CMS APD response to low energy neutrons

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- **The CMS APD and the anomalous signals**
- **Scale calibration**
- **Response to Cf and Am/Be sources**
- **Gain studies**

Thanks to many colleagues in CMS and others at CERN for useful discussions

APDs in CMS detector at LHC

CMS is one of 2 general purpose experiments at the LHC at CERN

Electromagnetic Calorimeter has 61,200 $PbWO_4$ crystals in barrel part,
each read out with two APDs

APD characteristics include:

- fast (~ nsec)
- operating gain = 50
- magnetic field and radiation resistant,
- insensitive to electromagnetic shower leakage

Their development (over ~10 years – thank you Hamamatsu!)
allowed CMS to be a compact, affordable detector

Overall performance outstanding – robust, stable

However in CMS operation at LHC, in 1 of ~400 events there is a
large anomalous signal in one of the 122,400 APDs

Anomalous signals in CMS

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Anomalous signal spectrum falls rapidly as function of signal size but reaches ~10^7 photoelectrons

Suppressed in trigger and data analysis by event topology, signal shape and timing. They do not affect physics performance of CMS

see poster of D. Petyt

Origins:

1) Large specific ionisation due to
- interaction of hadrons with silicon of the APD
- interaction of hadrons with protective epoxy layer in front

In particular interaction of low energy (~1 MeV) neutrons (many in CMS)

2) ? Induced internal breakdown – no clear evidence

Hamamatsu S8148 APD in CMS at LHC

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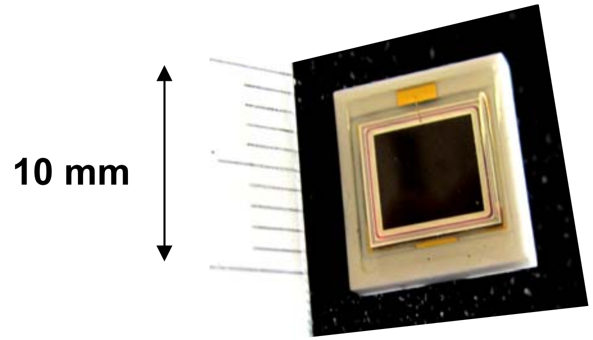
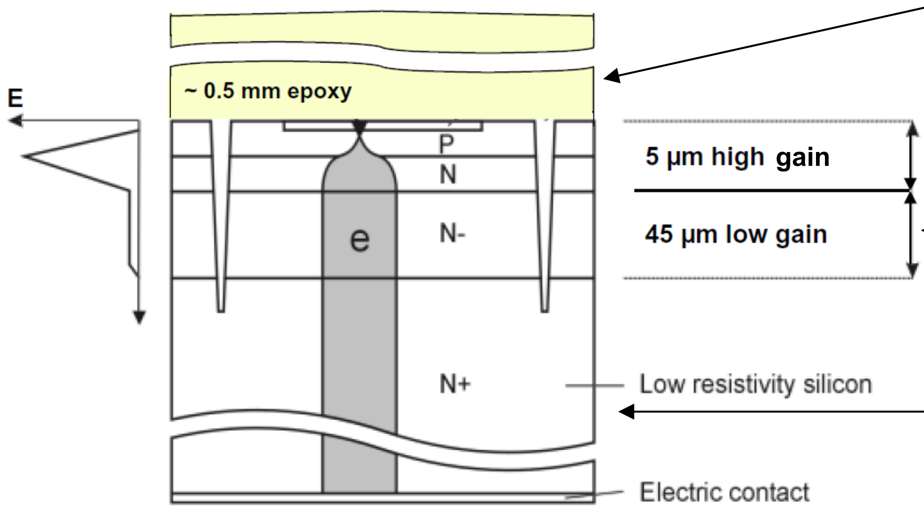


Silicon reverse structure APD
5x5 mm² active area

(Schematic not to scale)



Protective epoxy (C_x-O_y-H_z-X)

High gain M (eg = 50)

Low gain (eg 1.4 for M = 50)

Thick bulk silicon, no gain

Measurements reported here

APDs	**Standard CMS APD**
	Standard CMS APD with epoxy removed
Neutron sources	**^{241}Am/Be, ^{252}Cf**
Scale calibration	**LED, checked with response to gamma rays**
Other studies	**Insert materials between APD and source**
	Vary geometry
	Vary nominal gain (M)

^{241}Am/Be and ^{252}Cf neutron spectra

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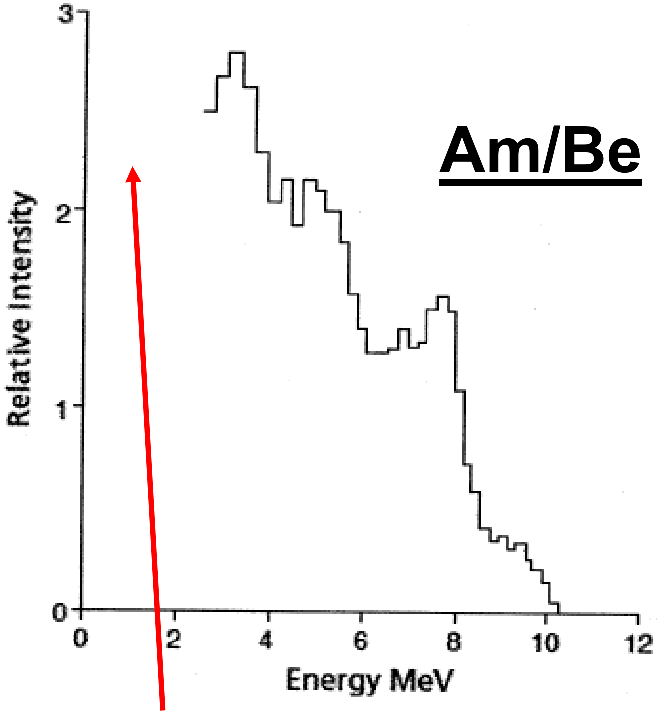
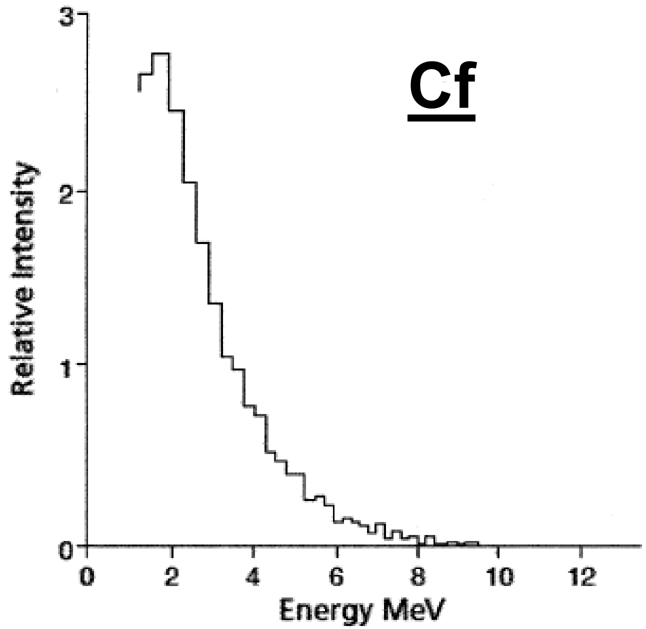
Plots from High Tech Sources data sheets





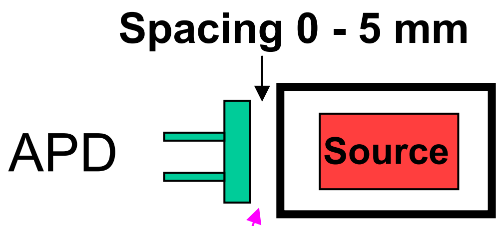
PLUS: 23% < 1 MeV (mean 400 keV)

And γ-rays at 13.9, .. 17.5, .. 59.5 keV
(absorbed by the 3mm Pb insert)

And γ-rays ≳ 1 MeV
(not seen)

And low level of α particles leaking out !

Set-up



closed steel cylinder:

Am/Be ~ 1 x 1 cm
Cf ~ 0.5 x 0.5 cm

Inserts – either none, or (eg)

3 mm Pb (to absorb low energy γ rays)

20 - 40 μm Al (always for APD without epoxy to stop α particles if nothing else inserted)

Source strengths (into 4π): **Am/Be 2200 Bq**
Cf 1000 Bq

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Read-out

APD → pre-amp → amp → 0 db ADC

→ Attenuator → N db ADC

Gain varied for dynamic range

Usually 24 db (= 1/16)

ADC charge integrating

Gate from discriminator on Amp output - threshold gain dependent

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Spectra shown

- Generally merger of different settings
- Always nominal gain (M) = 50, unless otherwise stated
- Compared spectra normalised to run time, unless otherwise stated.

Scale Calibration

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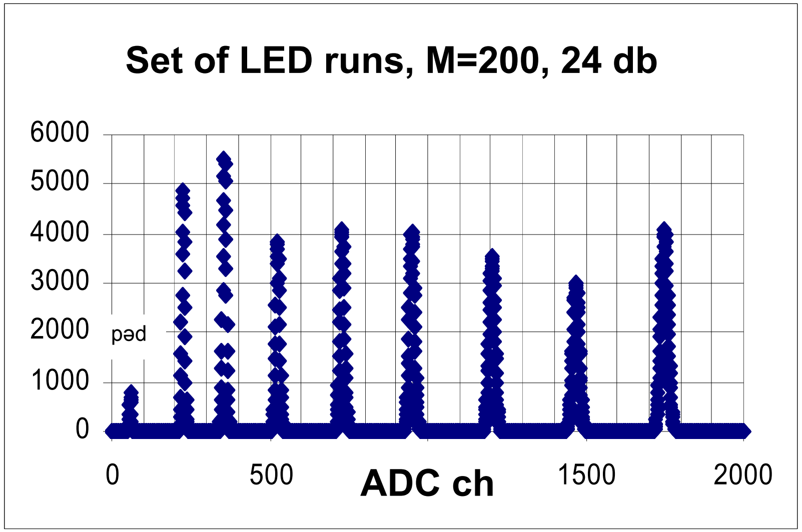
Scale Calibration

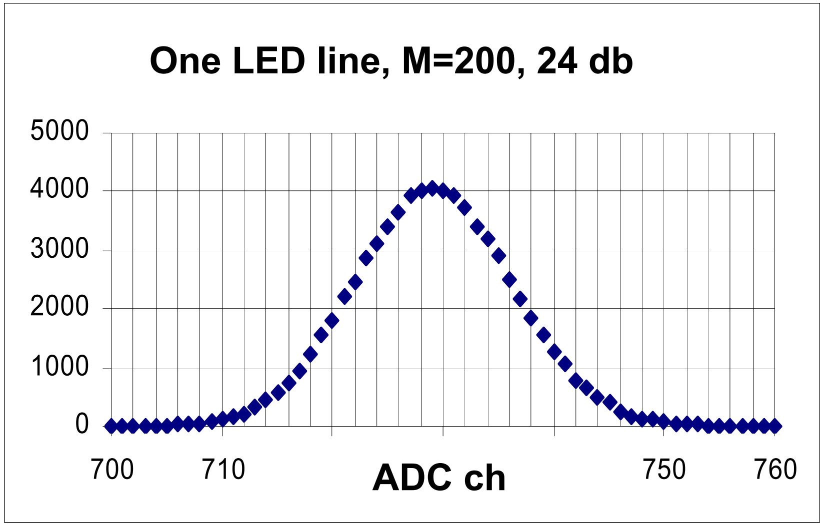
Illuminate with LED

If line width, σ, dominated by statistics of photo-electrons

No of p.e. = F/(σ /ADC ch)2** **(F = excess noise factor: 2 at gain 50**
3 at gain 200)

Vary light intensity: p.e. per ADC ch should be constant





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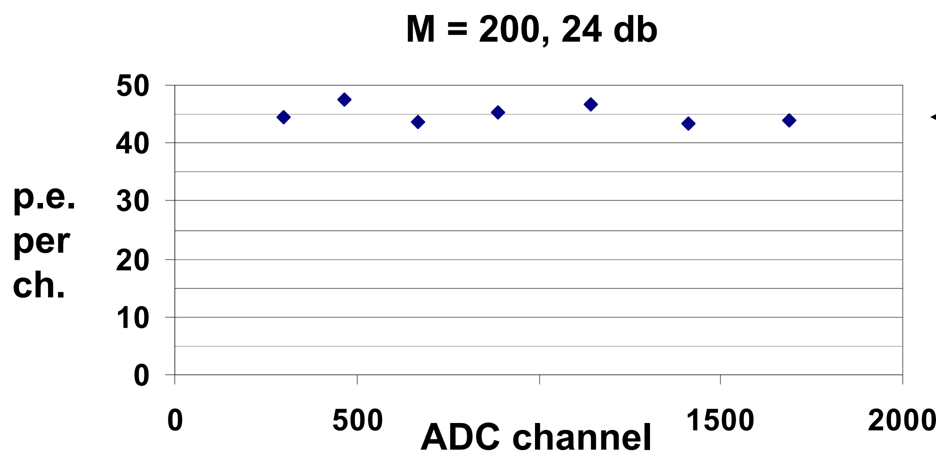
Scale Calibration



Constant ± 4%

Results for different M, db, consistent

M = 200, 24 db: 45 p.e./ch relative amp gain = 0.25
M = 50, 24 db: 165 p.e./ch relative amp gain = 1
M = 50, 32 db: 445 p.e./ch relative amp gain = 2.5

Lines from γ-rays from ^{241}Am, ^{55}Fe consistent

Scale calibration reliability ~ 25% (estimated)

Results

Response standard APD to ^{252}Cf

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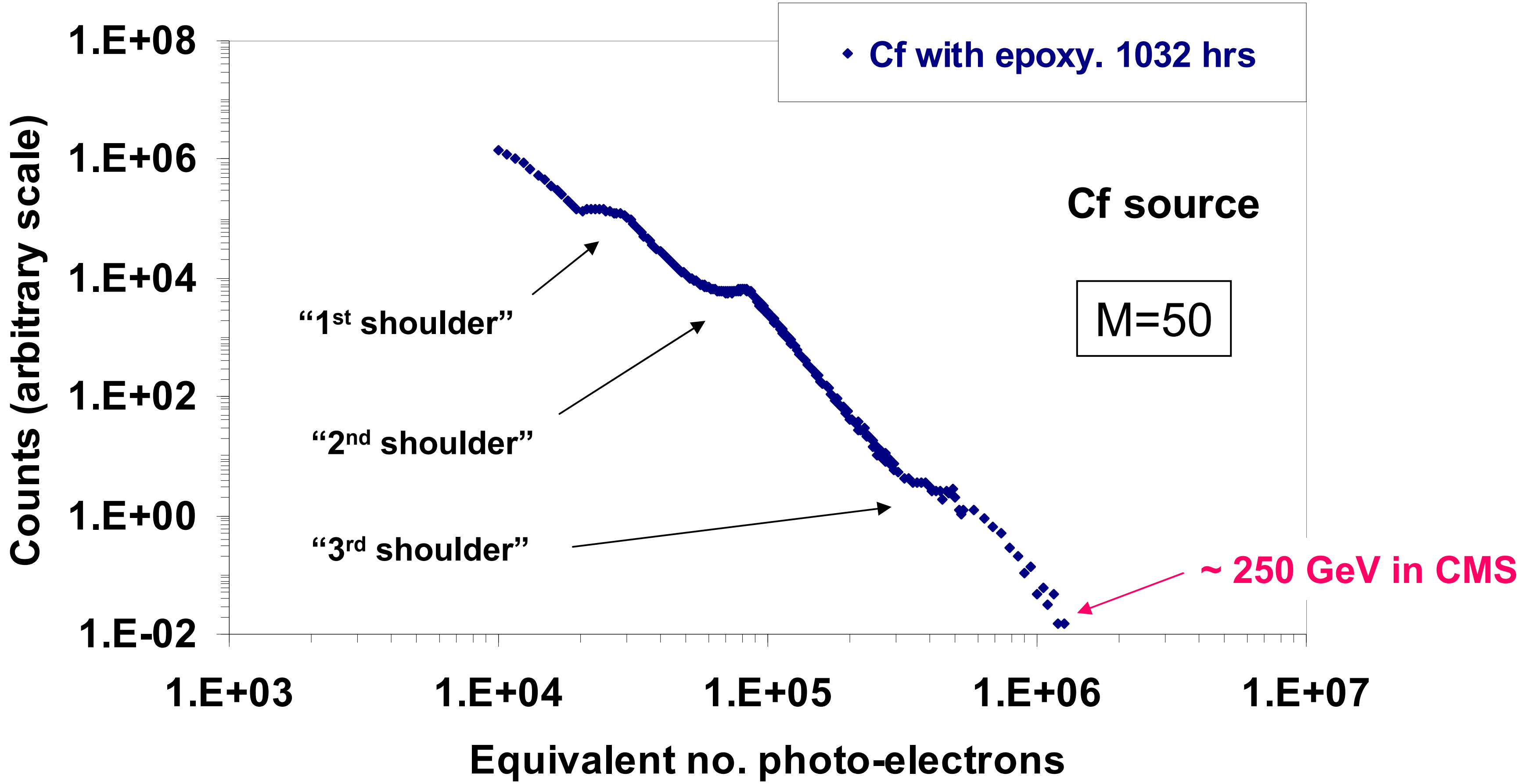
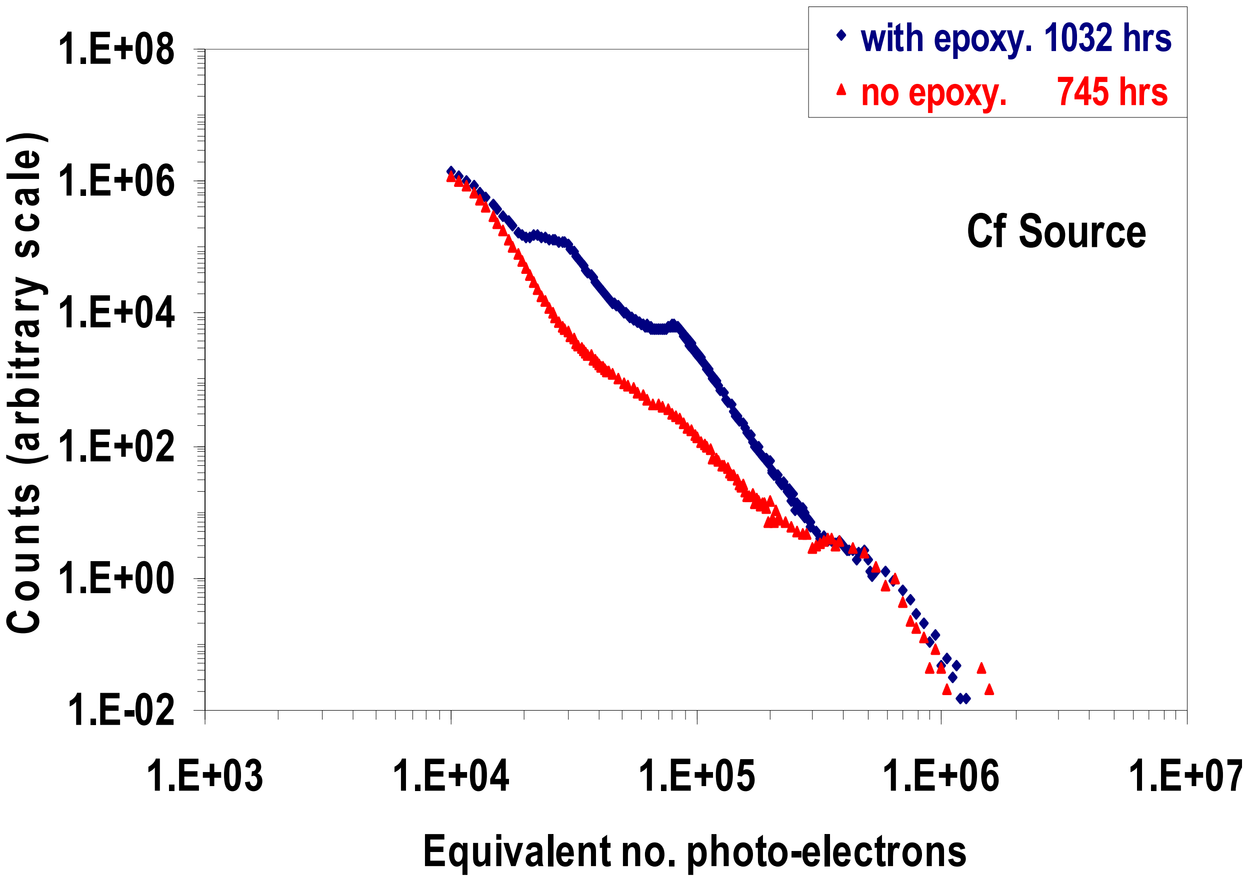


Basic spectrum: 2 x 8 orders of magnitude, limited by source strength

With/without epoxy. ^{252}Cf source



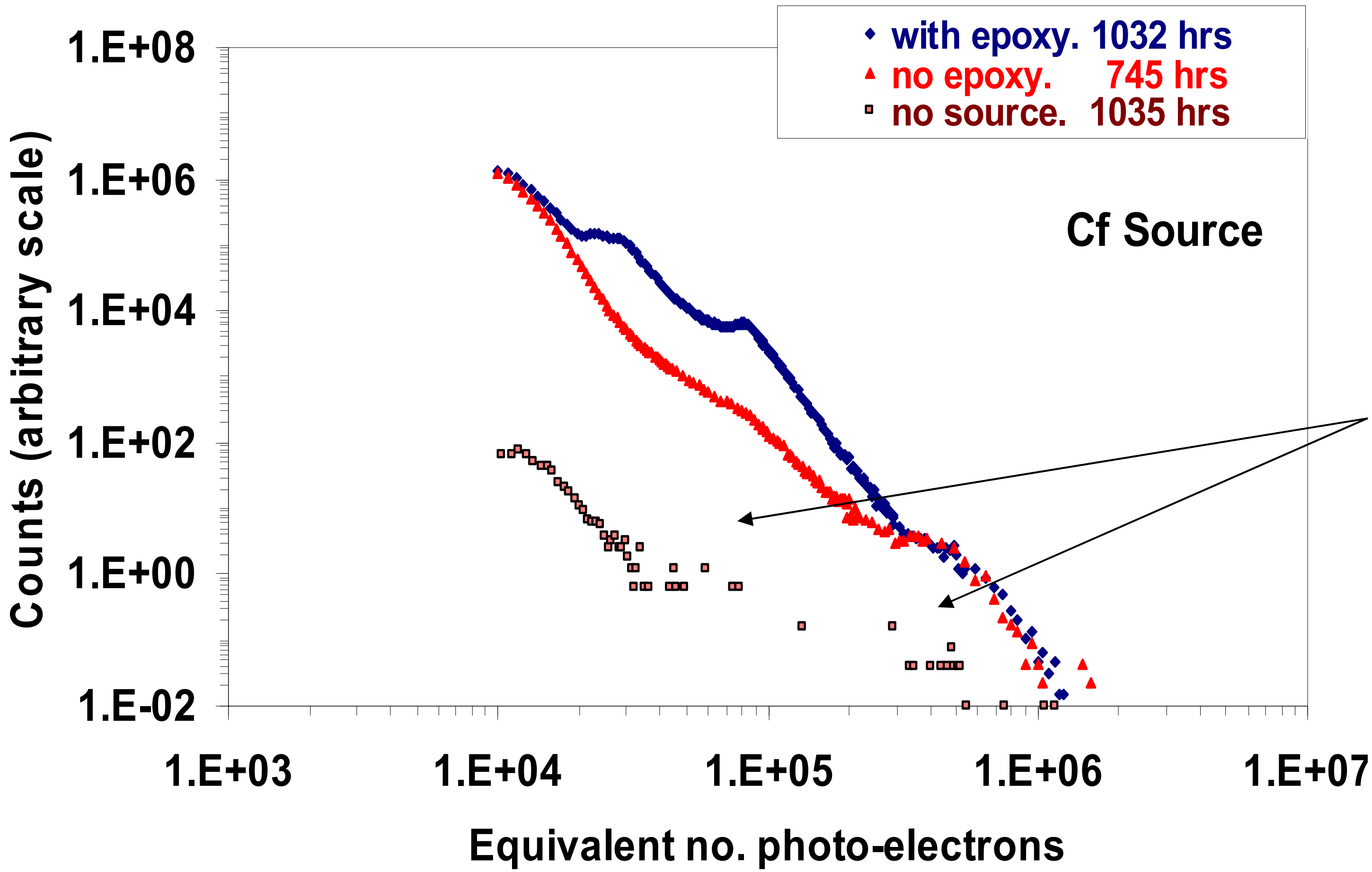
Compare to APD with epoxy removed

(run time normalised)

Enhancements, 1st and most of 2nd shoulders due to epoxy

But signal without epoxy also large, with some structures too.

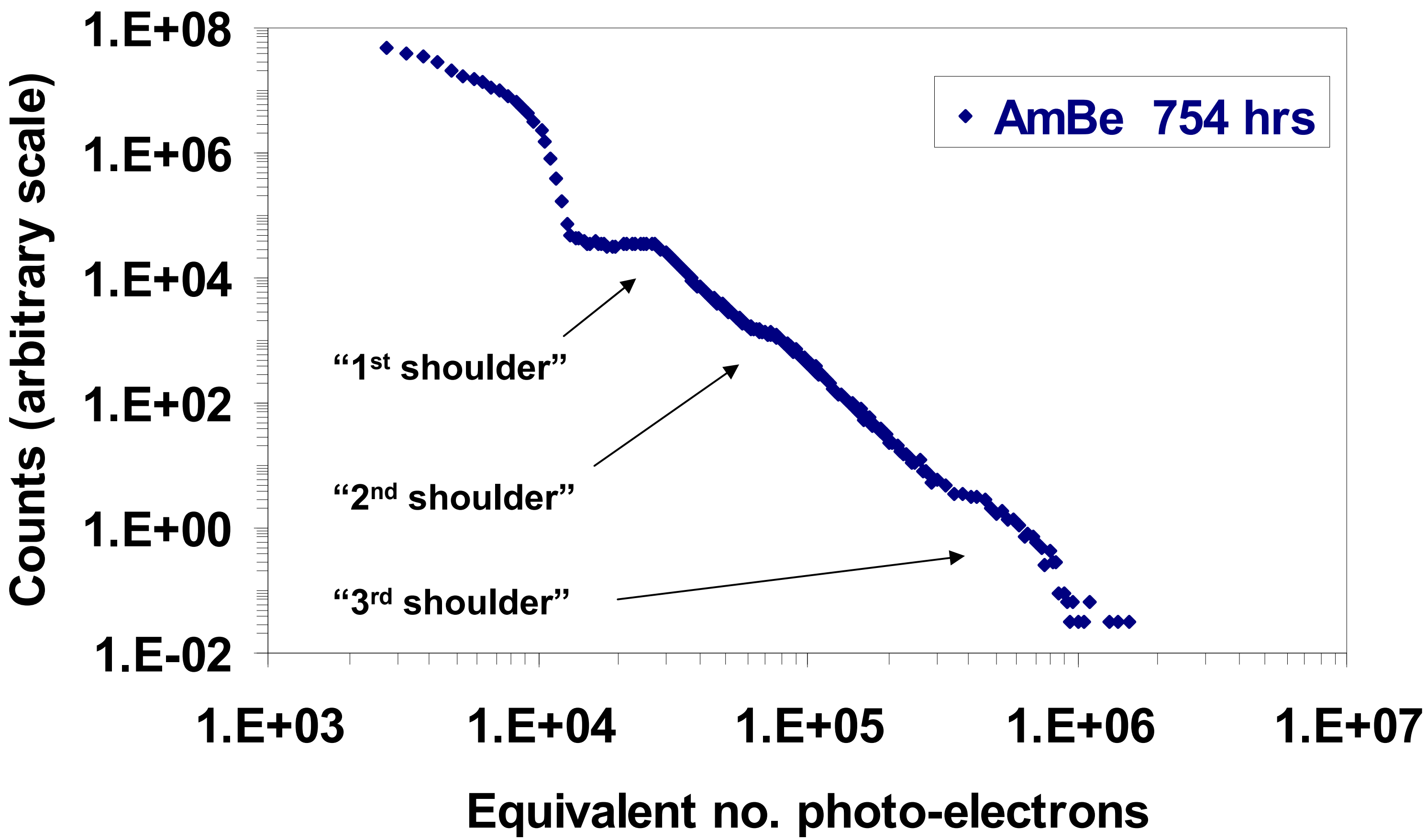
No background



Long run with no source:

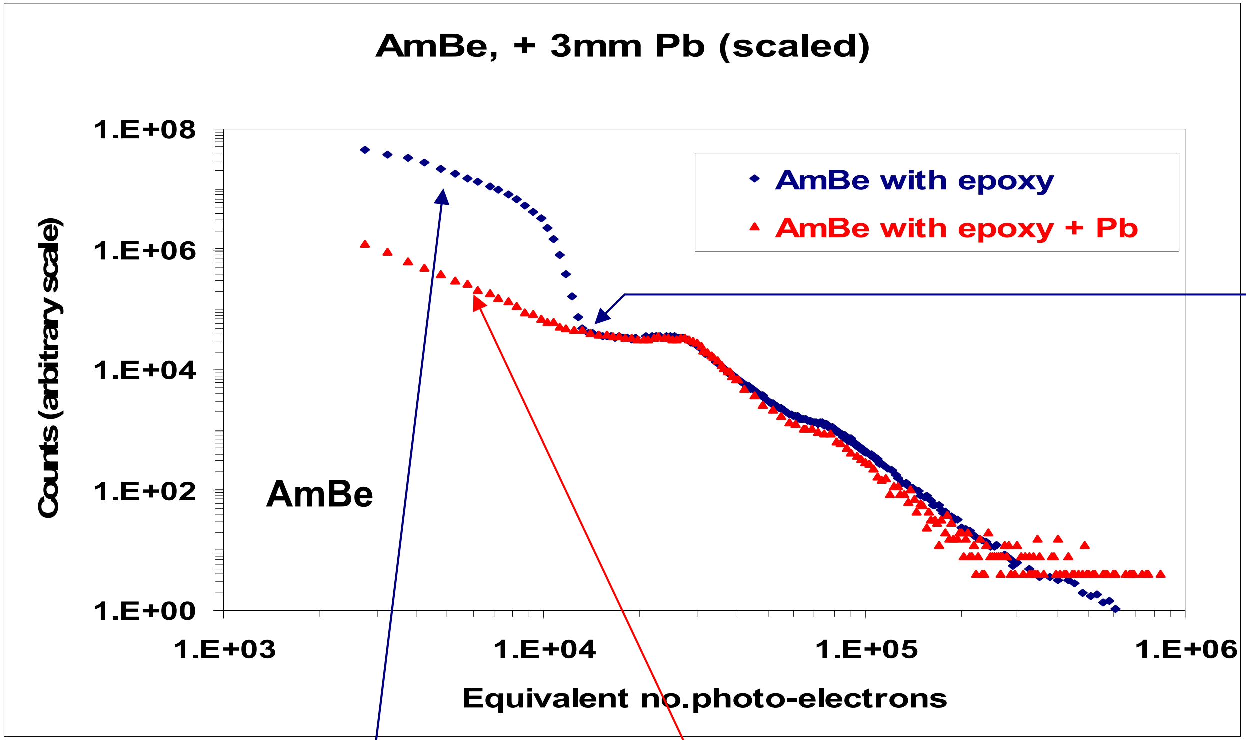
Background negligible

Am-Be source. Standard APD



Similar enhancements at same places, strengths different

Am-Be, Cf with 3 mm Pb inserted



Spectra with Pb scaled to match epoxy structures (Source-APD distance larger)

End of 60 keV γ response

γ-rays from AmBe absorbed by Pb

(Pb has no effect with Cf source – rise below 1st shoulder not from low energy γ)

Am-Be with C or CH_2 inserted

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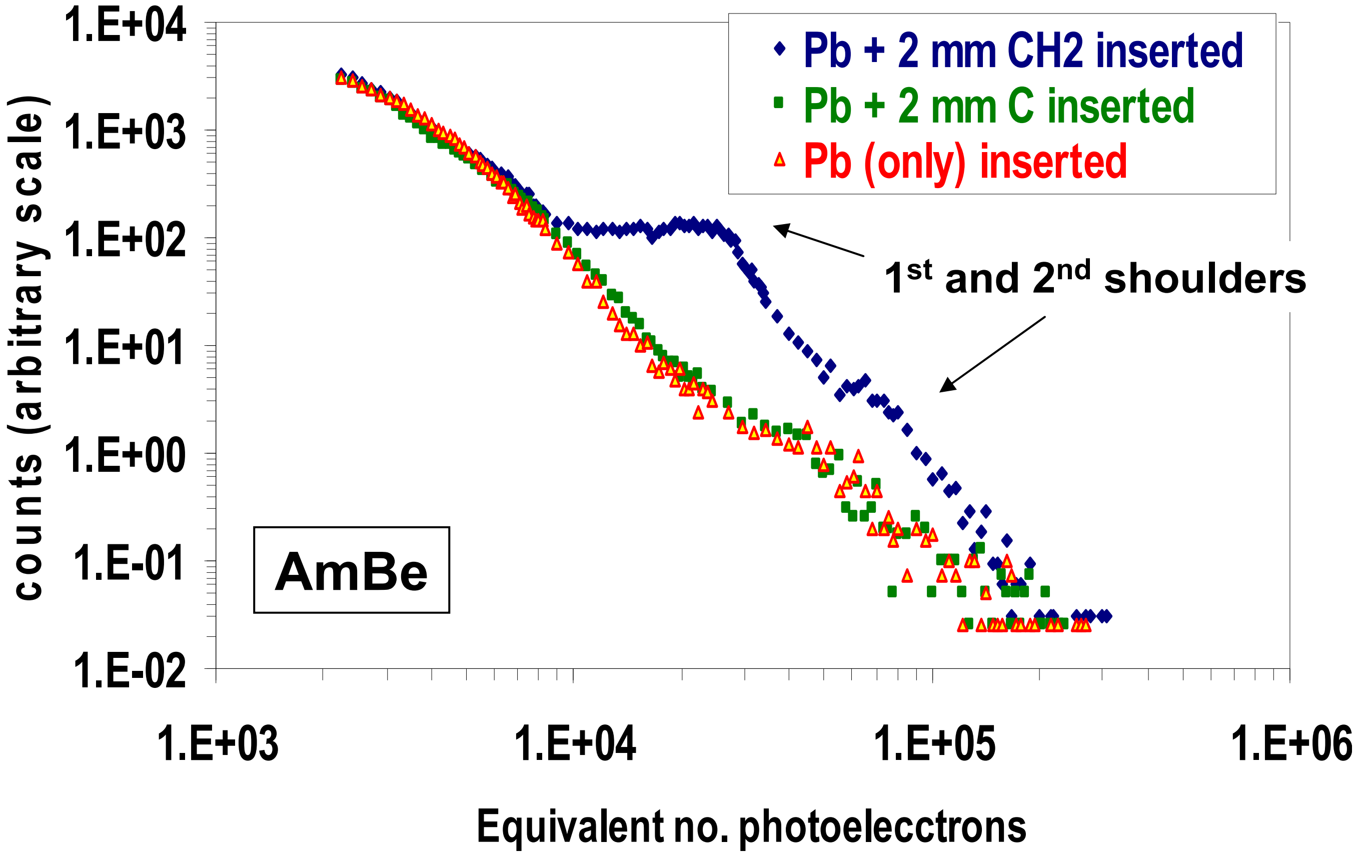

All spectra have 3 mm Pb inserted

Adding 2 mm C leaves spectrum unchanged.

Adding 2 mm CH_2 produces same enhancements as the epoxy

Am-Be, source behind

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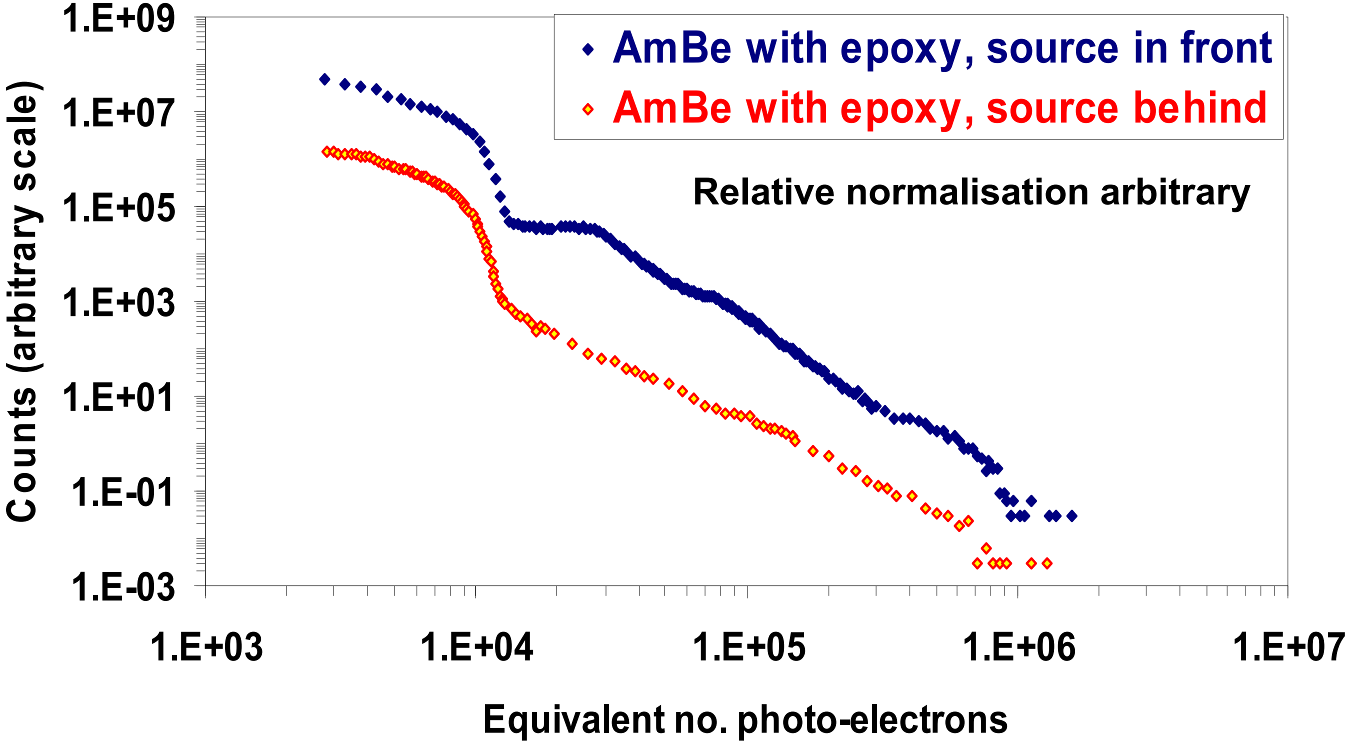
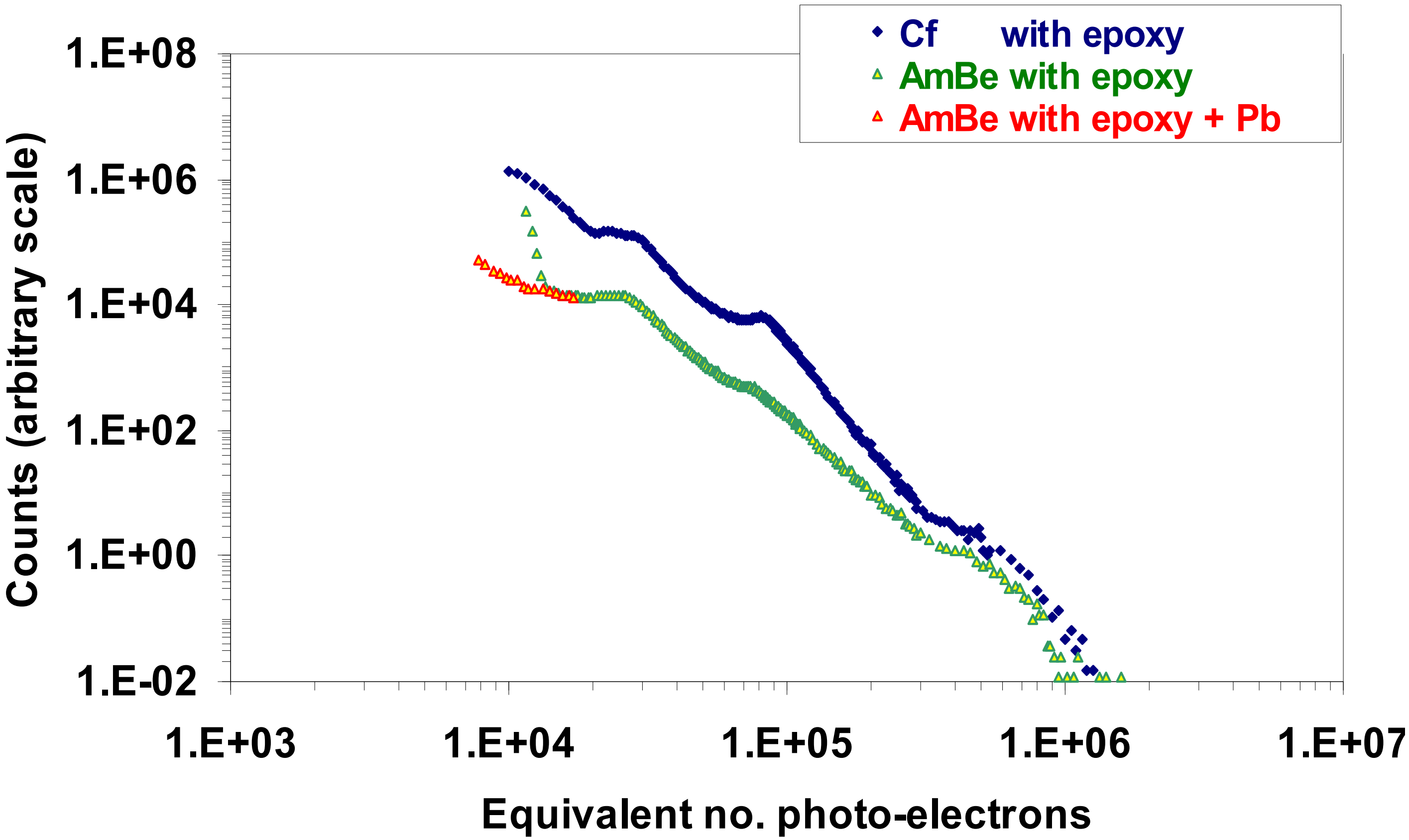


Epoxy-induced enhancements absent if source is behind the APD.

Conclusion: epoxy-induced signals are recoil protons from neutrons scattering off the hydrogen

Compare ^{251}Cf and Am-Be response



Normalised to time + source strength

Estimated ± 30%

Response per neutron much larger for Cf:

Implies neutrons < 3 MeV are "worse" *(have larger cross section)*

Conclusions so far (1)

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1) Hydrogen in epoxy **gives distinct substantial contribution with two clear structures (shoulders)**

Origin of shoulders?

- neutron energy spectrum is broad, isotropic
- no constraint on proton recoil angle/energy
- present in differing strengths with both sources

➔ not related to proton energy spectrum but rather to thickness of layers inside APD

eg 1st shoulder from protons stopping in high gain region?
2nd shoulder from … … low gain region?

(But 2nd shoulder also visible without epoxy, as is 3rd shoulder)

Conclusions so far (2)

2) Spectrum from interactions in APD also important, extend to larger amplitudes

Origin presumably mainly n-Si scattering

Origin of remaining structures unclear

3) Stronger response to Cf than to AmBe source (per neutron)

n-p and n-Si scattering cross sections rise to lower energies

Gain studies

Vary nominal gain: ^{251}Cf, no epoxy

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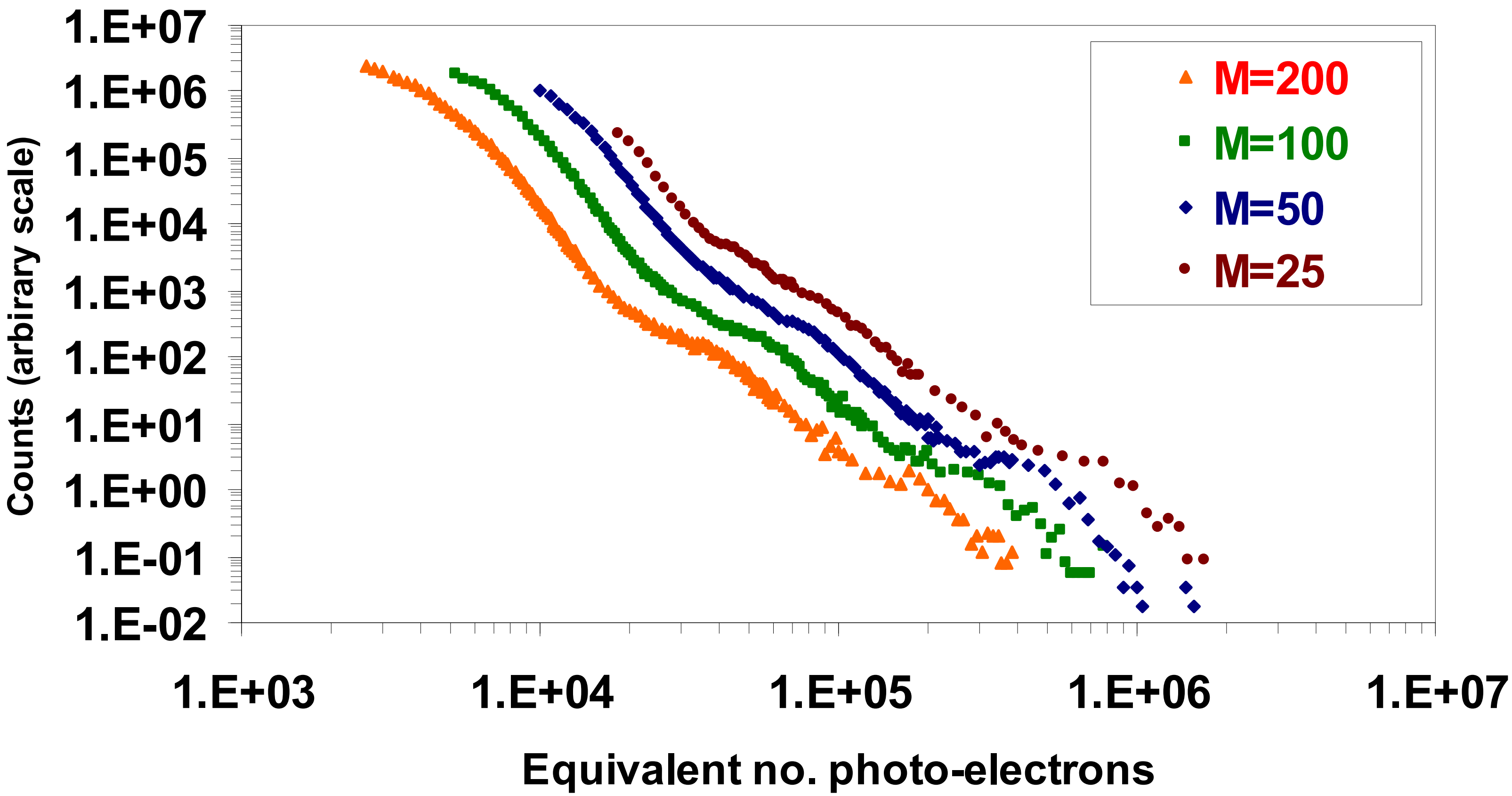

Signal grows more slowly than nominal gain

Vary nominal gain: AmBe, with epoxy

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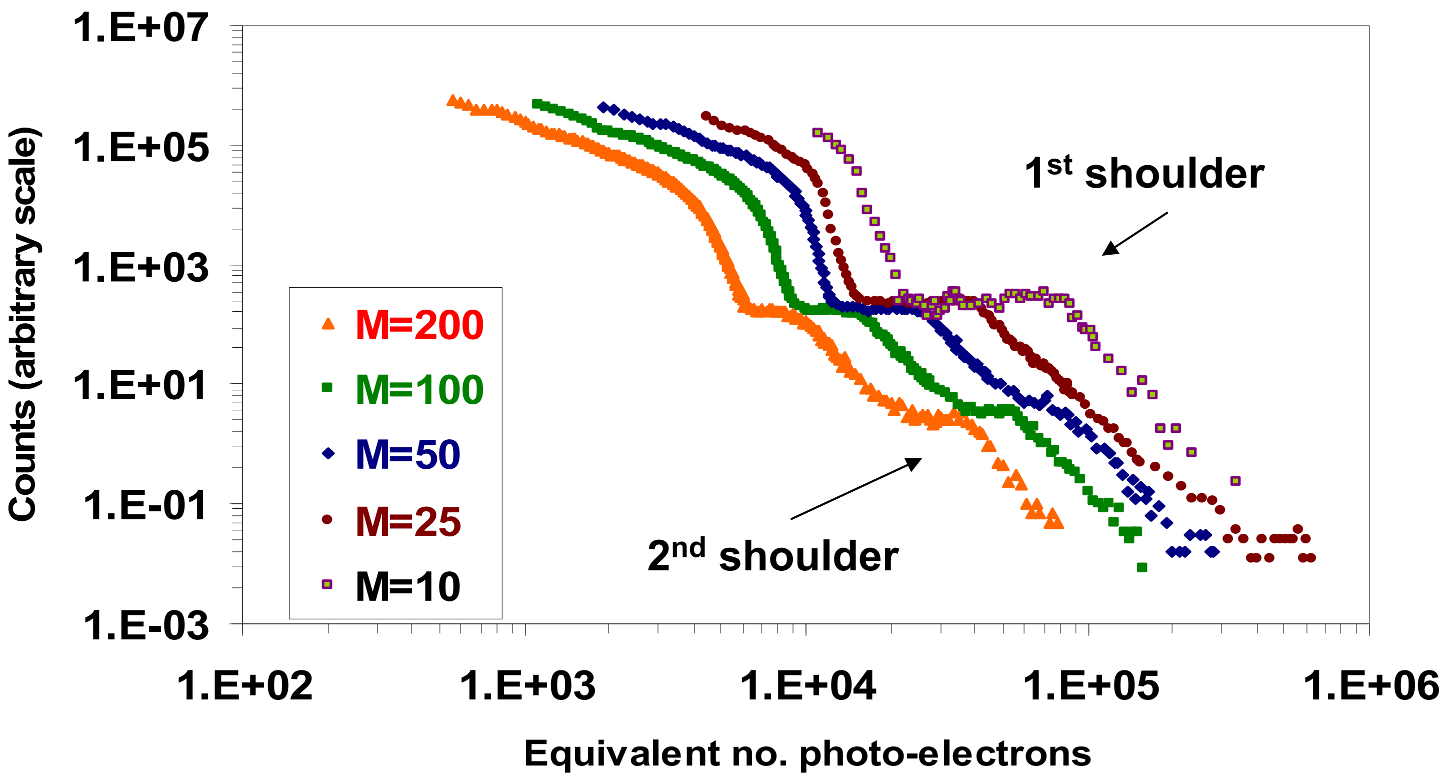

Epoxy signals also grow more slowly than nominal gain – but differently:

2nd shoulder clear at M=200, gone at M=25,10: Higher gain than Si signals

1st shoulder clearer at M=10 than at M=200: Lower gain than Si signals

Scans as function of nominal gain

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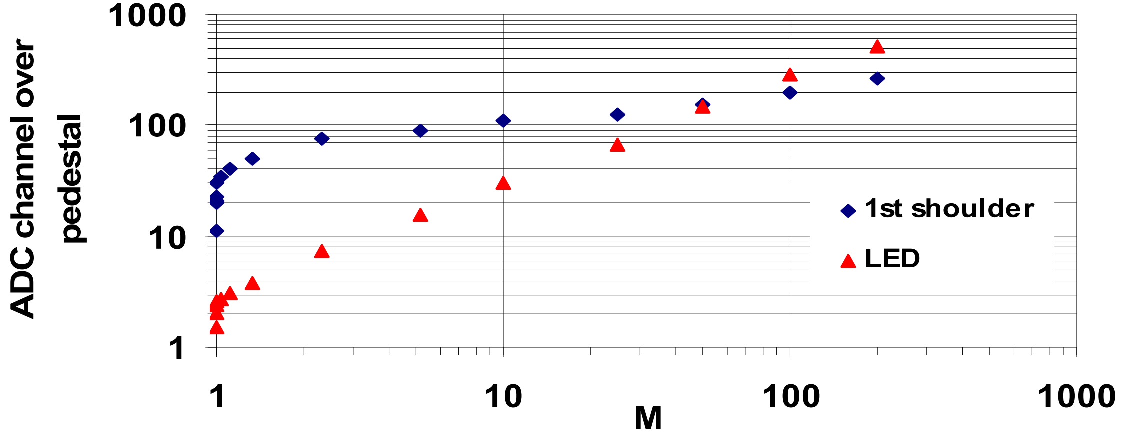
Position 1st shoulder and LED line vs M



- LED follows nominal gain through avalanche amplification region
- Position of 1st shoulder moves much more slowly

Conclusion: effective gain 1st shoulder ca. 4 at M=50

(previous figs imply somewhat higher gain for rest of spectrum)

Probable reason : quenching of amplifying E-field by heavy ionisation

Some numbers on shoulders

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Positions of shoulders, using equivalent no. p.e. scale, 3.6 eV/e

	No. p.e.	keV	keV *(50/4)
1st shoulder	26000	95	1200
2nd shoulder	80000	290	3600
3rd shoulder	500000	1800	22500

To account for effective gain = 4 *(1st shoulder)*

For comparison:

5 µm Si stops	440 keV proton	*? 1st shoulder*
50 µm Si stops	2000 keV proton	*? 2nd shoulder*

(but protons not at normal incidence, so effective thickness of layers larger)

Roughly right for 1st, 2nd shoulders, but magnitudes very rough, don't quite scale

(3rd shoulder does not fit picture – but is not epoxy induced)

CMS Simulations

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No simulations of these data, but simulations of CMS data

Broad agreement on:

importance of the epoxy for low energy neutrons
(epoxy thickness not main issue as the energies are usually low)

importance of signals from nuclear interactions with Si in APD

(In CMS many other particles also pass through APDs,
but interaction cross sections not as large)

For full simulation, need: gain quenching
APD detailed structure (complex)

Conclusions

- Significant and large response to low energy neutrons
- Hydrogen content in epoxy significant source
- Gain is substantially quenched
- CMS simulations in broad agreement

Reminder: the signals are identified and removed in CMS and do not impact the physics output

➔ see David Petyt's poster

Back-ups

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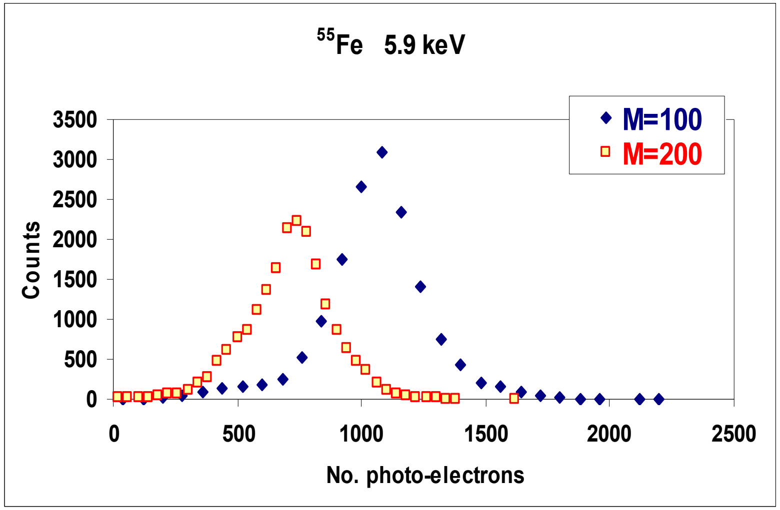
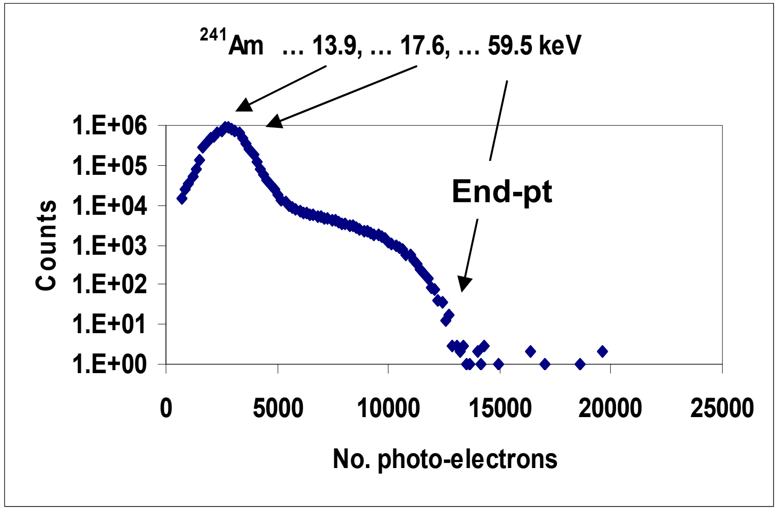
Check of Scale Calibration

No. photo-electrons from LED calibration





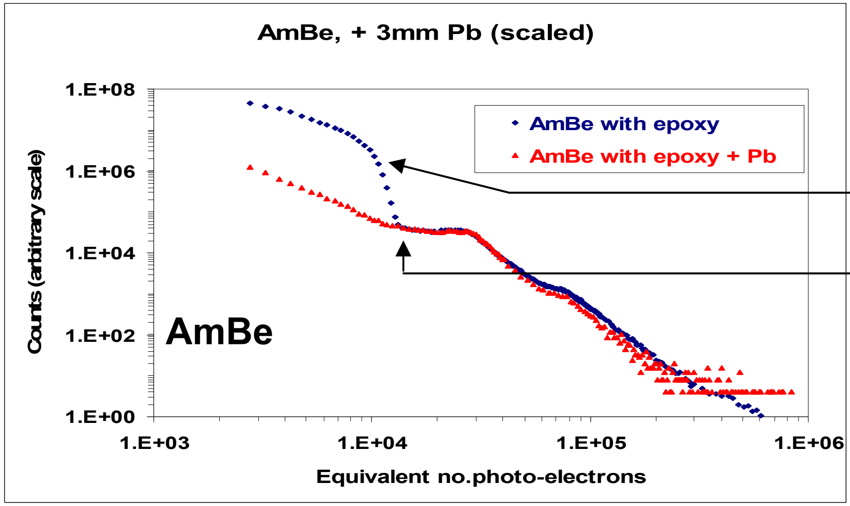
No. p.e. released if all the energy captured

5.9 keV ➔ 1640 p.e.

13.9 keV ➔ 3750 p.e.
17.6 keV ➔ 4900 p.e
59.5 keV ➔ 16500 p.e.

Reduced response broadly consistent with known effect

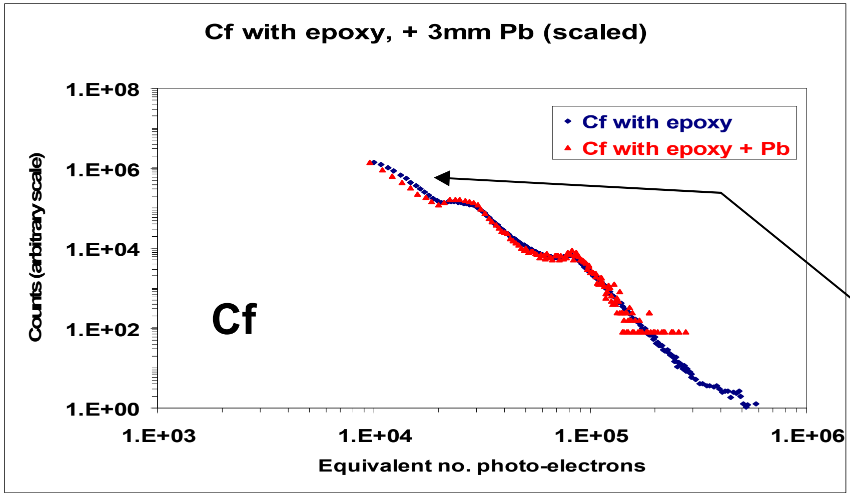
Am-Be, Cf with 3 mm Pb inserted



Signals from gammas from AmBe suppressed by Pb

End of 60 keV γ response

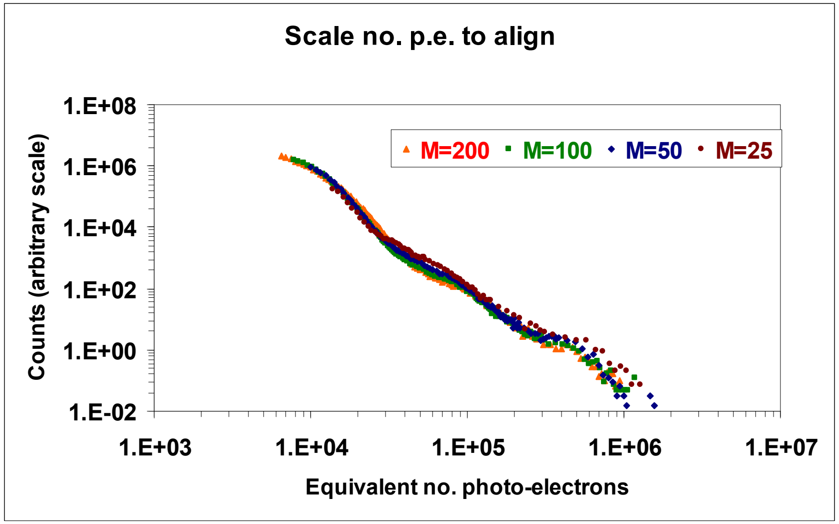
Spectra with Pb inserted scaled to match epoxy structures (Source-APD distance larger)



No effect with Cf source

- rise below 1st shoulder not low energy gammas

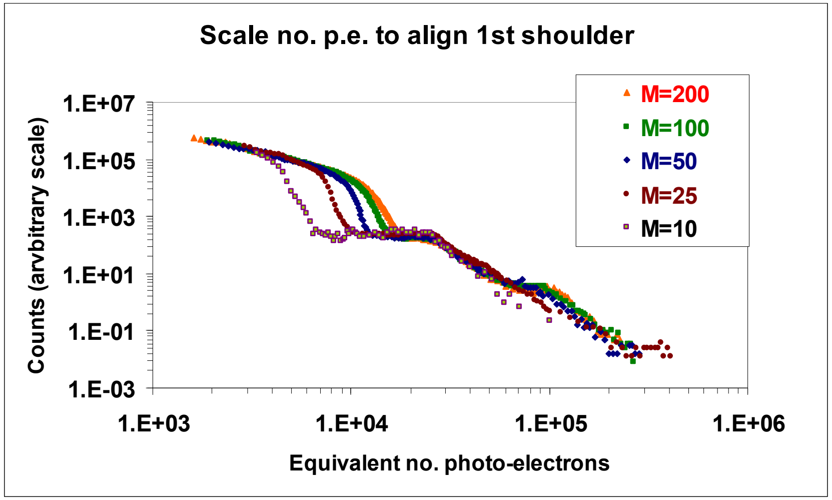
Scale no. p.e. to align curves



Cf, no epoxy

No. p.e. scaling factors

M	No epoxy (Cf)	Epoxy 1st shoulder (AmBe)
10		0.3
25	0.75	0.65
50	1	1
100	1.5	1.7
200	2.5	2.9



AmBe. with epoxy