Precision beta-spectrometry with semiconductor detectors

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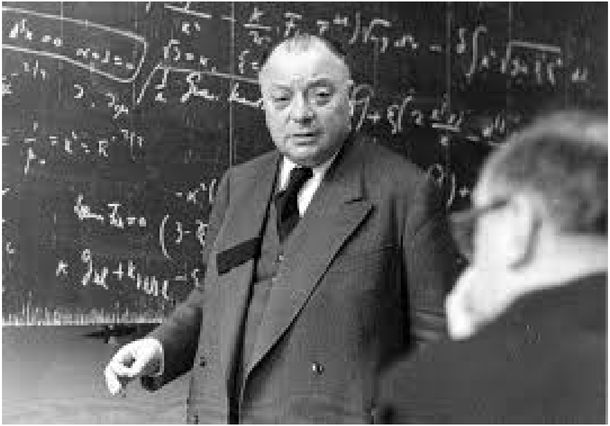
Beta-spectrometry



The continious shape of shape of beta-spectra was discovered by W.Pauli in 1930

beta-decay

Beta-decays could be classified as

- (super-) allowed ($\Delta\pi = 0, \Delta I = 0, 1$)
- first forbidden ($\Delta\pi = -1, \Delta I = 0, 1$)
- first forbidden unique($\Delta\pi = -1, \Delta I = 2$)
- second,third... forbidden

All transitions but allowed can't take place considering single nucleon. And here the story begins...

Beta-decay

Beta-decay shape could be expressed as:

$$N(W) = Kp^2(W - W_0)^2 H(W) F(Z,W),$$

Where the following correction factors are present:

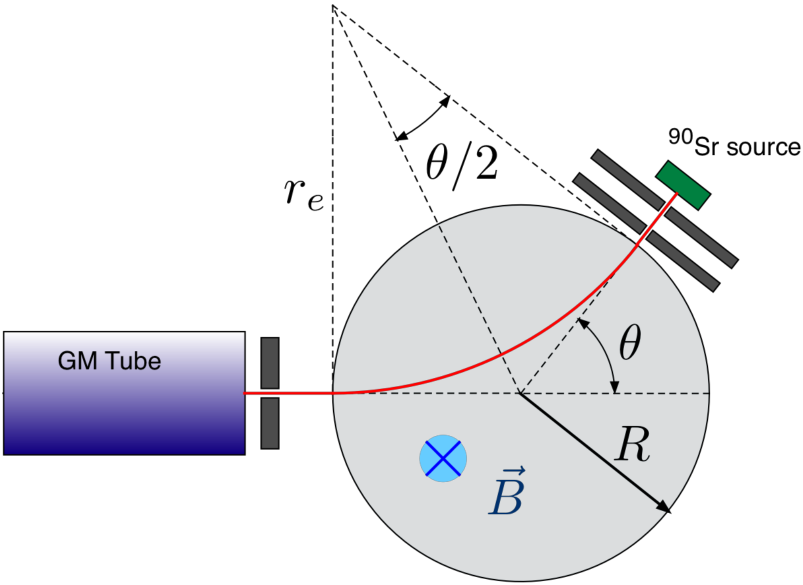
- **shape factor** $H(W)$;
- Fermi function $F(Z,W) = F_C(Z,W) L_0(Z,W) C(Z,W) S(Z,W) G(Z,W) B(W)$;
  - Coulomb interaction $F_C(Z,W)$;
  - electromagnetic finite-size correction $L_0(Z,W)$;
  - weak finite-size corrections $C_V(Z,W)$, $C_A(Z,W)$;
  - screening correction $S(Z,W)$;
  - radiative corrections $G_\beta(Z,W)$, $G_\nu(Z,W)$;
  - weak magnetism correction $B(W)$.

Beta-spectrometry

Main kinds of beta-spectrometers are

- Magnetic spectrometers
- Electrostatic spectrometers
- Scintillators
- Semiconductor detectors
- bolometers, TPCs and other special kinds

Magnetic spectrometers



Magnetic spectrometers

- Zero Fano factor
- Perfect resolution
- narrow energy range
- High price and size
- difficulties with reaching high energies

Electrostatic spectrometers

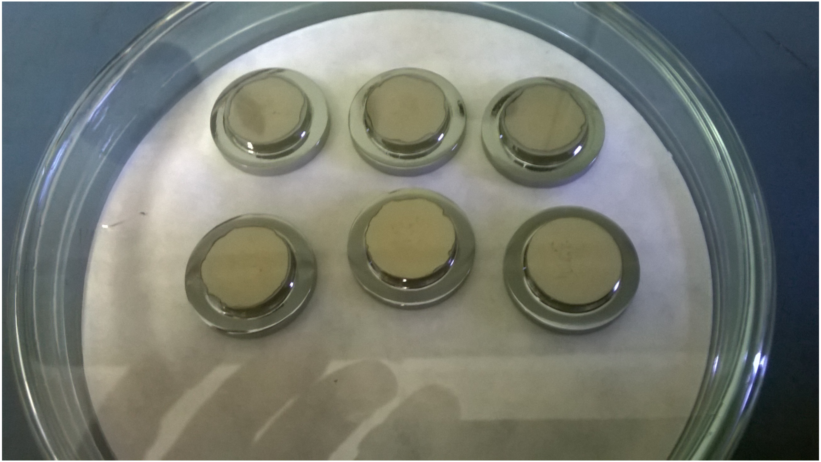
- Zero Fano factor
- Perfect resolution
- Integral spectrum measurement
- High price and size
- difficulties with reaching high energies

Scintillator spectrometers

Scintillator spectrometers

- Calorimetric detector
- freedom of shapes and sizes
- possibility of internal source usage
- Poor resolution
- systematics related with light collection
- systematics related with quenching

Semiconductor spectrometers



Semiconductor spectrometers

- small Fano factor (of order of 0.08 - 0.12)
- Decent resolution
- Calorimetric detector
- predictable energy response of the detector
- Limited shape variety
- impossibility of internal source usage

...This means having a nontrivial spectrometer response function

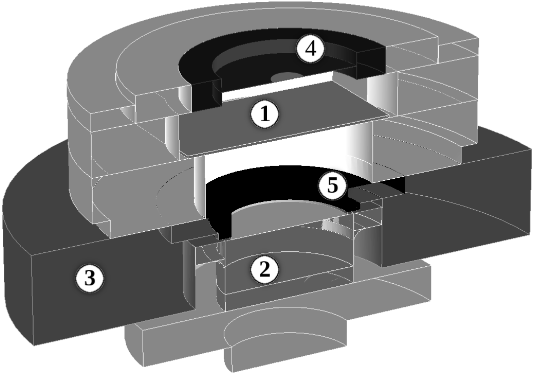
Semiconductor spectrometer: a way out

Still, it is possible to find a way out of the situation. This means description of the spectrometer response through a Monte-Carlo simulation. The setup requirements are:

- the source should be maximally predictable:
  - source thickness is to be minimized
  - source substrate should guarantee minimal scattering
  - source thickness distribution is to be measurable independently from beta spectrum
- the spectrometer geometry should be well known
  - the detector should be collimated well to prohibit electron reach zones of incomplete charge collection
  - the setup geometry and materials should be well established

The simulation could be done with Geant4.10.4: G4EmStandardPhysics_option4 package.

The semiconductor spectrometer in use



1 - transmission PIPS detector

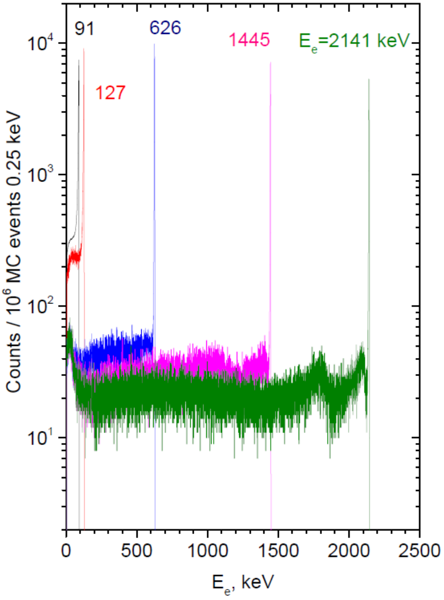
2 - Si(Li) full absorption detector

3 - Aluminum detector holder

4 - radioactive source

5 - tungsten collimator

Simulated spectrometer response function



The spectrometer response function shows significant fraction of events with partial energy deposit in the detector. These events are due to backscattering on the detector, the source substrate and the setup construction elements as well as due to bremsstrahlung-related effects

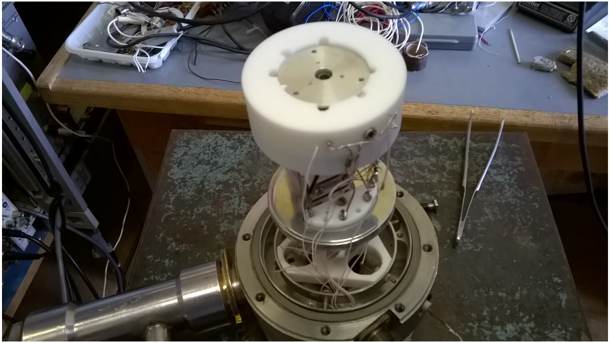
Thin source production

Production of a thin source is crucial for the experiment. The source has to satisfy the following conditions:

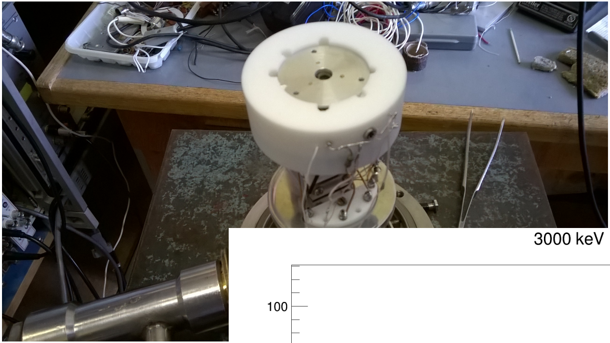
- The maximum thickness should correspond to 2.4 MeV loss for 5.4 MeV alpha or less
- The source structure should be possible to reconstruct reliably through shape of alpha-lines from ^{241}Am and ^{244}Cm
- The source should still have substantial activity in order not to have excesses systematics from background and to preserve statistics
- non-^{144}Ce activity should be limited

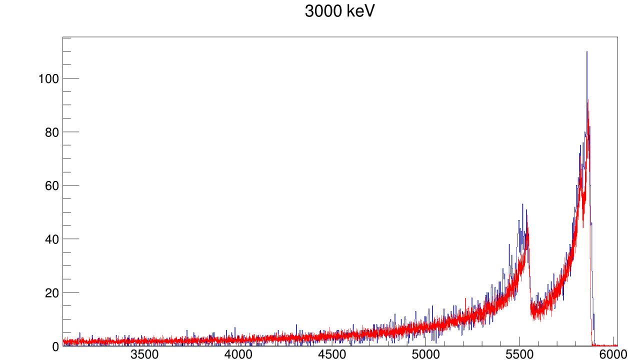
Taking into account that the source contains non-active Ce, that is a challenge. But in all other case we can not control its shape at all.

Thin source production: results(source #1)

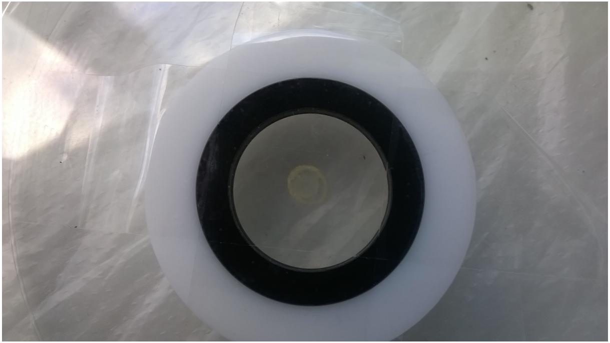


Thin source production: results(source #1)





Thin source production: results (source #2)



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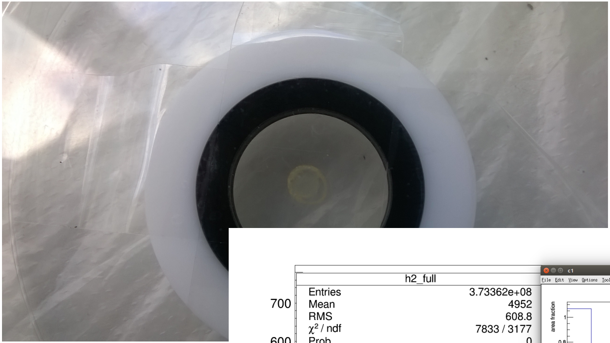
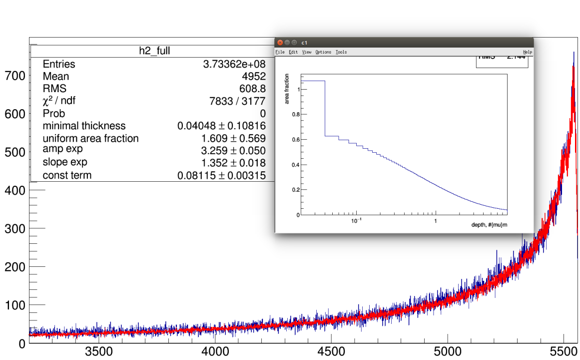
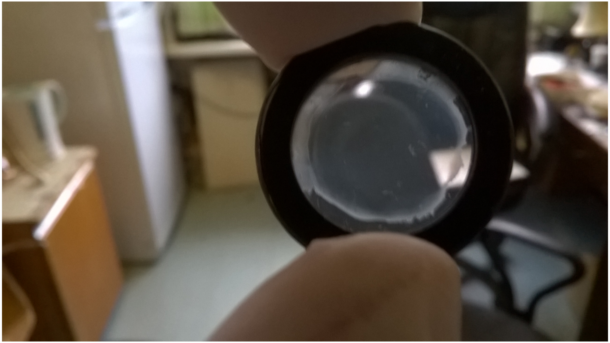
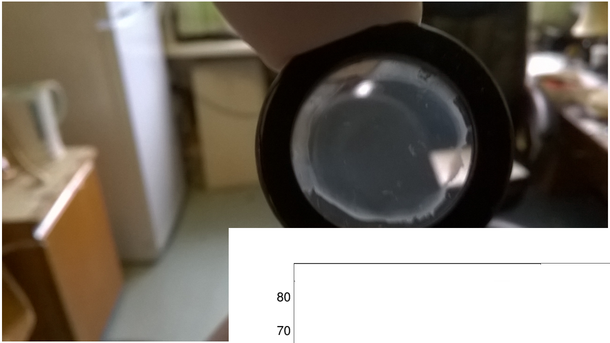


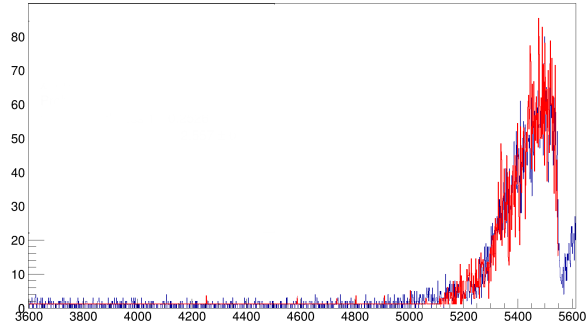


Thin source production: results (source #3)



Thin source production: results (source #3)





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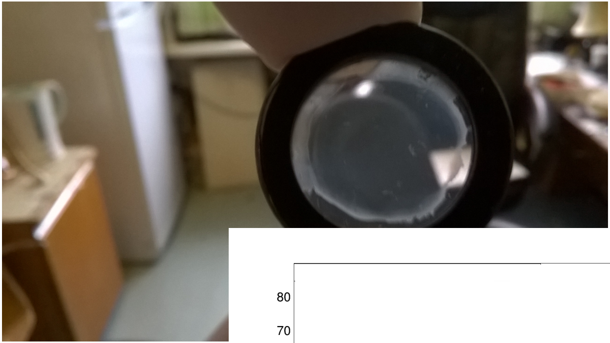
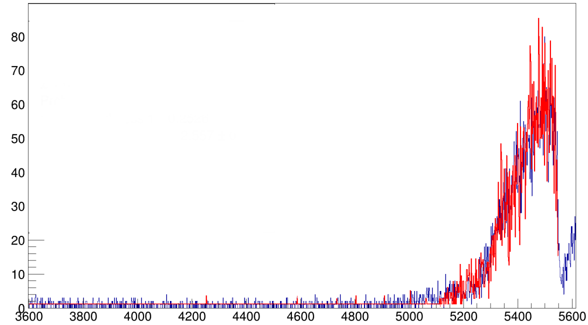
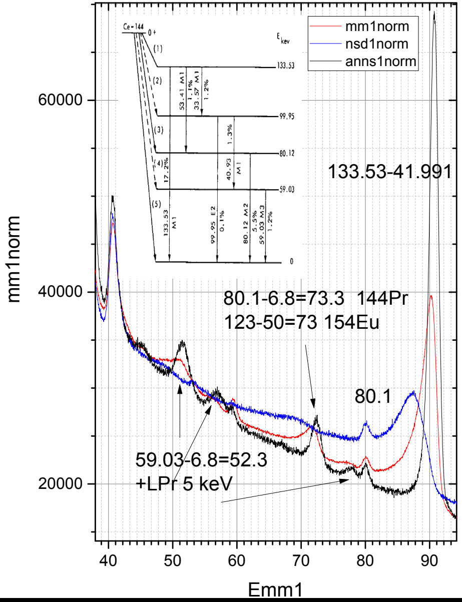
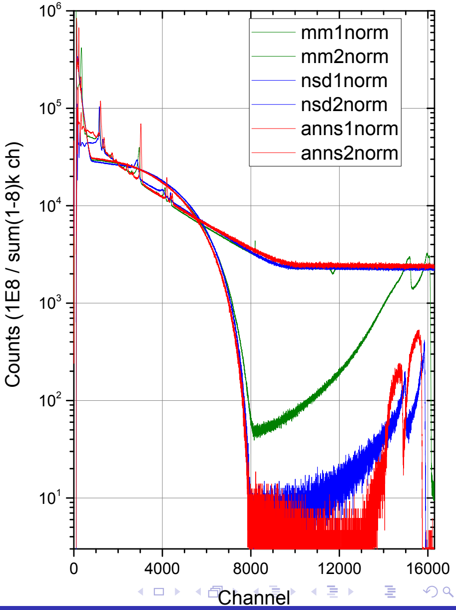


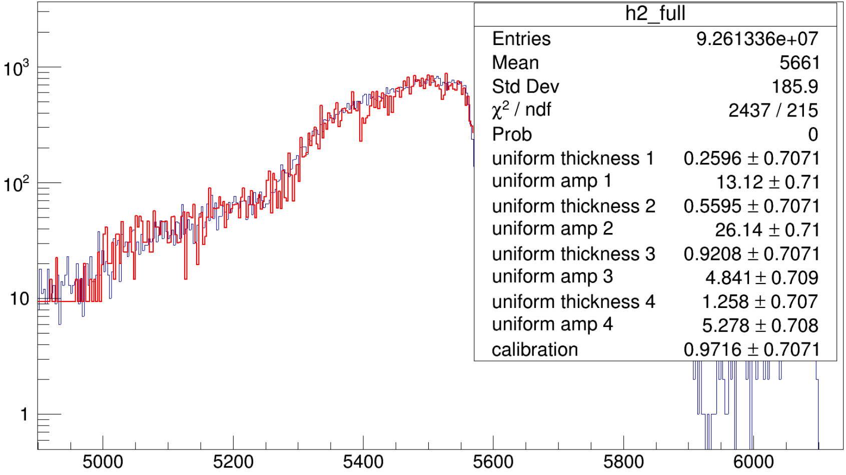


Thin source production: sources comparison

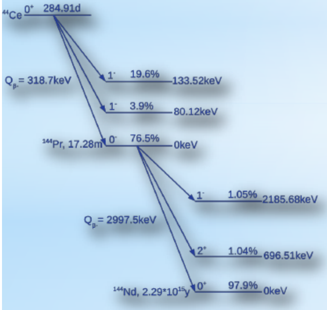




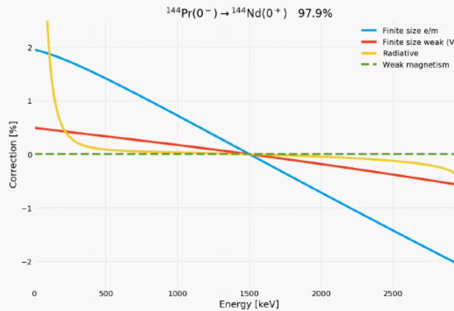
Source activity thickness distribution: fitting the alphas



^{144}Ce - ^{144}Pr decay



^{144}Ce – fission fragment,
5% in spent fuel
E_0 = 3.0 MeV
τ = 411 days.
7.5 кW/MCi
300 г/MCi
10 kBq
V. G. Khlopin Radium Institute

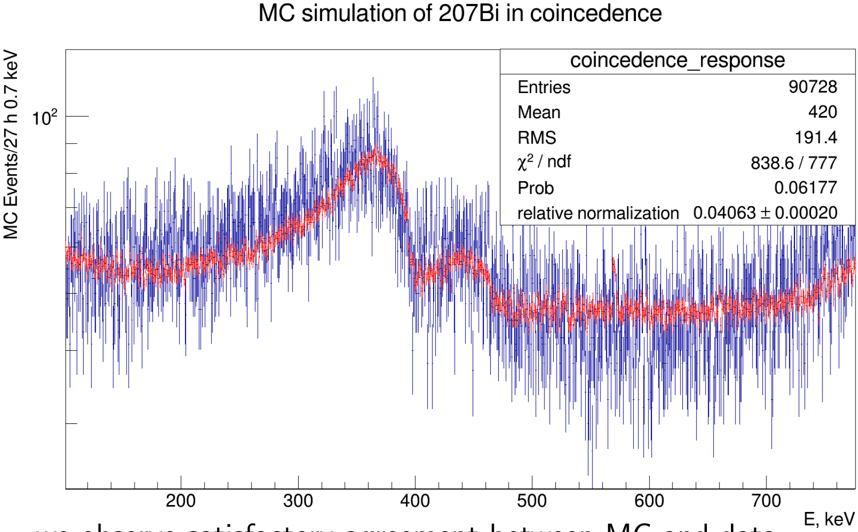


Q_β ^{144}Ce	Q_β ^{144}Pr	γ ^{144}Ce	γ ^{144}Pr
318.7 (76.5%)	2997.5 (97.9%)	133.5 (11.1%)	696.5 (1.3%)
185.2 (19.6%)	2301.0 (1.04%)	80.1 (1.36%)	2185.7 (0.69%)
238.6 (3.9%)	811.8 (1.05%)	41.0 (0.26%)	1489.1 (0.28%)

^{144}Ce - ^{144}Pr allowed component selection

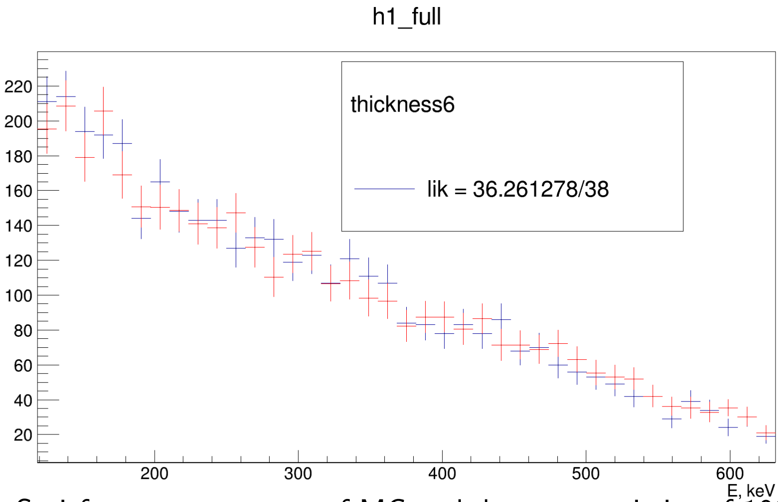
Allowed transition could be selected through coincidences with NaI(Tl) detector for gamma-energies exceeding 696 keV. The analysis was performed offline thanks to usage of CAEN V1725 board.

Monte-Carlo simulation test on ^{207}Bi calibration



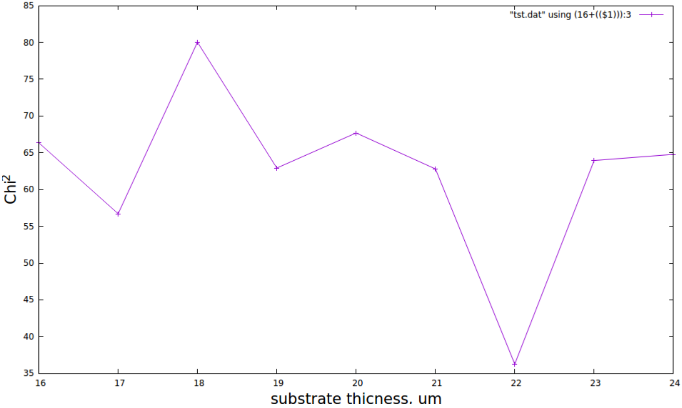
we observe satisfactory agreement between MC and data (conversion electrons of ^{207}Bi)

Monte-Carlo simulation test on $0^- \to 1^-$ transition



Satisfactory agreement of MC and data on statistics of 10000 events in allowed transition

Monte-Carlo simulation: establishment of substrate thickness



The χ^2 value has very strong dependence upon substrate thickness: this value should be treated with extreme care

Conclusions

- Beta-spectrometry with semiconductor detectors has good perspectives
- modern versions of Geant4 electromagnetic physics allow satisfactory modeling of electron scattering
- spectrometer geometry could have serious impact on the results and should be taken with care

Thank You for Your attention