographic axis to the CCD surface



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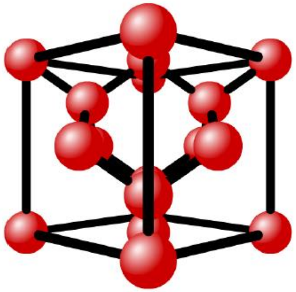

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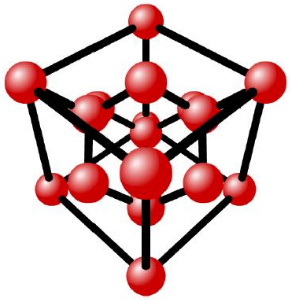

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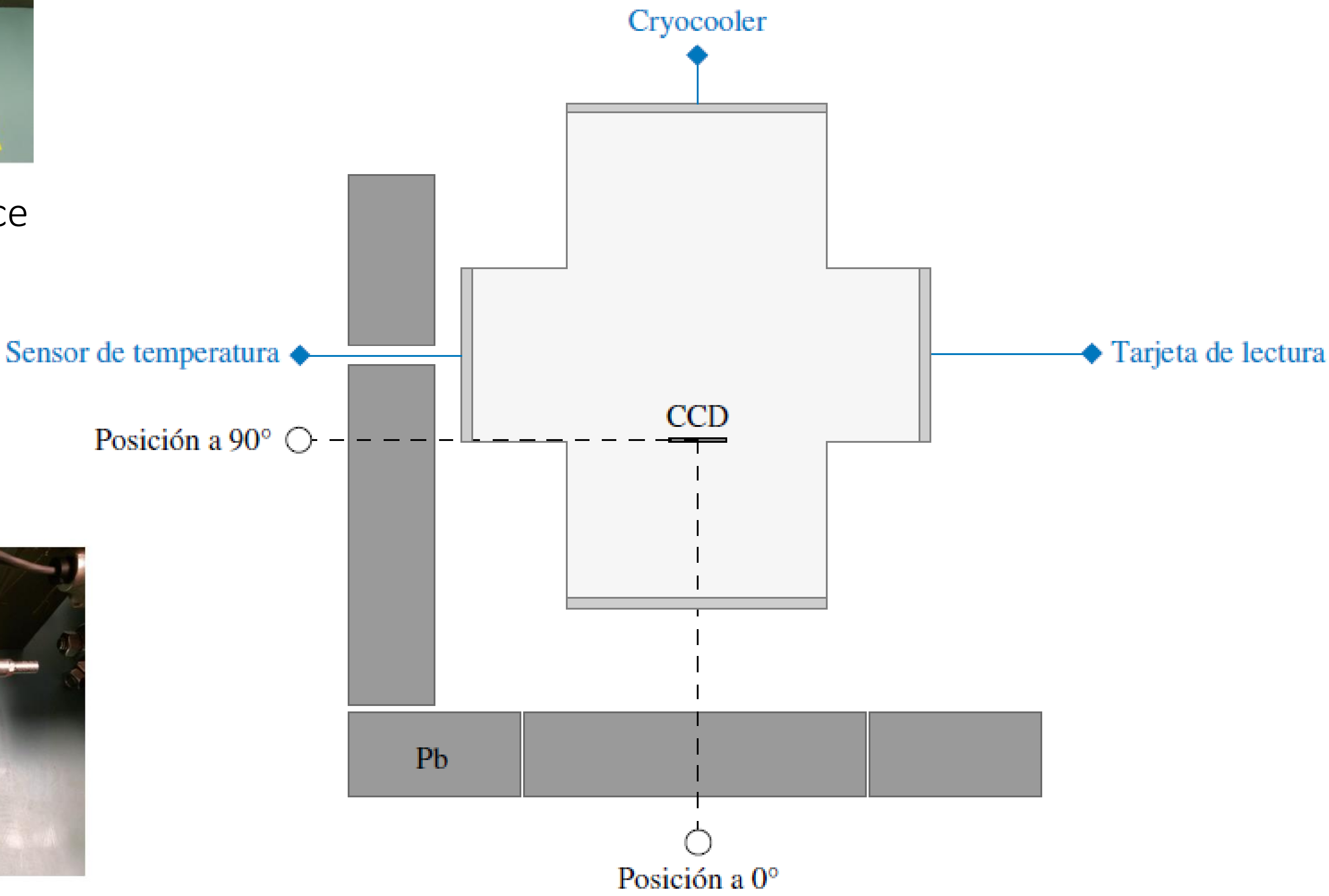
EXPERIMENTAL SCHEME

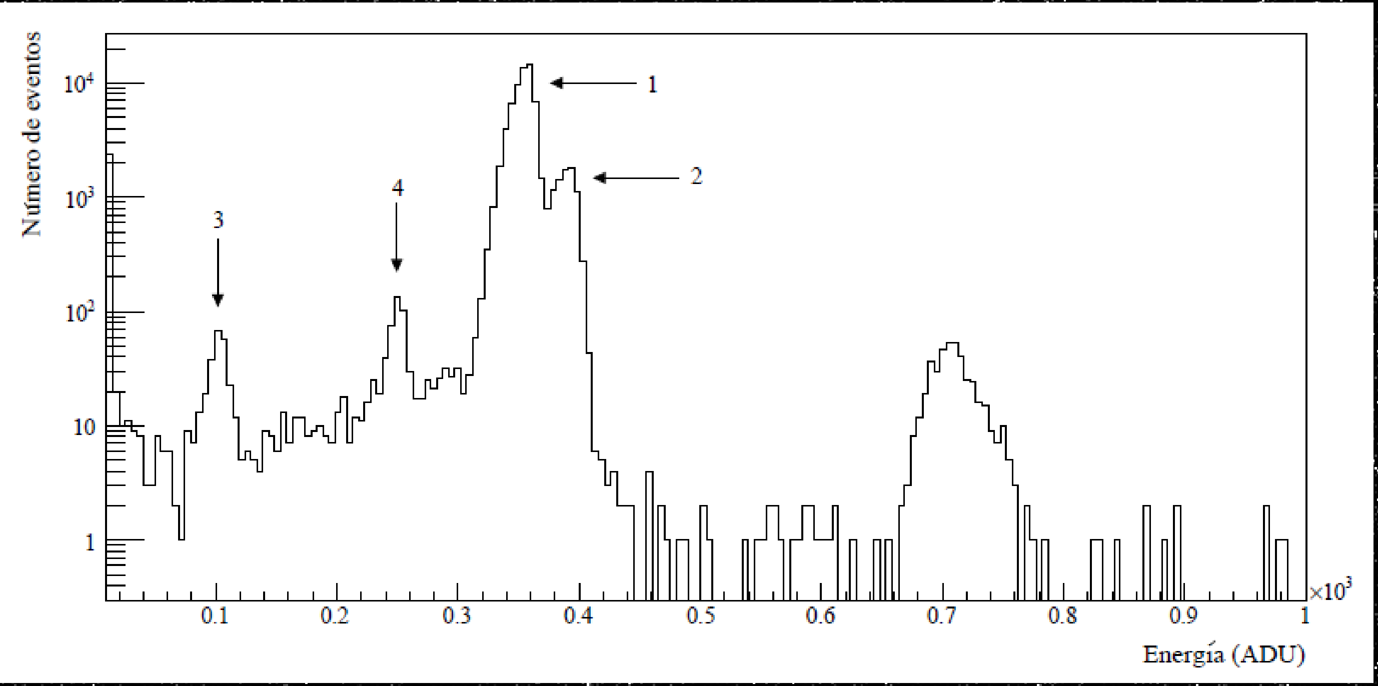
^{252}Cf neutron source

^{60}Co gamma source



BUT FIRST… CALIBRATION

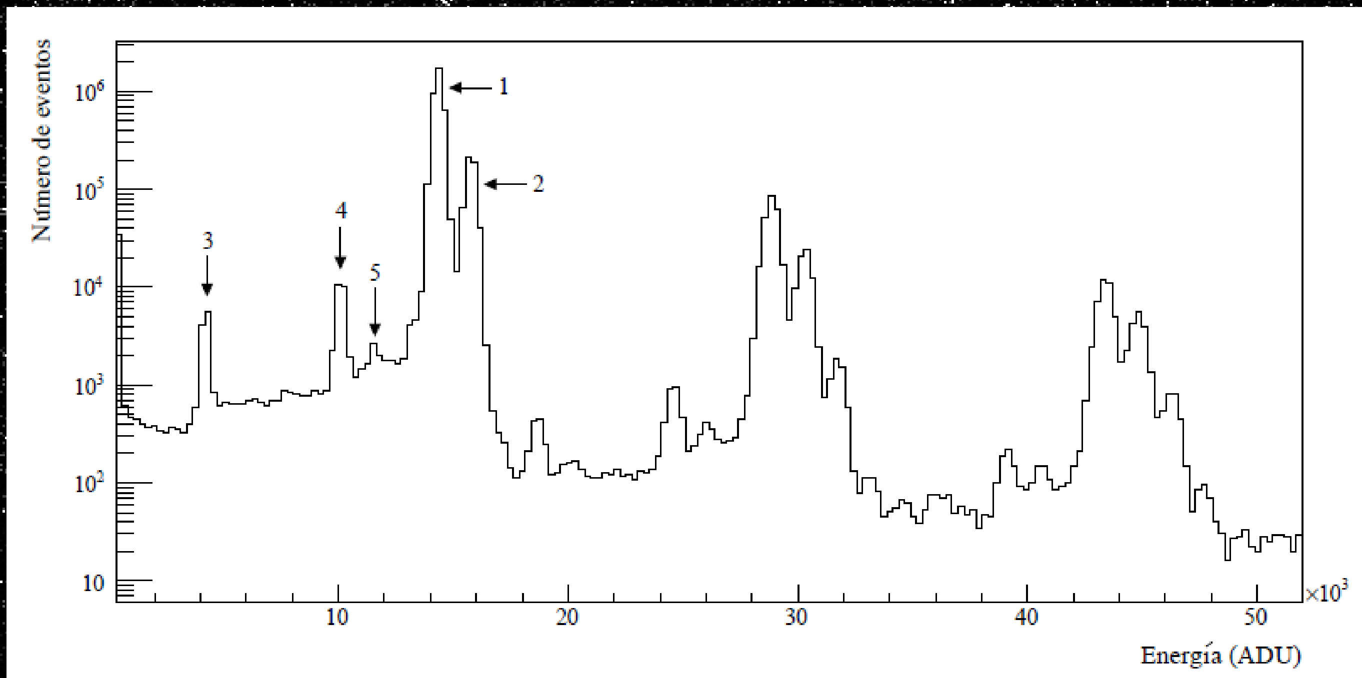
X ray source - ^{55}Fe



T=8 µs

Total exposure time: 27 min

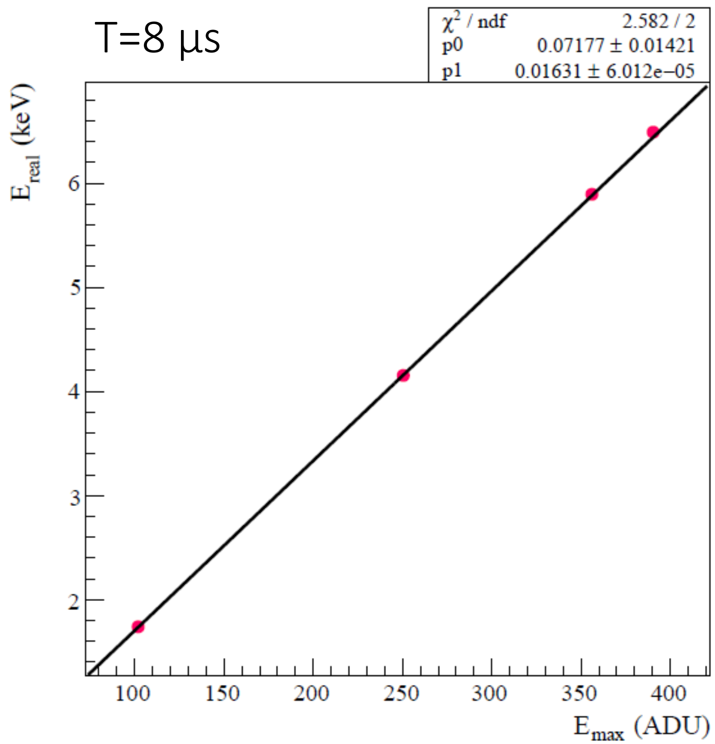
DETECTOR CALIBRATION



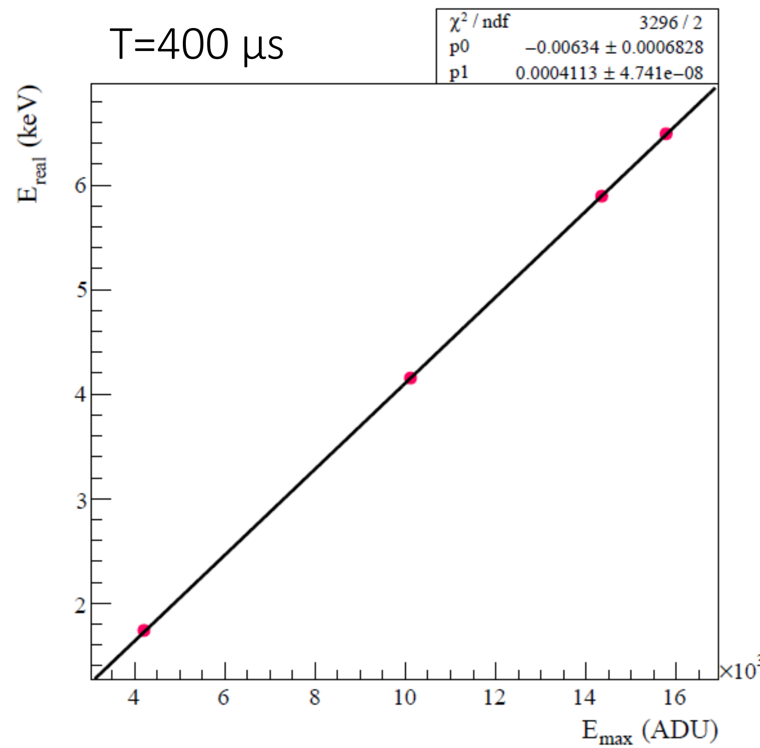
T=400 µs

Total exposure time : 74 hrs 23 min

- Peak 1. K_{α} - Mn (5.893 keV)
- Peak 2. K_{β} - Mn (6.490 keV)
- Peak 3. K_{α} - Si (1.740 keV)
- Peak 4. Scape α - Mn (4.153 keV)
- Peak 5. Scape β - Mn (4.750 keV)



cal = $(1.631 \pm 0.006) \times 10^{-2}$ keV / ADU

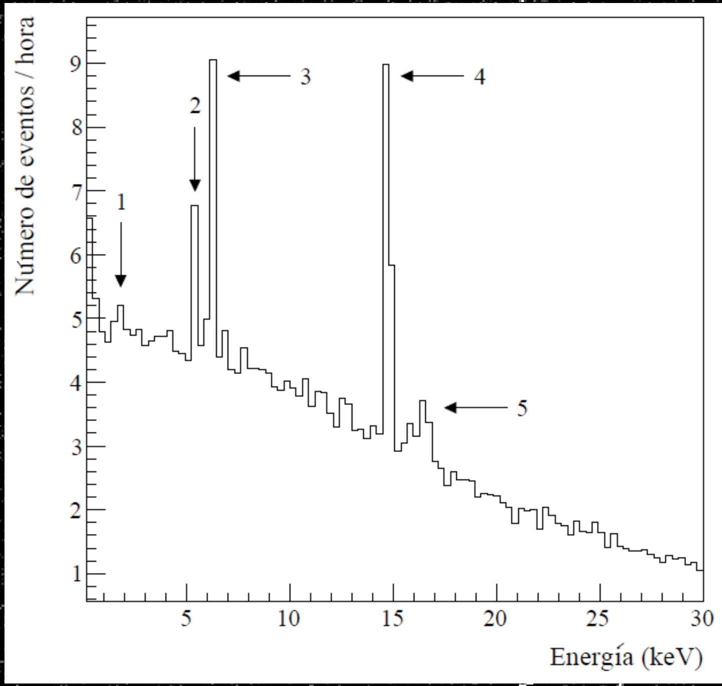


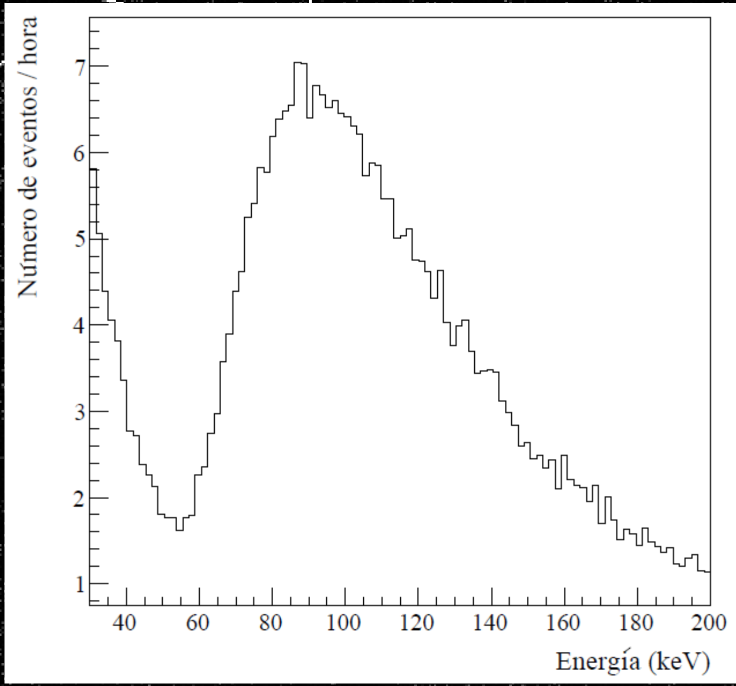
cal = $(4.112 \pm 0.001) \times 10^{-4}$ keV / ADU

BACKGROUND CHARACTERIZATION

T=400 µs

Total exposure time: 7 days 36 min





Peak 1. K_α - Si (1.740 keV)

Peak 2. K_α - Cr (5.410 keV)

Peak 3. K_α - Fe (6.397 keV)

Peak 4. K_α - Y (14.921 keV)

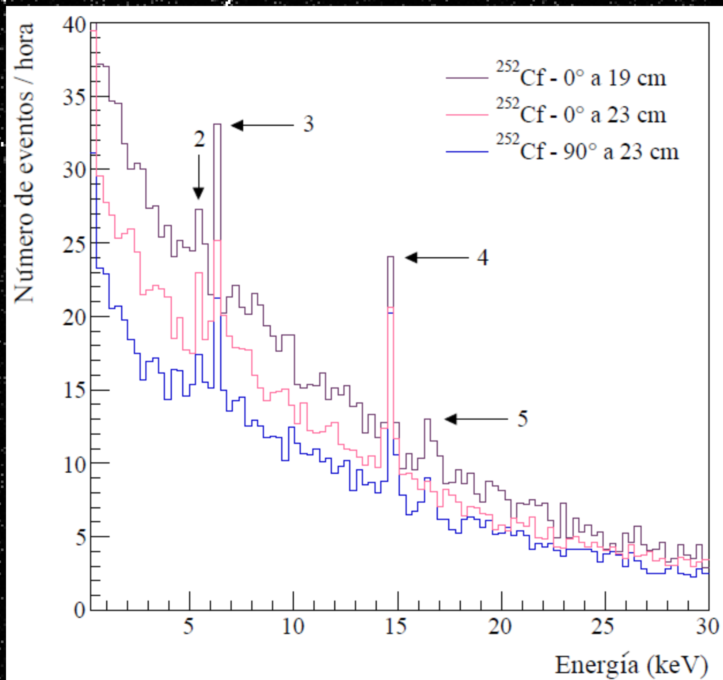
Peak 5. K_β - Y (16.738 keV)

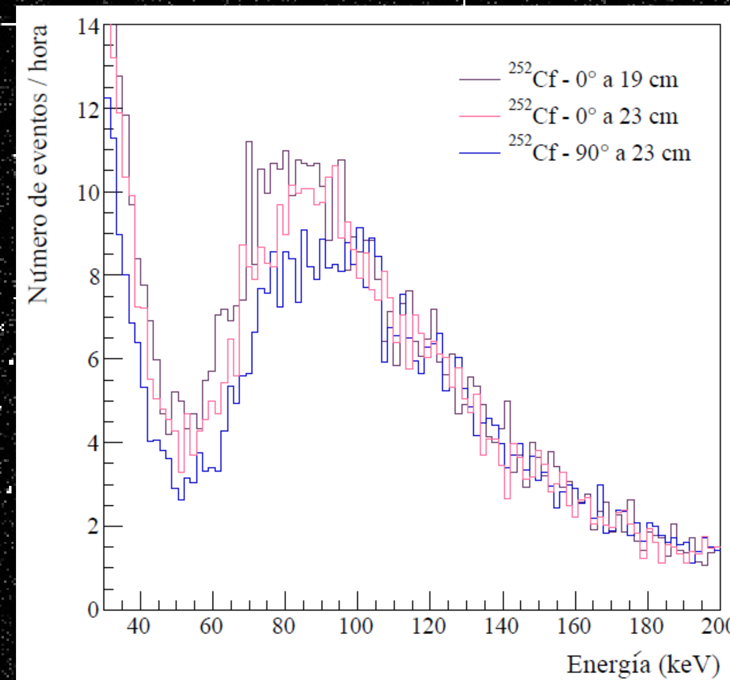
Landau curve with average deposition of

(5.009 ± 0.008) keV / pix

^{252}CF NEUTRON SOURCE EXPOSURE

3.81 µCi
1.76 x 10^4 neutrons / sec





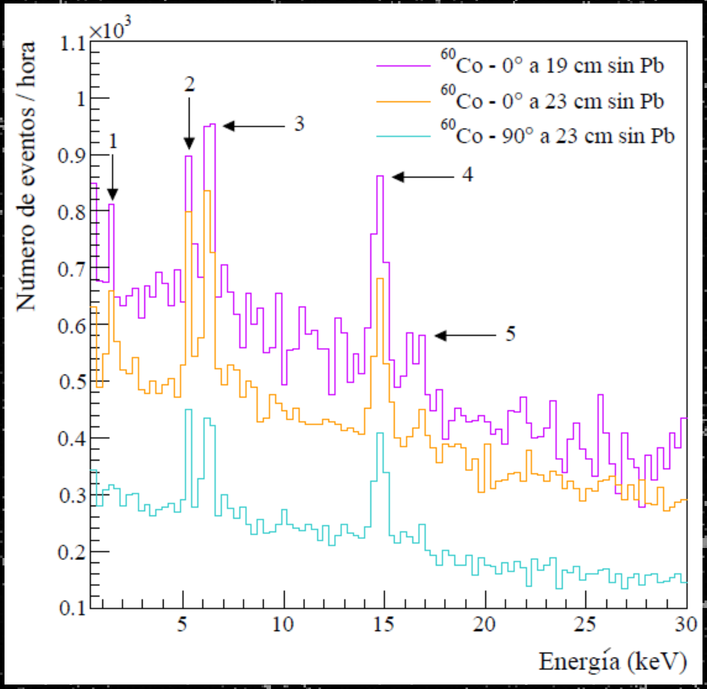
T=400 µs
Total exposure time:

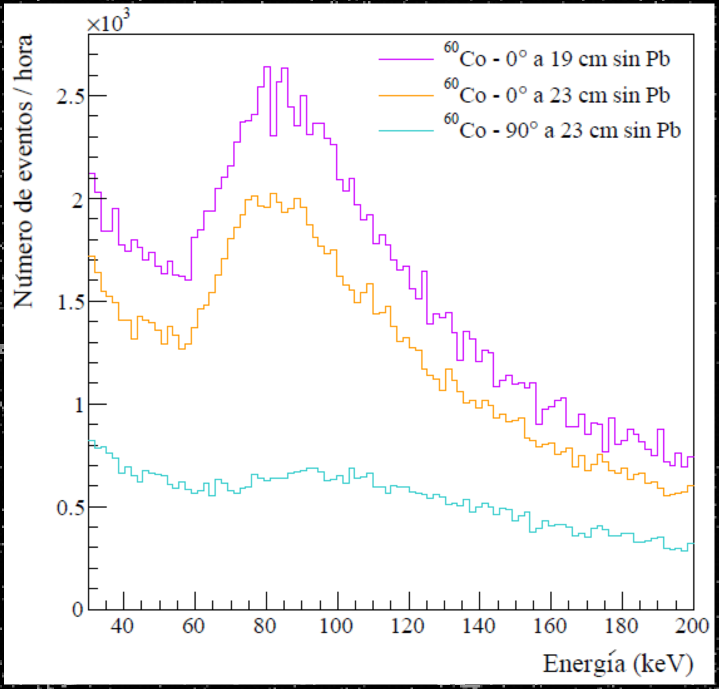
- 0° at 19 cm : 14 hrs 2 min
- 0° at 23 cm : 25 hrs 13 min
- 90° at 23 cm : 27 hrs

^{60}CO GAMMA SOURCE EXPOSURE WO PB

$^{60}Co \rightarrow {}^{60}Ni + e^{-} + \nu_e$

2 γ (1.17 and 1.33 MeV)



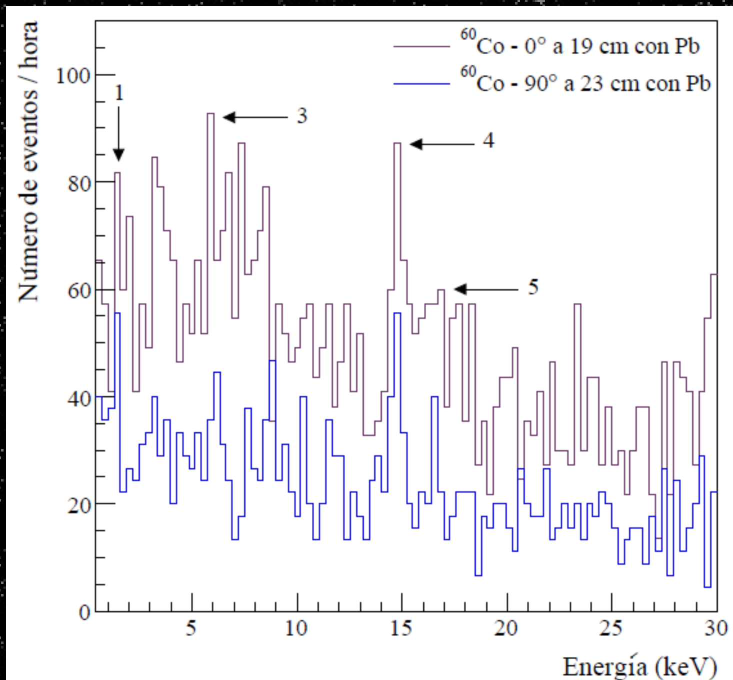


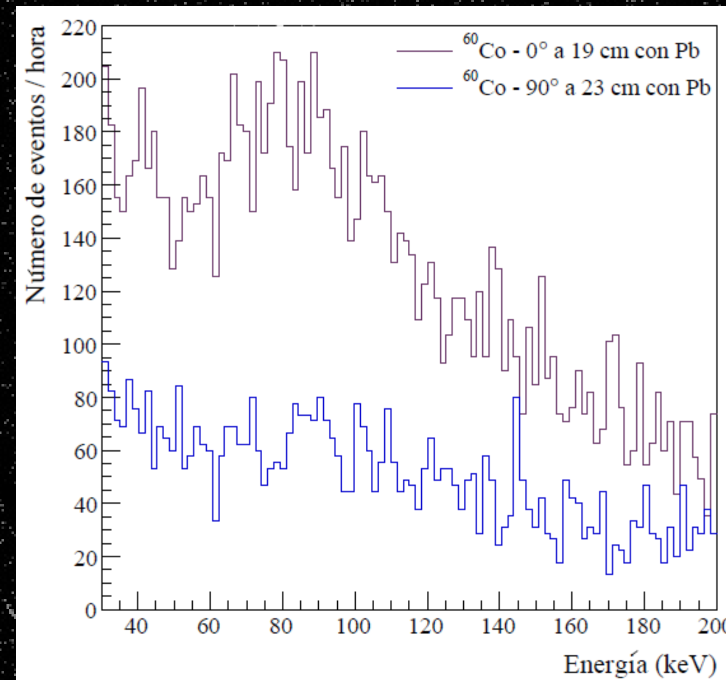
T=8 µs

Total exposure time:

- 0° at 19 cm : 21 min
- 0° at 23 cm : 53 min
- 90° at 23 cm : 1 hr 4 min

^{60}CO GAMMA SOURCE EXPOSURE W PB





T=8 μs

Total exposure time:

- 0° at 19 cm : 22 min
- 90° at 23 cm : 27 min

QUENCHING FACTOR

$$\varepsilon_M = Q(E_M)\,E_M$$

E_M - recoiling energy

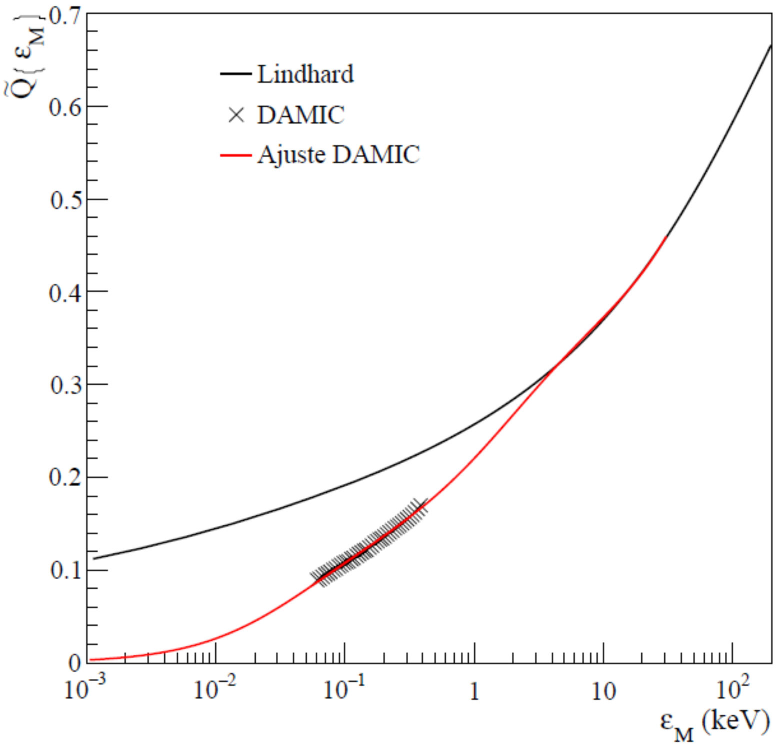
ε_M - energy deposited in form of ionization

- Lindhard

$$Q_L(E_M) = \frac{kg(\epsilon(E_M))}{1 + kg(\epsilon(E_M))}$$

$$k = 0.133\ Z^{2/3} A^{-1/2} \qquad g = 3\ \epsilon^{0.15} + 0.7\ \epsilon^{0.6} + \epsilon$$

$$\epsilon = 11.5\ Z^{-7/3} E_M$$



- Fit to DAMIC measurements (Phys. Rev. D 94, 082007, (2016))

$$\widetilde{Q}_D(\varepsilon_M) = \frac{p_3\varepsilon_M + p_4\varepsilon_M^2 + \varepsilon_M^3}{p_0 + p_1\varepsilon_M + p_2\varepsilon_M^2}$$

$$p_0 = 27.54 \pm 1.31 \qquad p_1 = 623.88 \pm 12.89 \qquad p_2 = 330.26 \pm 1.73$$

$$p_3 = 87.66 \pm 2.60 \qquad p_4 = 127.47 \pm 0.88$$

Neutron-nucleus elastic scattering problem

- Yukawa potential and Saxon-Woods matter distribution:

$$V(r) = V_0 \int \frac{e^{-\chi|\mathbf{r}-\mathbf{r}'|}}{|\mathbf{r}-\mathbf{r}'|} \widetilde{\rho}(r')\, d^3r'$$

- Diferential cross section:

$$\frac{d\sigma}{dE_M} = \left(\frac{\pi m M}{\mu^2 E_{mi}}\right) \frac{1}{2ME_M} \left[\frac{8\pi\mu\hbar\mathcal{C}V_0}{(\hbar^2\chi^2 + 2ME_M)} \int_0^\infty \frac{r'' \sin\left(\frac{\sqrt{2ME_M}}{\hbar} r''\right)}{\left[1 + \exp\left(\frac{r''-R}{a}\right)\right]} dr'' \right]^2$$

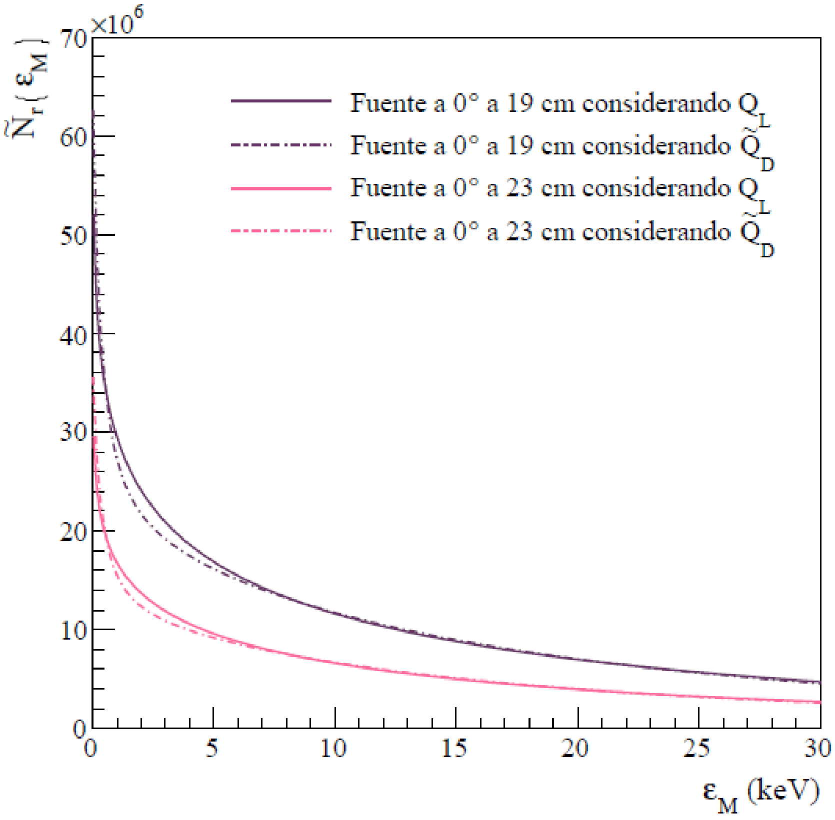
- Recoiling nuclei spectrum:

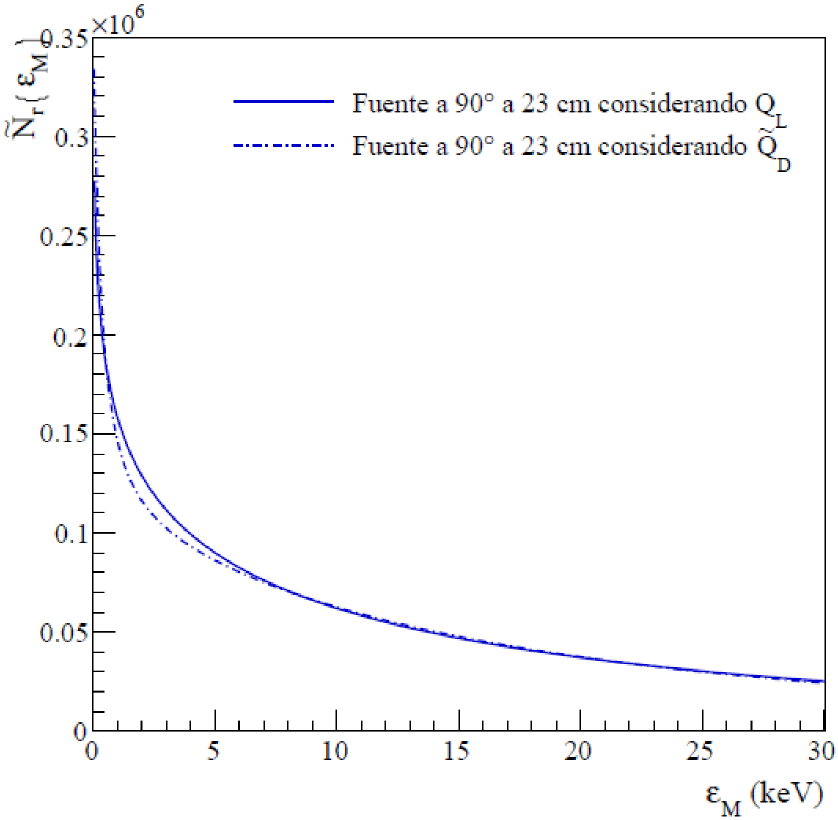
$$N_r(E_M) = \int_{\frac{mME_M}{4\mu^2}}^{\infty} N_n(E_{mi}) \frac{d\sigma}{dE_M} dE_{mi}$$

- Recoiling nuclei spectrum corrected by the quenching factor:

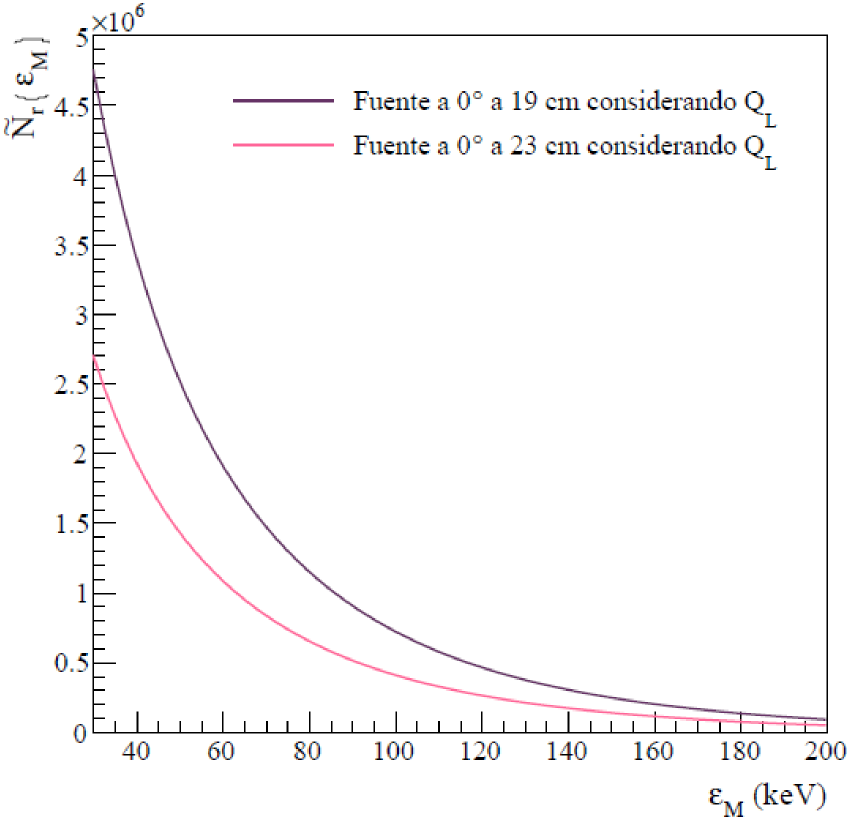
$$\widetilde{N}_r(\varepsilon_M) = N_r(E_M) \left(Q + E_M \frac{dQ}{dE_M}\right)^{-1} = N_r(E_M)\, \widetilde{Q}^{-1} \left(1 - \varepsilon_M \widetilde{Q}^{-1} \frac{d\widetilde{Q}}{d\varepsilon_M}\right)$$

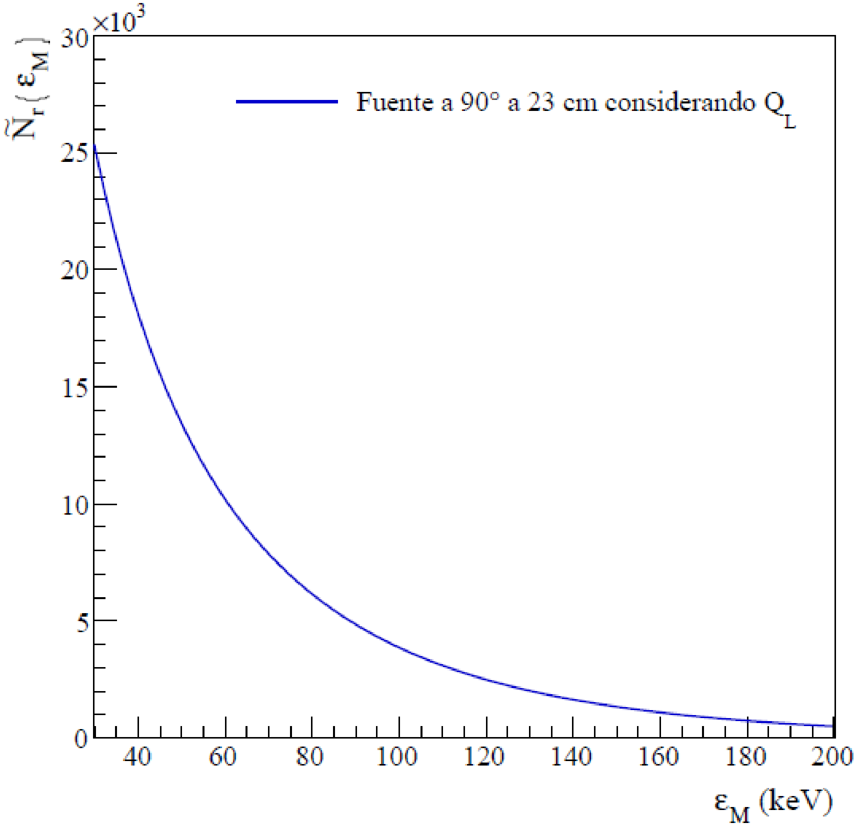
THEORETICAL SPECTRUM





THEORETICAL SPECTRUM

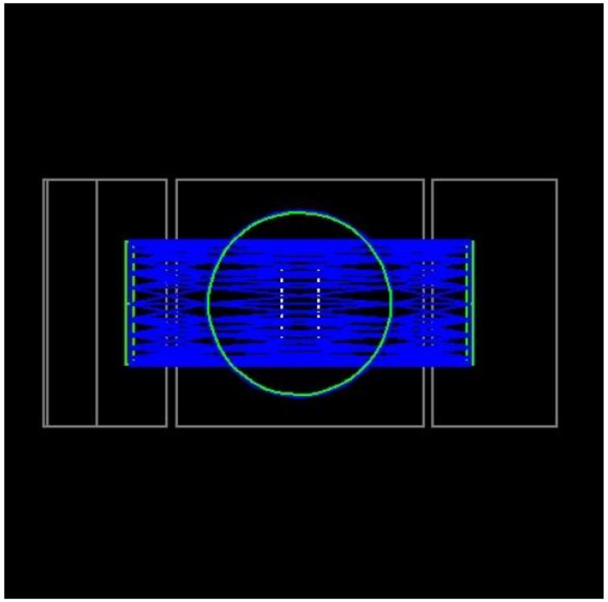


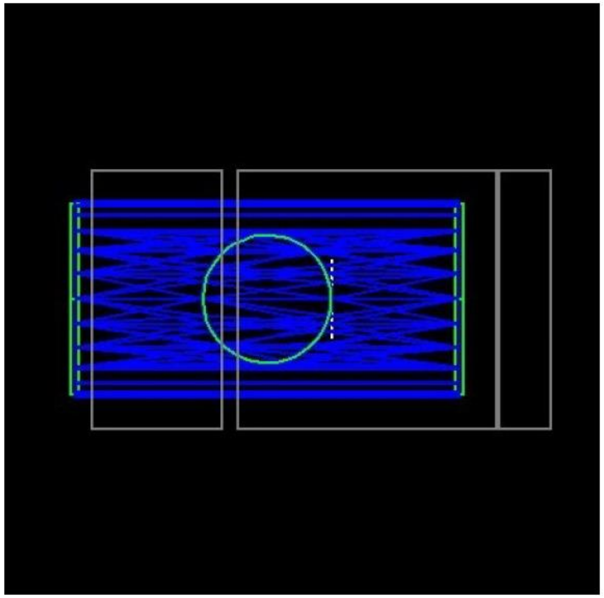


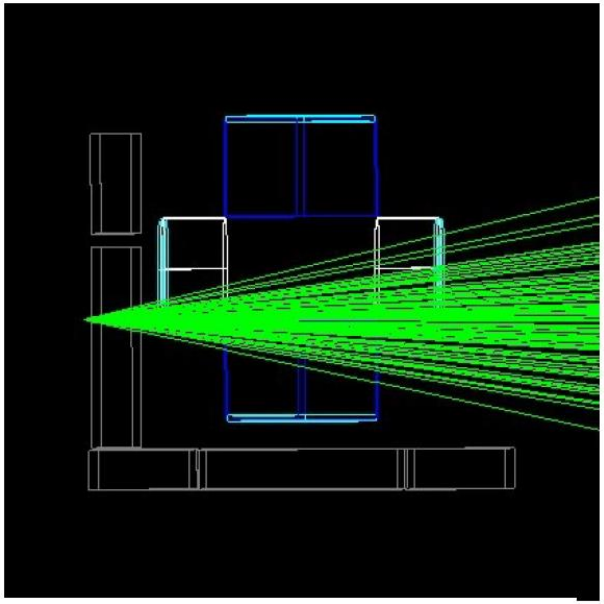
72 million neutrons with 7° of angular dispersion

Simulated neutron energy spectrum values:

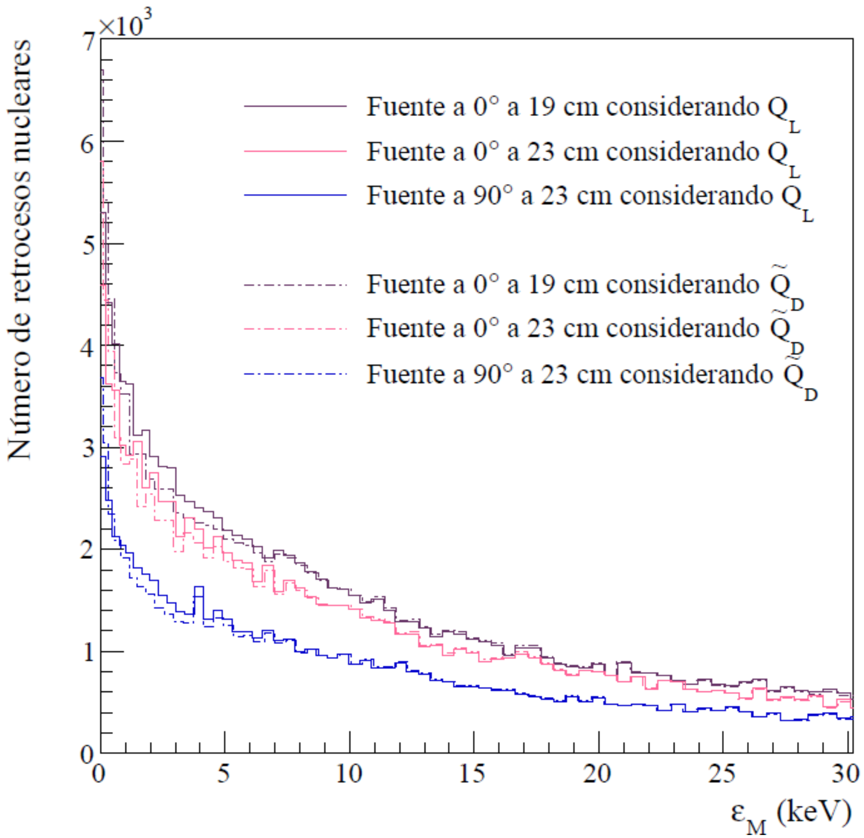
$N_0 = 29178.1 \pm 65.6$ $\alpha = (0.871 \pm 0.001)\ \text{MeV}^{-1}$ $\beta = (1.907 \pm 0.007)\ \text{MeV}^{-1}$

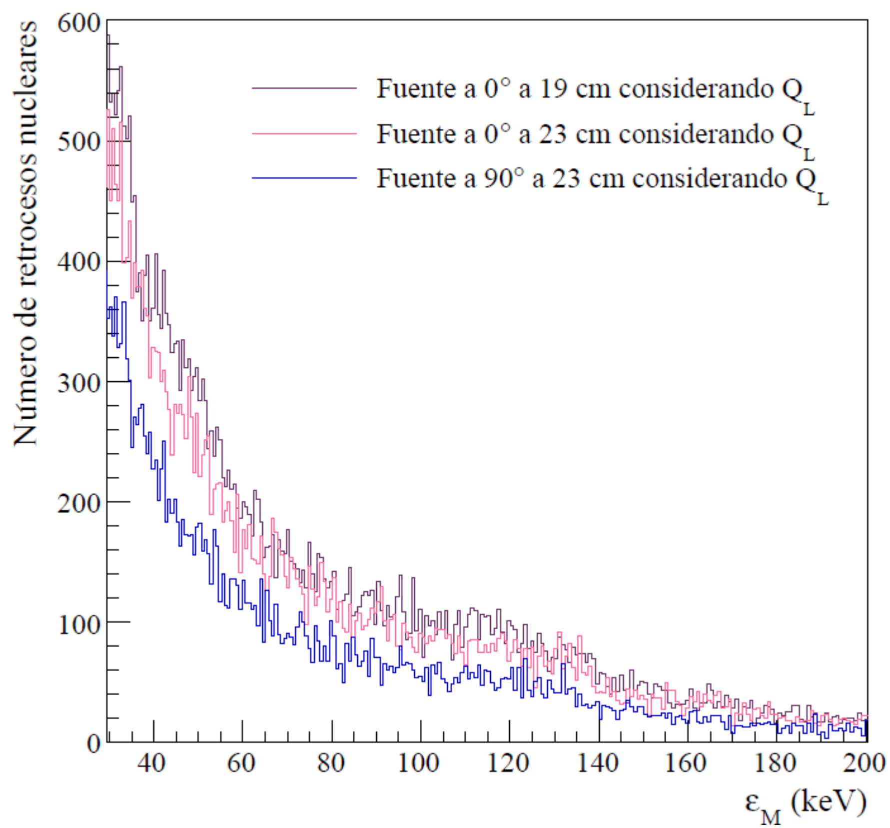




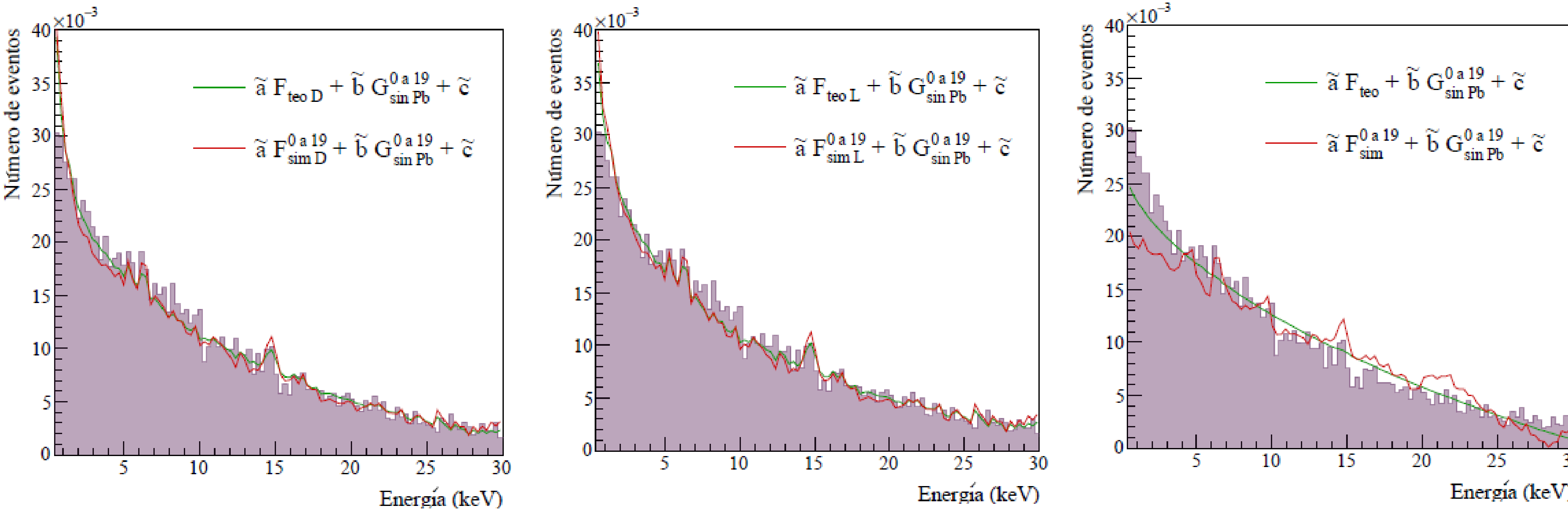


GEANT4 SIMULATION



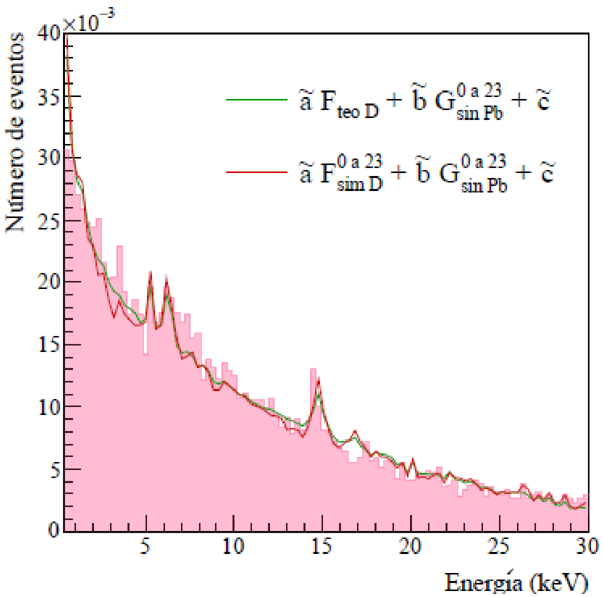


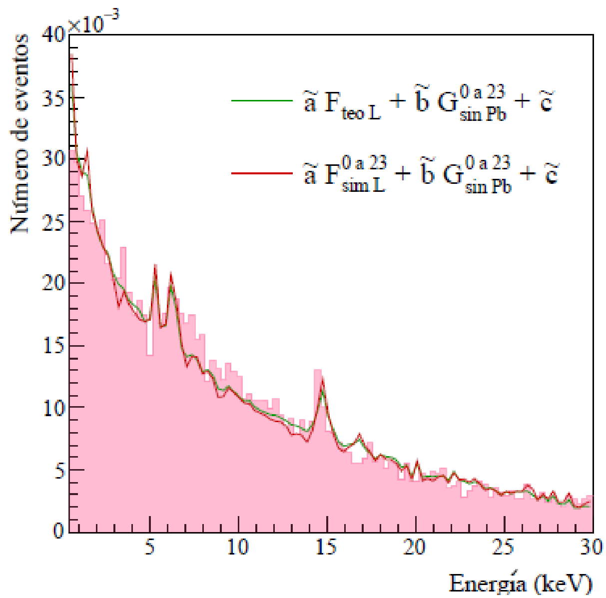
^{252}CF ENERGY SPECTRUM FITS

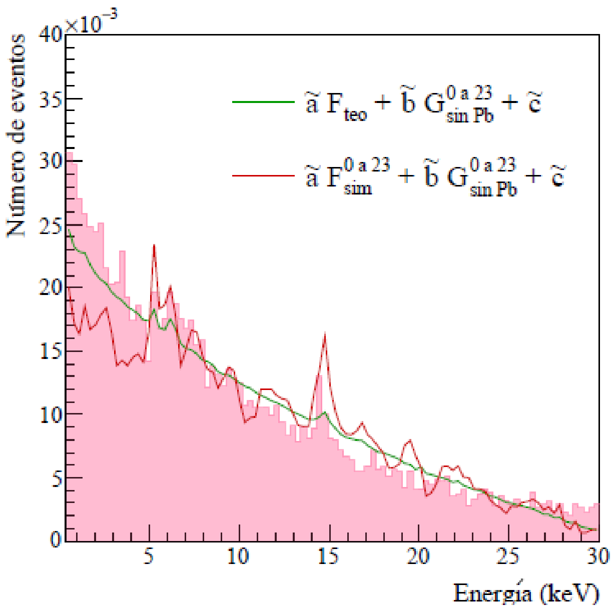


Ajuste al espectro $H^{0\ a\ 19}_{con\ Pb}$					
Espectro F	Espectro G	$\tilde{a}$	$\tilde{b}$	$\tilde{c}$ x 10^{-2}	χ^2 / ndf
$F_{teo\ D}$	$G^{0\ a\ 19}_{sin\ Pb}$	1.224 ± 0.032	0.304 ± 0.054	-0.540 ± 0.032	160.6 / 97
$F_{teo\ L}$		1.138 ± 0.030	0.404 ± 0.052	-0.555 ± 0.032	160.1 / 97
F_{teo}		3.283 ± 0.090	0.027 ± 0.062	-2.326 ± 0.046	261.9 / 97
$F^{0\ a\ 19}_{sim\ D}$		0.805 ± 0.022	0.550 ± 0.051	-0.376 ± 0.035	272.5 / 97
$F^{0\ a\ 19}_{sim\ L}$		0.753 ± 0.021	0.628 ± 0.049	-0.401 ± 0.034	242.4 / 97
$F^{0\ a\ 19}_{sim}$		3.433 ± 0.112	0.366 ± 0.061	-2.842 ± 0.065	638.6 / 97

^{252}CF ENERGY SPECTRUM FITS

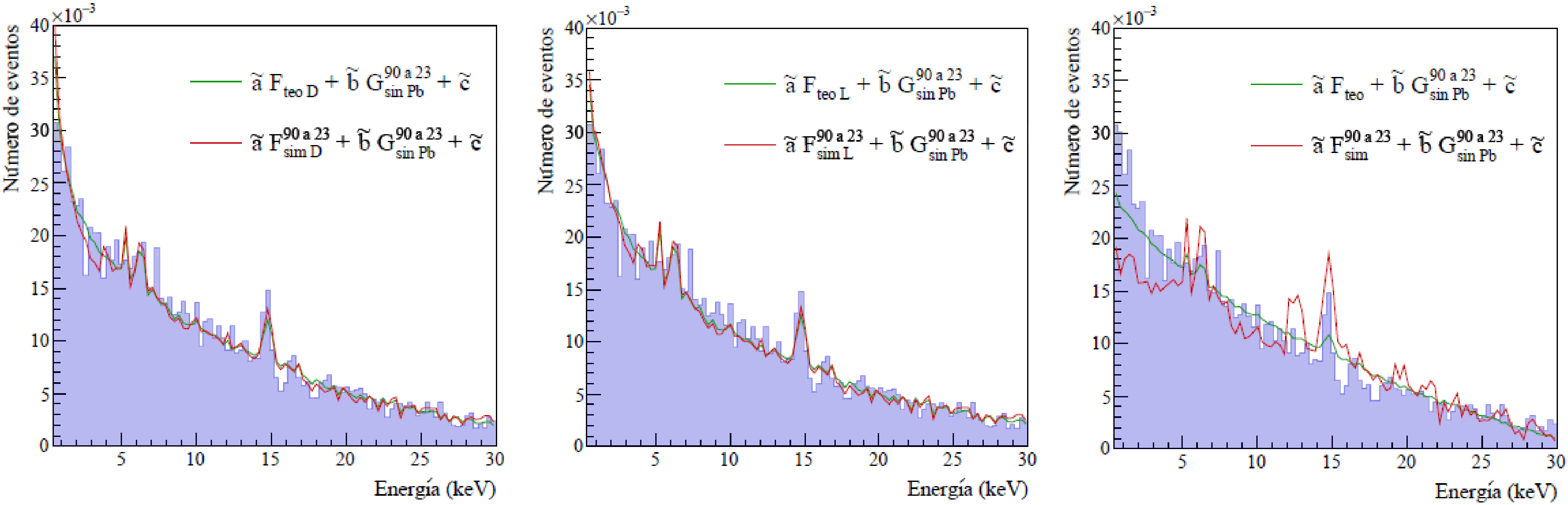






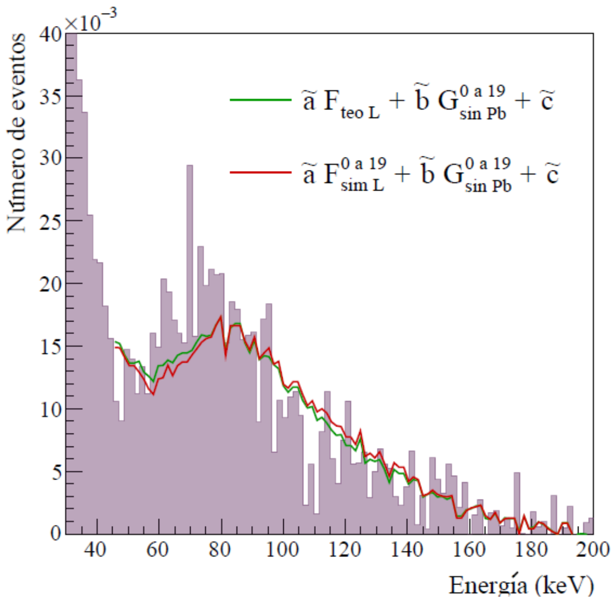
Ajuste al espectro $H^{0\ a\ 23}_{con\ Pb}$					
Espectro F	Espectro G	$\tilde{a}$	$\tilde{b}$	$\tilde{c}$ x 10^{-2}	χ^2 / ndf
$F_{teo\ D}$	$G^{0\ a\ 23}_{sin\ Pb}$	1.150 ± 0.031	0.480 ± 0.056	-0.641 ± 0.034	195.8 / 97
$F_{teo\ L}$		1.072 ± 0.028	0.576 ± 0.054	-0.658 ± 0.034	180.0 / 97
F_{teo}		3.102 ± 0.089	0.185 ± 0.066	-2.303 ± 0.041	383.6 / 97
$F^{0\ a\ 23}_{sim\ D}$		0.766 ± 0.021	0.720 ± 0.052	-0.502 ± 0.036	278.2 / 97
$F^{0\ a\ 23}_{sim\ L}$		0.719 ± 0.019	0.789 ± 0.051	-0.522 ± 0.036	239.5 / 97
$F^{0\ a\ 23}_{sim}$		2.697 ± 0.111	0.844 ± 0.065	-2.591 ± 0.061	1017 / 97

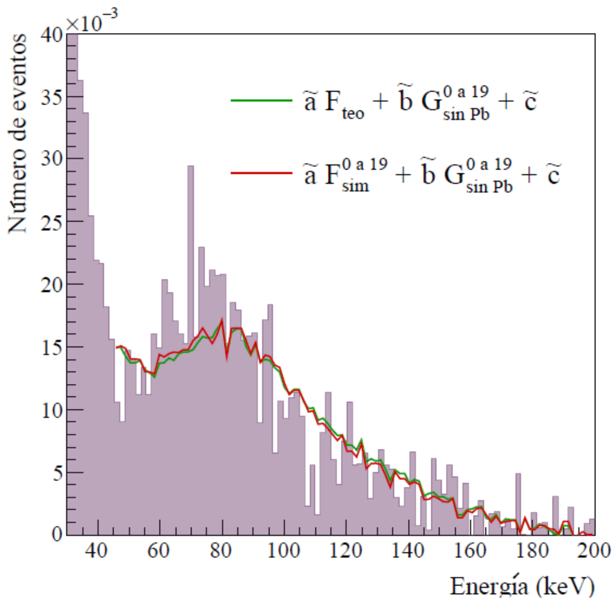
^{252}CF ENERGY SPECTRUM FITS



Ajuste al espectro $H^{90\ a\ 23}_{con\ Pb}$					
Espectro F	Espectro G	$\tilde{a}$	$\tilde{b}$	$\tilde{c}$ x 10^{-2}	χ^2 / ndf
$F_{teo\ D}$	$G^{90\ a\ 23}_{sin\ Pb}$	1.092 ± 0.034	0.479 ± 0.056	-0.584 ± 0.032	174.6 / 97
$F_{teo\ L}$		1.009 ± 0.032	0.567 ± 0.054	-0.590 ± 0.032	182.1 / 97
F_{teo}		2.981 ± 0.099	0.218 ± 0.065	-2.214 ± 0.050	272.1 / 97
$F^{90\ a\ 23}_{sim\ D}$		0.755 ± 0.024	0.658 ± 0.053	-0.430 ± 0.035	229.0 / 97
$F^{90\ a\ 23}_{sim\ L}$		0.705 ± 0.023	0.721 ± 0.051	-0.443 ± 0.034	217.4 / 97
$F^{90\ a\ 23}_{sim}$		2.365 ± 0.118	0.929 ± 0.060	-2.344 ± 0.074	781.4 / 97

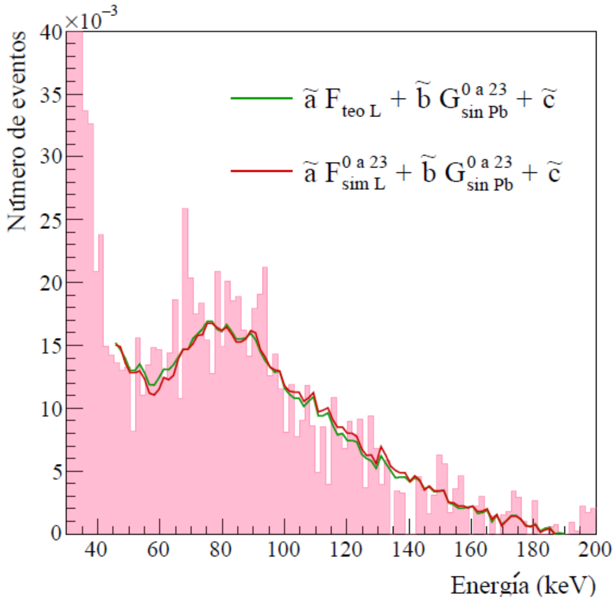
^{252}CF ENERGY SPECTRUM FITS

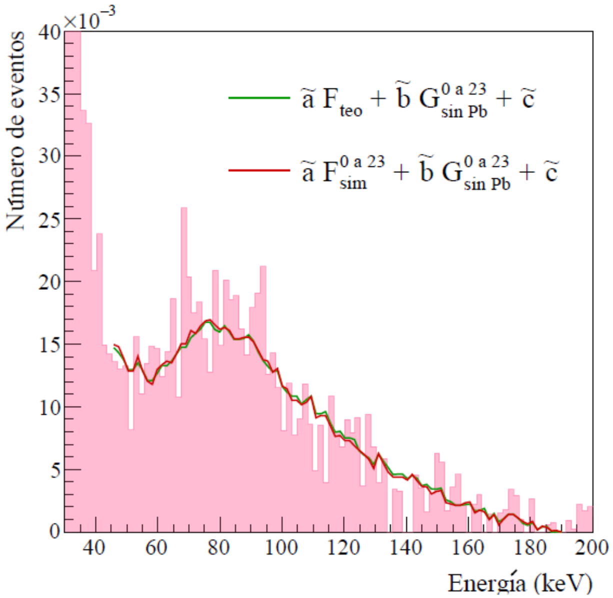




Ajuste al espectro $H^{0\ a\ 19}_{con\ Pb}$					
Espectro F	Espectro G	$\tilde{a}$	$\tilde{b}$	$\tilde{c}$ x 10^{-2}	χ^2 / ndf
$F_{teo\ L}$	$G^{0\ a\ 19}_{sin\ Pb}$	0.305 ± 0.050	1.174 ± 0.101	-0.601 ± 0.067	111.6 / 88
F_{teo}		0.443 ± 0.071	1.029 ± 0.117	-0.608 ± 0.066	109.9 / 88
$F^{0\ a\ 19}_{sim\ L}$		0.293 ± 0.056	1.231 ± 0.102	-0.643 ± 0.066	121.6 / 88
$F^{0\ a\ 19}_{sim}$		0.448 ± 0.067	1.107 ± 0.104	-0.685 ± 0.062	104.5 / 88

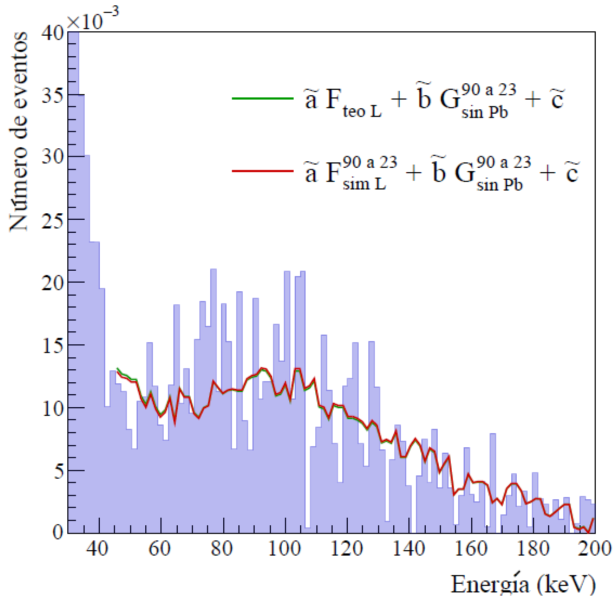
^{252}CF ENERGY SPECTRUM FITS

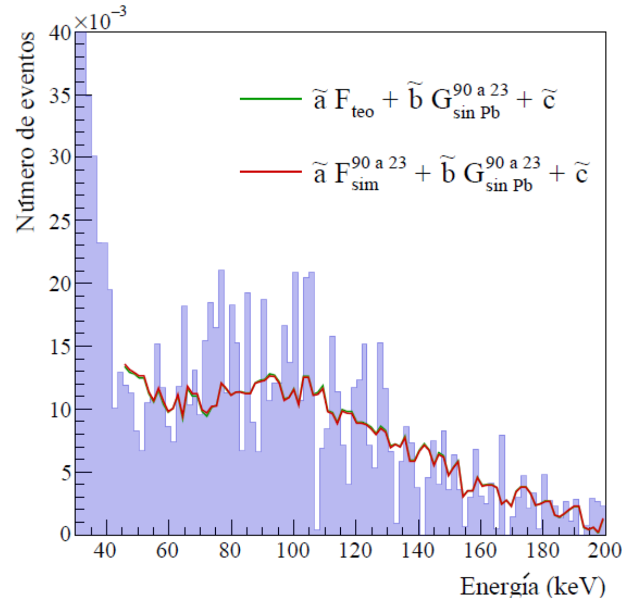




Ajuste al espectro $H^{0\,a\,23}_{con\,Pb}$					
Espectro F	Espectro G	$\tilde{a}$	$\tilde{b}$	$\tilde{c}$ x 10^{-2}	χ^2 / ndf
$F_{teo\,L}$	$G^{0\,a\,23}_{sin\,Pb}$	0.269 ± 0.045	1.239 ± 0.094	-0.642 ± 0.062	129.0 / 88
F_{teo}		0.382 ± 0.065	1.122 ± 0.108	-0.652 ± 0.062	129.3 / 88
$F^{0\,a\,23}_{sim\,L}$		0.274 ± 0.052	1.276 ± 0.095	-0.675 ± 0.061	136.6 / 88
$F^{0\,a\,23}_{sim}$		0.365 ± 0.059	1.207 ± 0.095	-0.715 ± 0.058	125.9 / 88

^{252}CF ENERGY SPECTRUM FITS





Ajuste al espectro $H^{90\ a\ 23}_{con\ Pb}$					
Espectro F	Espectro G	$\tilde{a}$	$\tilde{b}$	$\tilde{c}$ x 10^{-2}	χ^2 / ndf
$F_{teo\ L}$	$G^{90\ a\ 23}_{sin\ Pb}$	0.026 ± 0.062	1.705 ± 0.196	-0.896 ± 0.144	120.3 / 88
F_{teo}		0.079 ± 0.090	1.602 ± 0.227	-0.847 ± 0.150	119.7 / 88
$F^{90\ a\ 23}_{sim\ L}$		0.005 ± 0.074	1.757 ± 0.204	-0.927 ± 0.146	120.5 / 88
$F^{90\ a\ 23}_{sim}$		0.093 ± 0.079	1.593 ± 0.197	-0.850 ± 0.134	119.1 / 88

FINAL REMARKS

- Good calibration and background characterization.
- The ^{252}Cf energy spectrums, at $0.4 \leq E \leq 30$ keV, have more neutronic contribution. Gamma rays promote the appearance of fluorescence peaks.
- Gamma rays contribution to the ^{252}Cf energy spectrums at $30 \leq E \leq 200$ keV, is much higher than the neutronic one.
- The corrected theoretical and simulated spectrums with the fit of the quenching factor of DAMIC measurements seem to fit well the experimental spectrums.
- The theoretical and simulated spectrums of recoiling nuclei seem to fit well the experimental spectrums.
- The channeling effect is more probable to occur when $30 \leq E \leq 200$ keV but, due to the large contribution of gamma rays, in this study, a directional dependence in the experimental spectrums is not identified.

THANK YOU!