Scintillation efficiency measurement of Na recoils in NaI(Tl) below the DAMA/LIBRA energy threshold

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Outline

1. Overview of the NaI(Tl) quenching experiment

- Scientific Motivation
- The NaI(Tl) neutron scattering experiment
- Results and Implications

2. Technical Discussions on this measurement

- Uncertainty sources and mitigation
- What was done right in this measurement
- What could have been done better

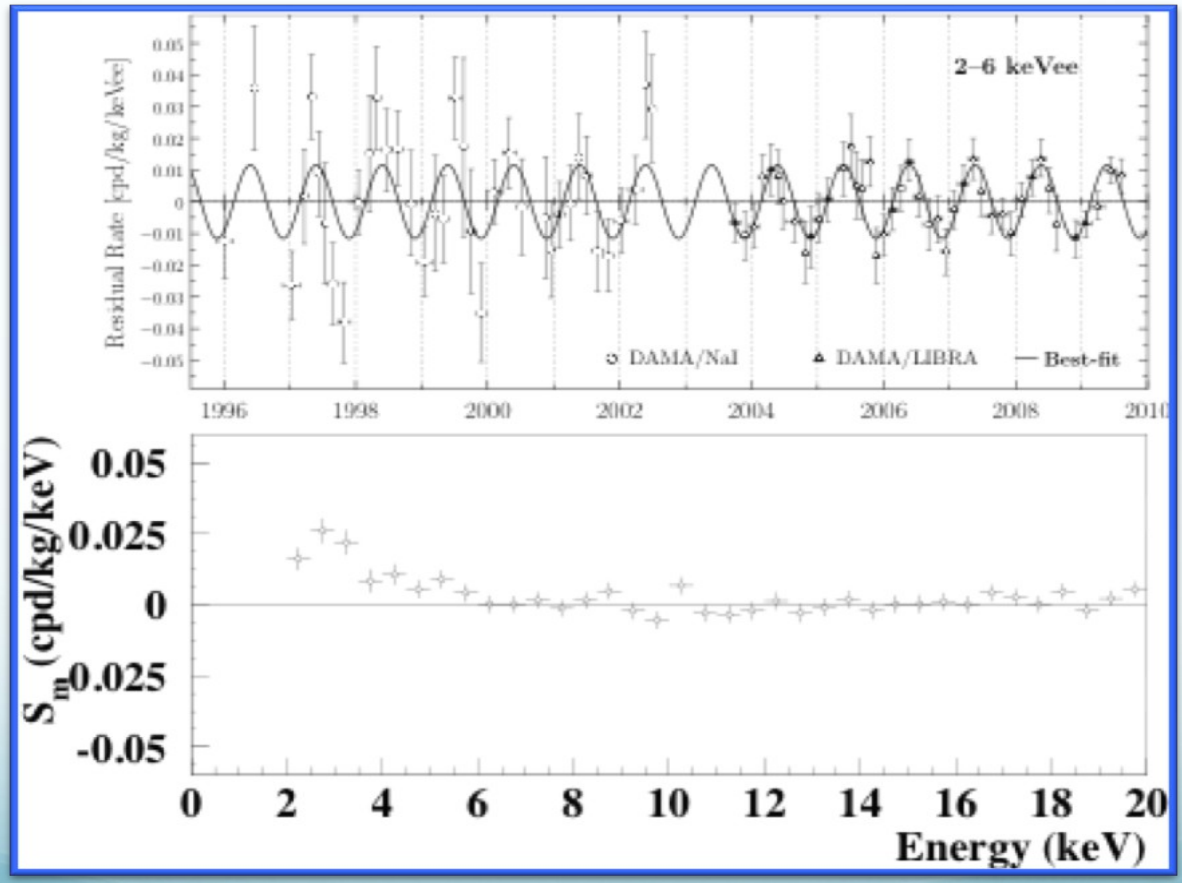
3. Conclusion

Xu et al, Phys. Rev. C 92, 015807

http://dx.doi.org/10.1103/PhysRevC.92.015807

Motivation – the DAMA controversy

Have we detected dark matter yet? DAMA says yes, others say no.



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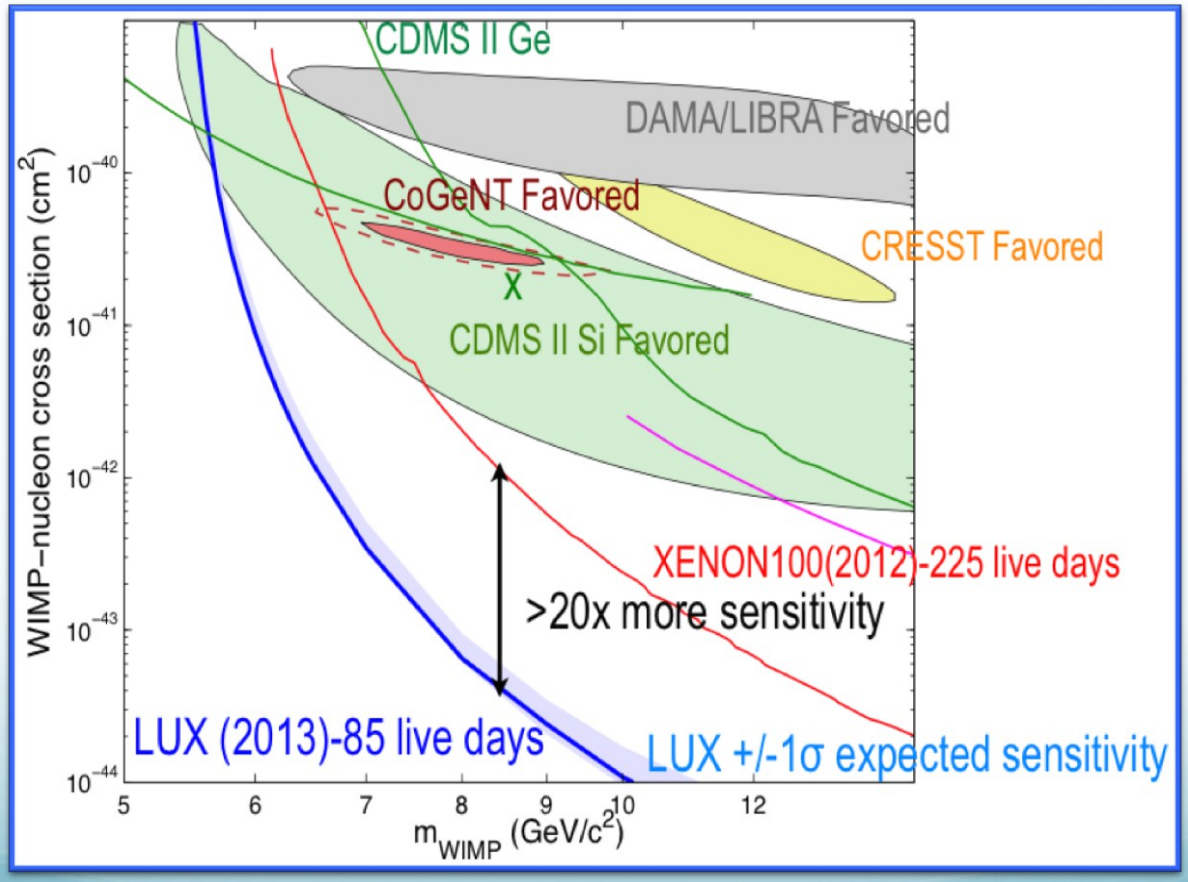


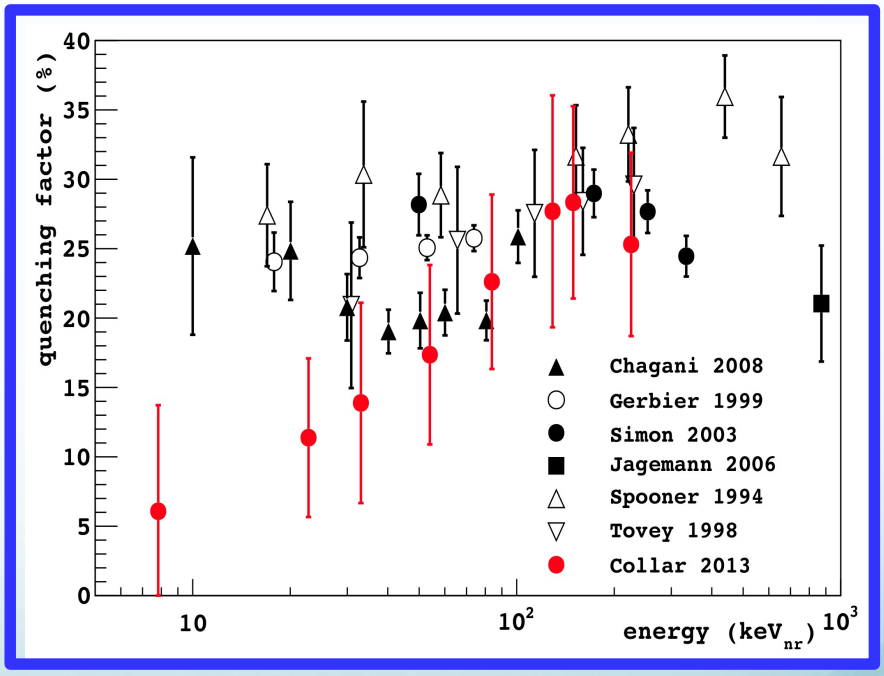
Motivation – Quenching in NaI(Tl)

If DAMA is seeing dark matter, what can we say about dark matter?

DAMA signal region: (2, 6) $keV_{ee,}$ what is the nuclear recoil energy?

DAMA reported scintillation quenching factors of 0.3 and 0.09 for Na and I respectively (^{252}Cf calibration, spectral fit).

Conflicting results from other energy-dependent measurement in the DAMA energy region of interest



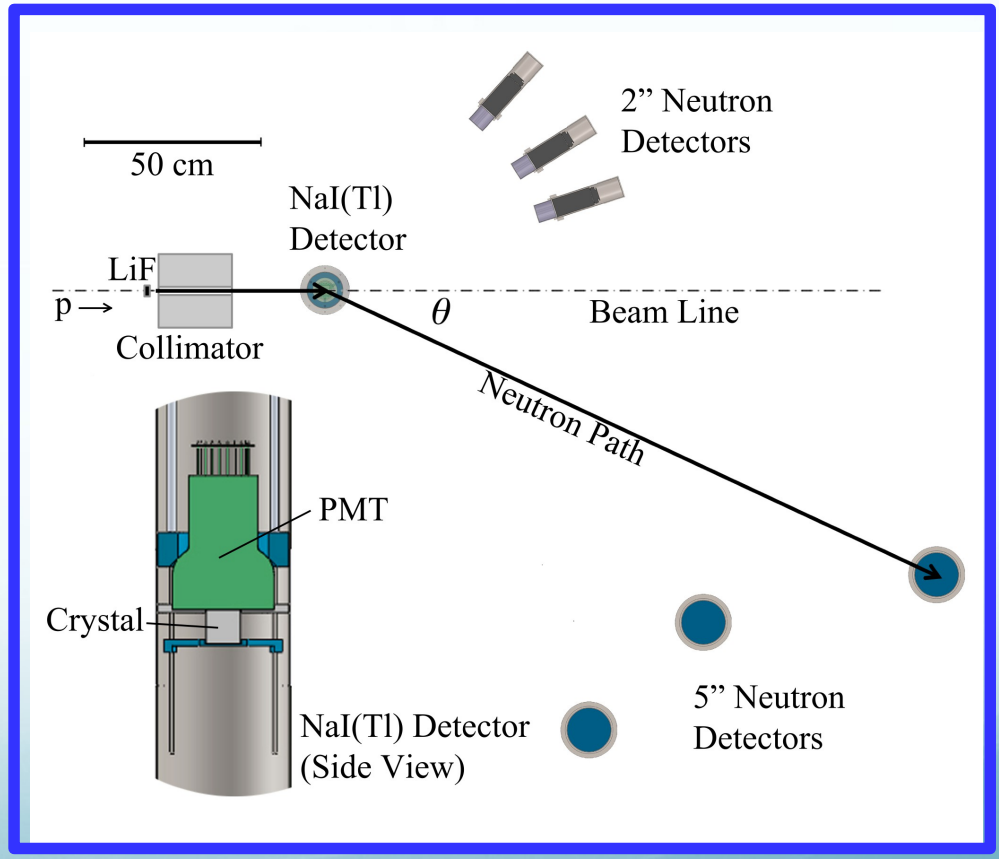
Experimental setup

Goal: ~5% measurement 5-50 keV_{nr} Na recoils

Reliable Na nuclear recoil calibration for NaI(Tl) experiments

Features:

- Low energy neutrons
- Pulsed beam, neutron tagging (double-TOF methods)
- Small NaI(Tl) crystal (low multiple scattering)
- High light yield
- Low energy threshold
- PSD methods
- Multiple angles measured at the same time



Event selection – Time of flight

TOF1: time of flight from LiF to NaI(Tl)

TOF2: time of flight from LiF to liquid scintillator (LS) neutron detectors

Vertical bands:

LiF gammas

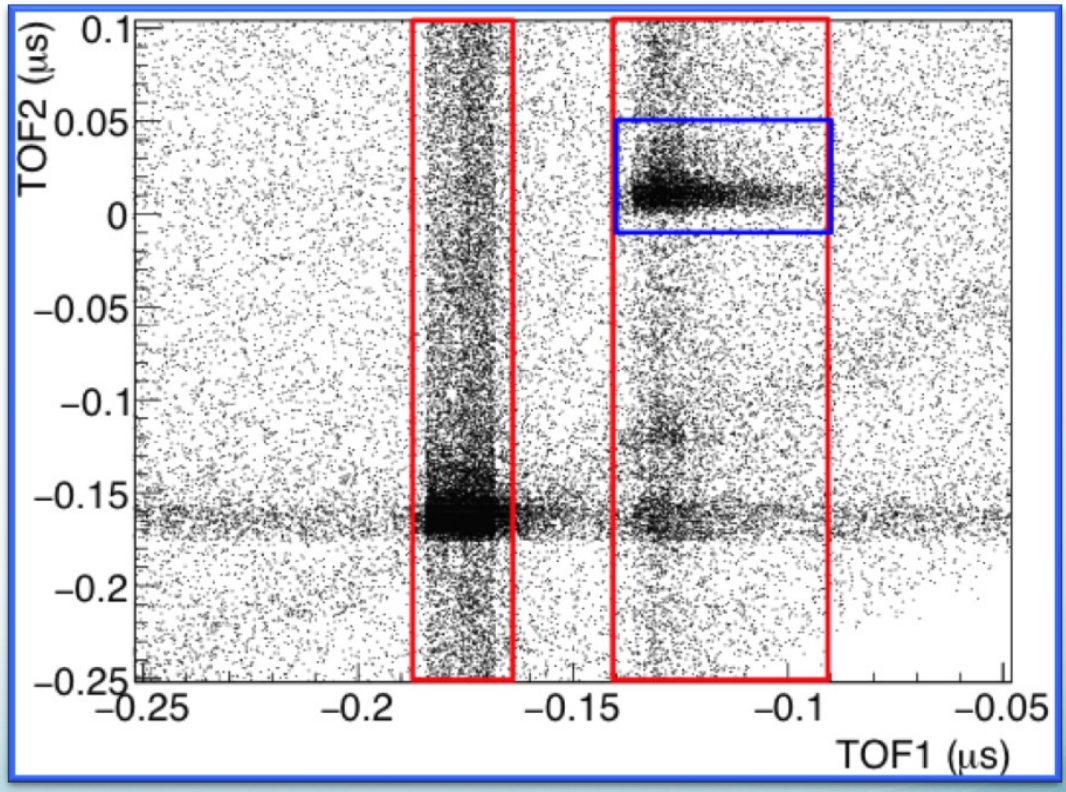
LiF neutrons (in NaI(Tl))

Horizontal band:

LiF gammas (in LS detectors)

Box (blue):

Neutron induced nuclear recoils!

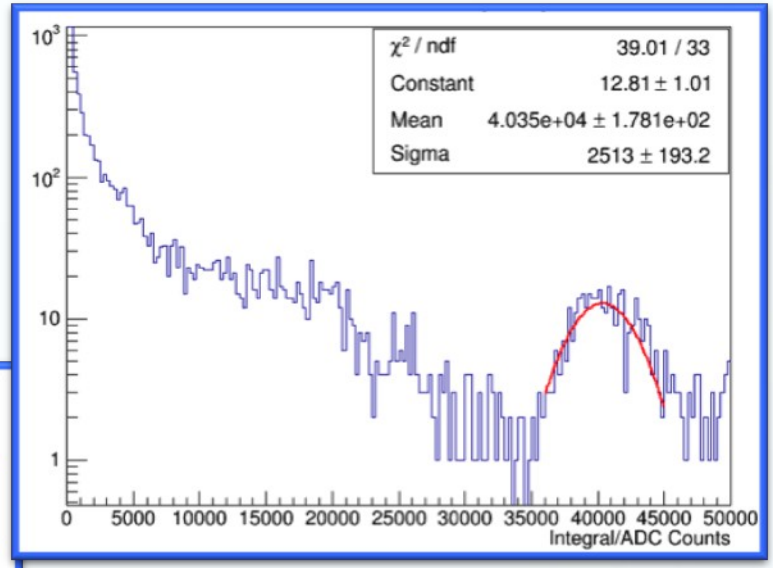


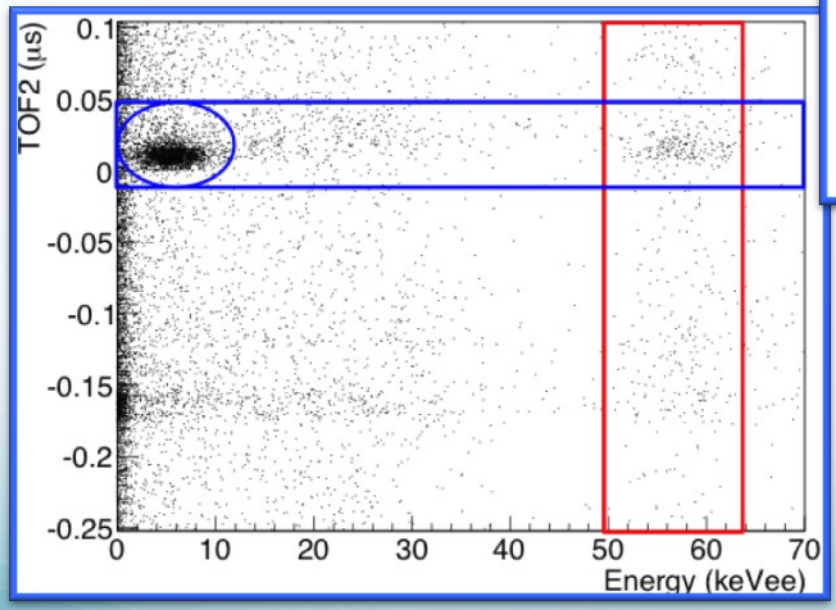
Energy calibration (in-run)

Neutron inelastic scattering on ^{127}I (57.6keV gamma)

Provide in-run energy calibration

Monitor and correct light yield





- **Advantages:**
  - In-run calibration
  - Uniform distribution in NaI(Tl)
  - Sharp peak

Neutron scattering simulation

Simulation package: Geant4.9.6.p3 (custom-built user interface)

80 processors x 300 hours = >10 billion neutron events (<4 degrees)

Hits recorded in NaI(Tl):

1.Na recoils

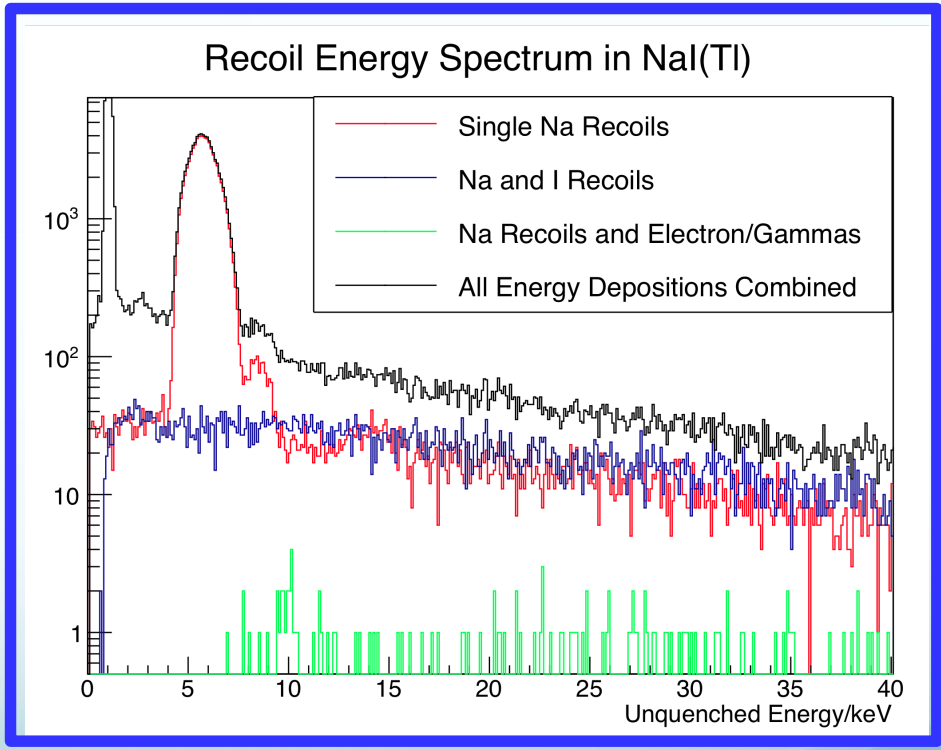
2.I recoils

3.Neutrons below production threshold

4.Gamma/e (inelastic)

5.Mixture of above

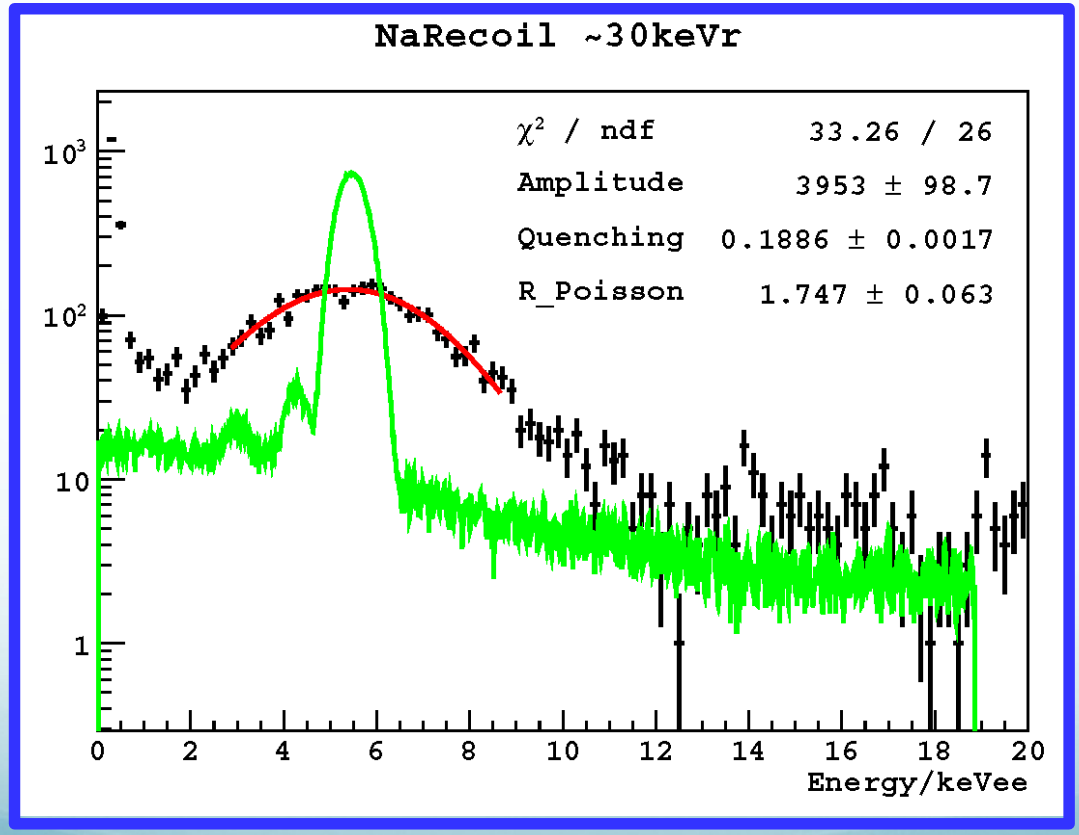
Single Na recoils dominate the signal region!



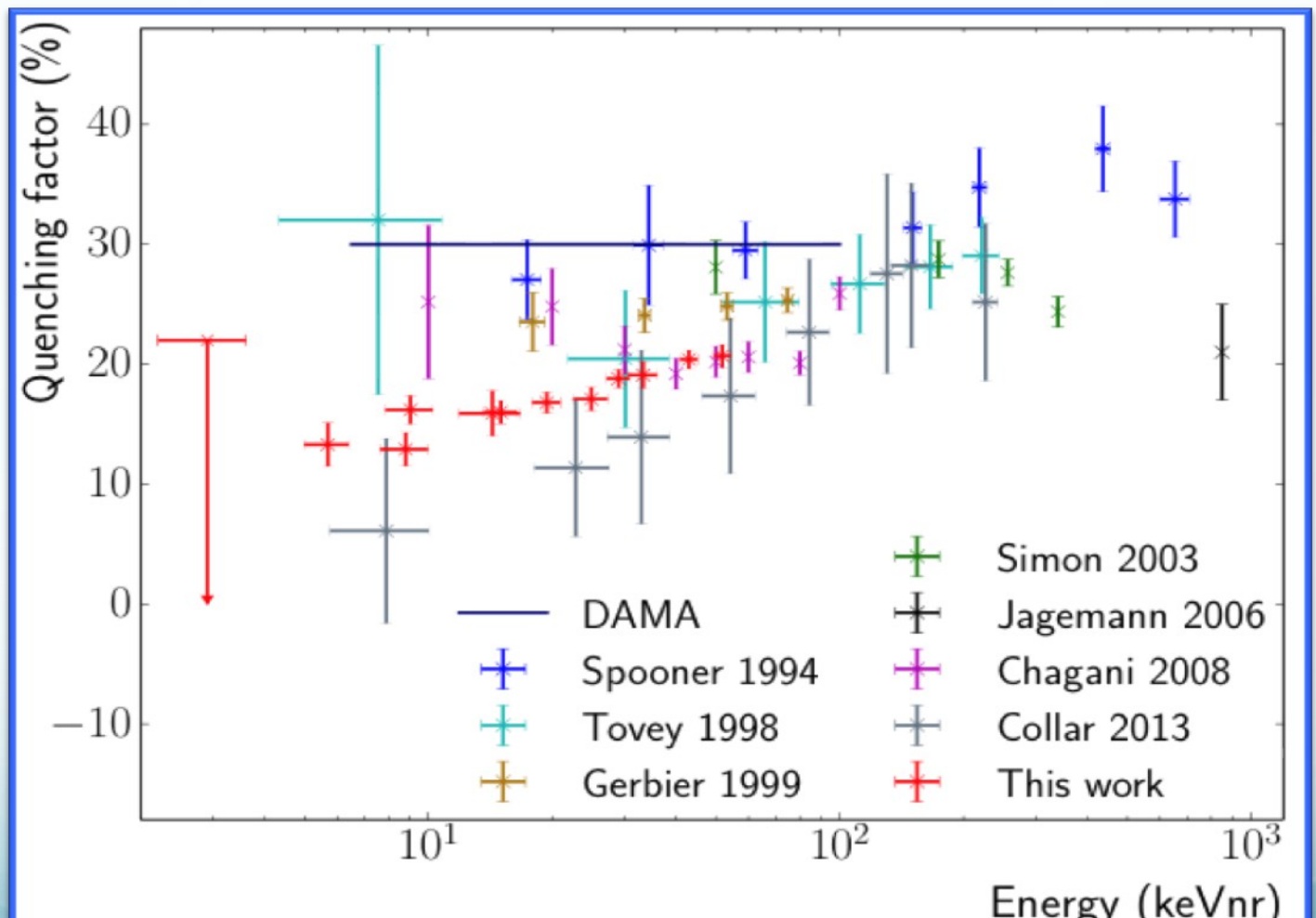
Quenching factor evaluation

Fit observed Na recoil spectra to simulation around the peak region.

Uncertainties will be discussed in details later.



Na quenching results

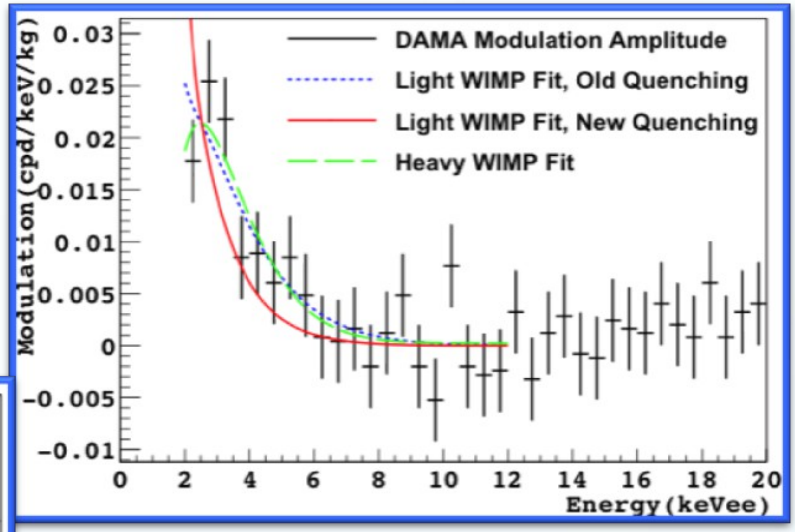


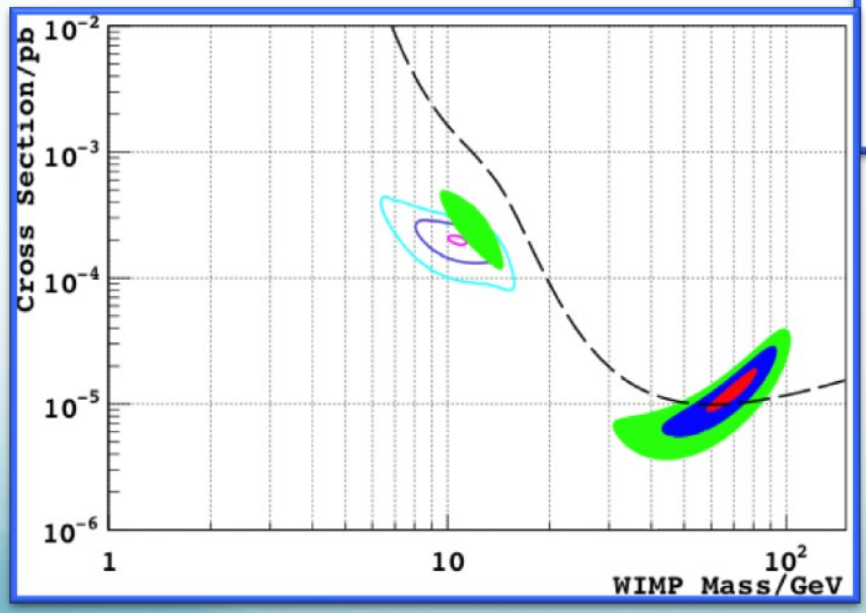
Implications of new Na quenching results

Light WIMP fit is disfavored.

χ_{min}/N.D.F. = 38/18, P < 0.01

DAMA/LIBRA signal is not compatible with the standard WIMP picture.





Best fit at high mass WIMP predicts a total rate higher than observed.

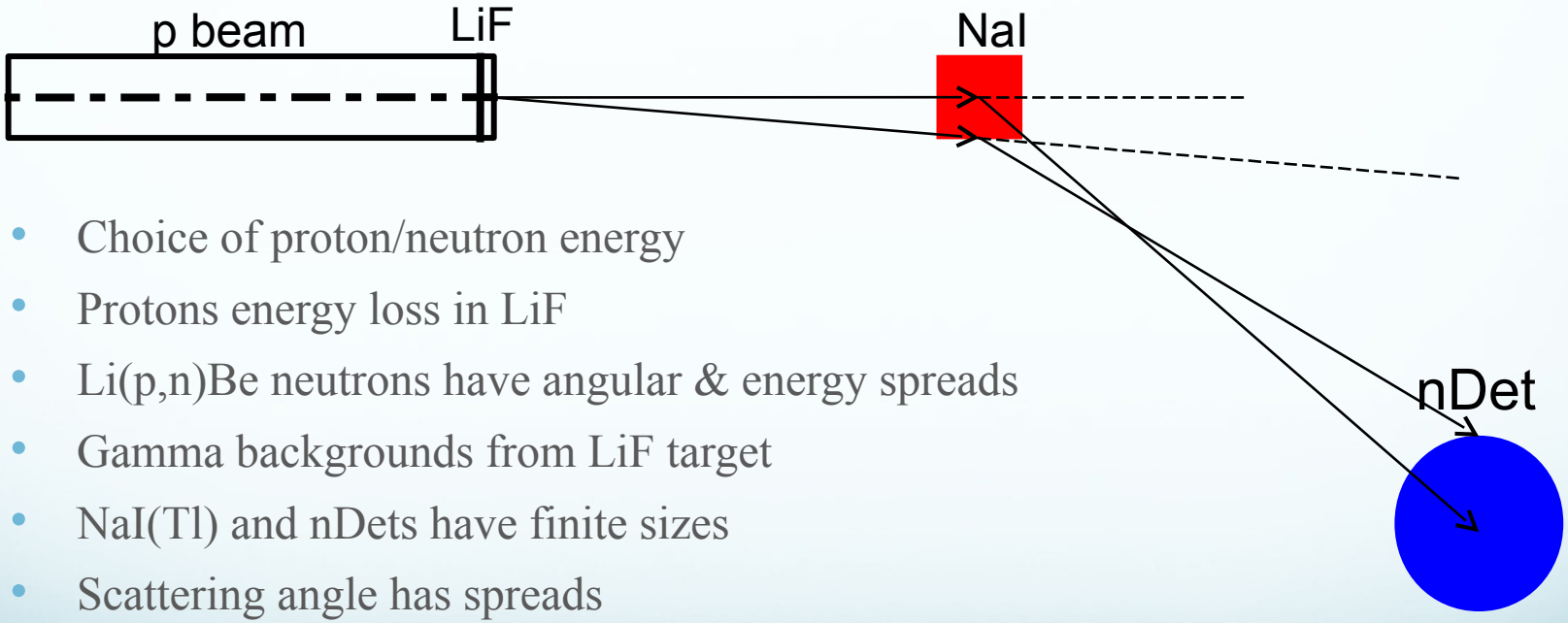
KIMS ruled out the DAMA/LIBRA heavy WIMP model-independently using CsI crystals.

Technical Discussions

Uncertainties in the measurement

1. Statistic uncertainties: event rate

2. Systematic uncertainties



- Choice of proton/neutron energy
- Protons energy loss in LiF
- Li(p,n)Be neutrons have angular & energy spreads
- Gamma backgrounds from LiF target
- NaI(Tl) and nDets have finite sizes
- Scattering angle has spreads
- Multiple scattering exists: Na, I, Na+Na, Na+I…
- Background event contaminations

Beam-related Uncertainties

Beam facility: Tandem accelerator at the Notre Dame University

Statistical uncertainty:

- Pulse intensity: ~ 60,000 protons/pulse (20nA)
- Proton energy chosen: 2.44 MeV (σ [p-n] & σ [n-Na])
- LiF target thickness: 0.52 mg/cm^2

Systematic uncertainties:

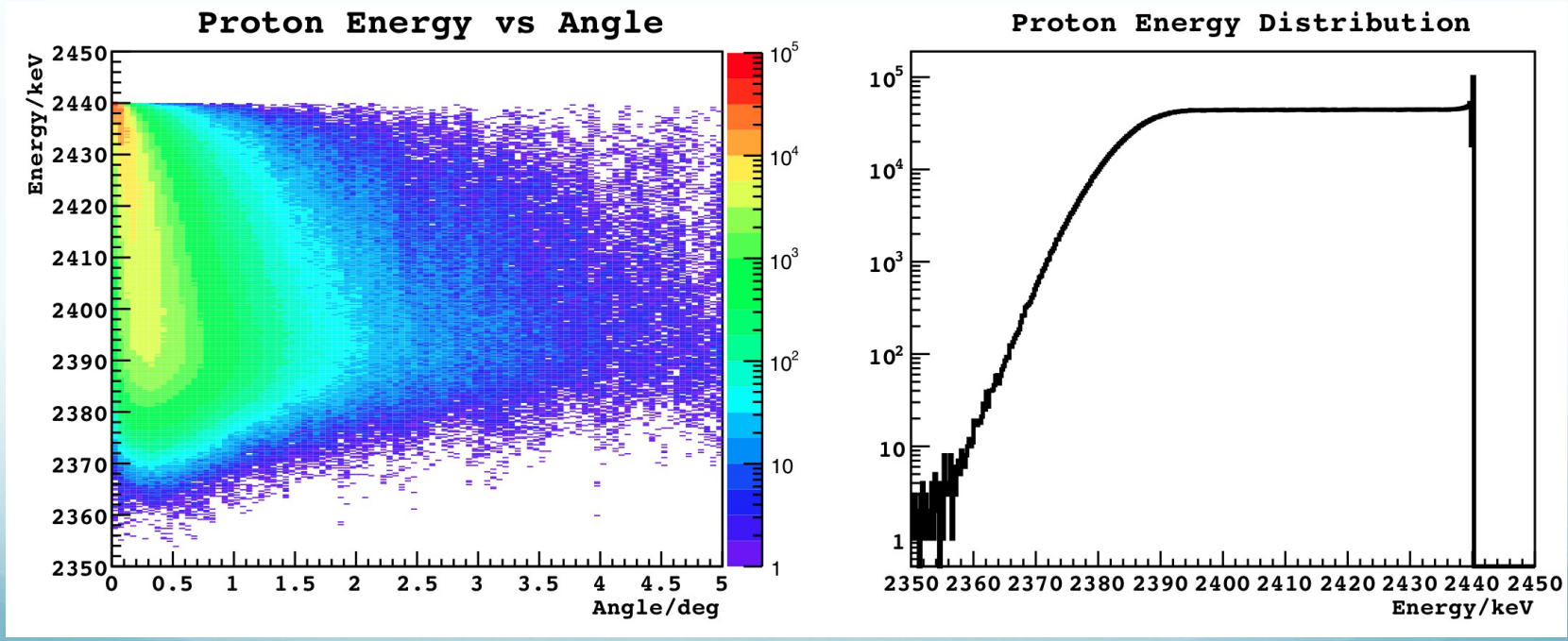
- Neutron energy spread (from LiF thickness): ~700+/- 35 keV
- Gamma background: Tantalum backing to absorb proton with low gamma production
- Pulse width: ~2ns (TOF uncertainty)
- Pulse period: 101.5 x N ns (N=6, 8) reduce pileups

Proton energy loss in LiF

Protons lose up to ~70 keV energy in LiF before Li(p,n)Be

Neutron energy: 700 +/- 35 keV

Simulation agrees with NIST pstar data

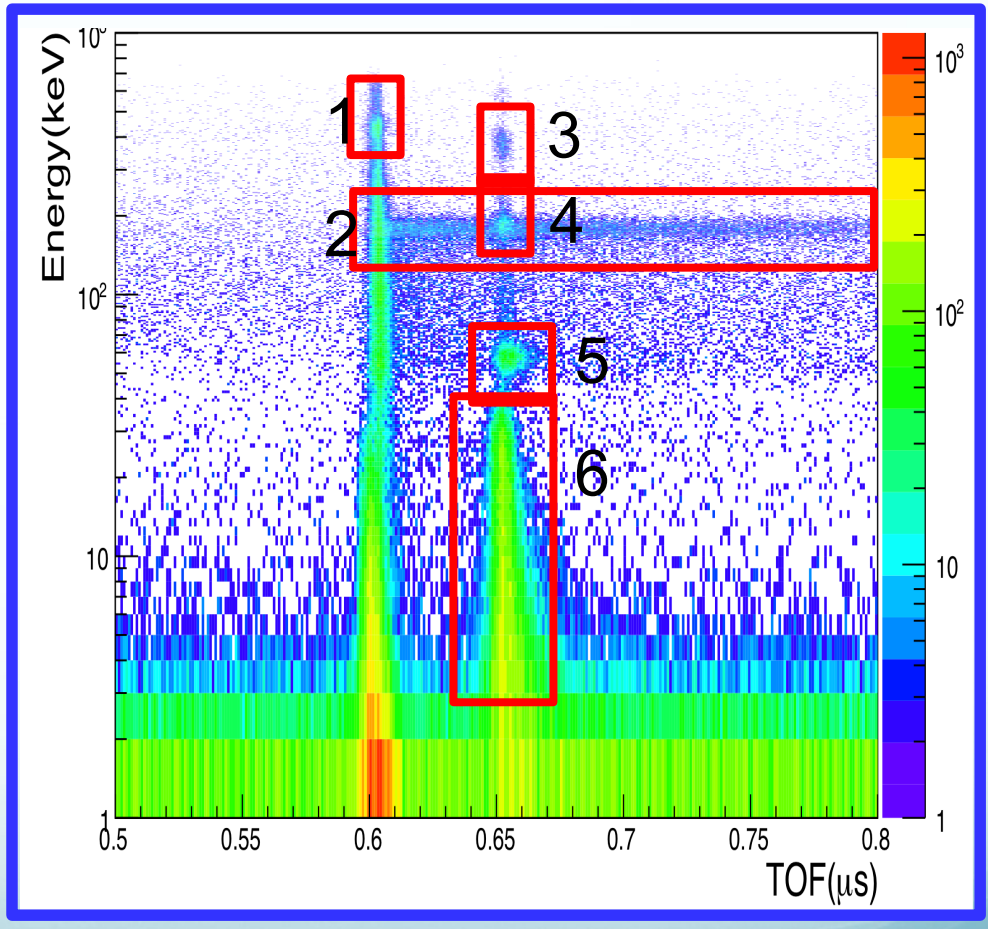


“Pure neutron scattering”?

Not only neutrons!

1. ^{7}Li excitation (478keV)
2. ^{19}F excitation (197keV, 89 ns half life)
3. ^{23}Na excitation (440keV)
4. ^{127}I excitation (203keV)
5. ^{127}I excitation (58keV)
6. ^{23}Na recoils

Continuous gamma background not labelled.

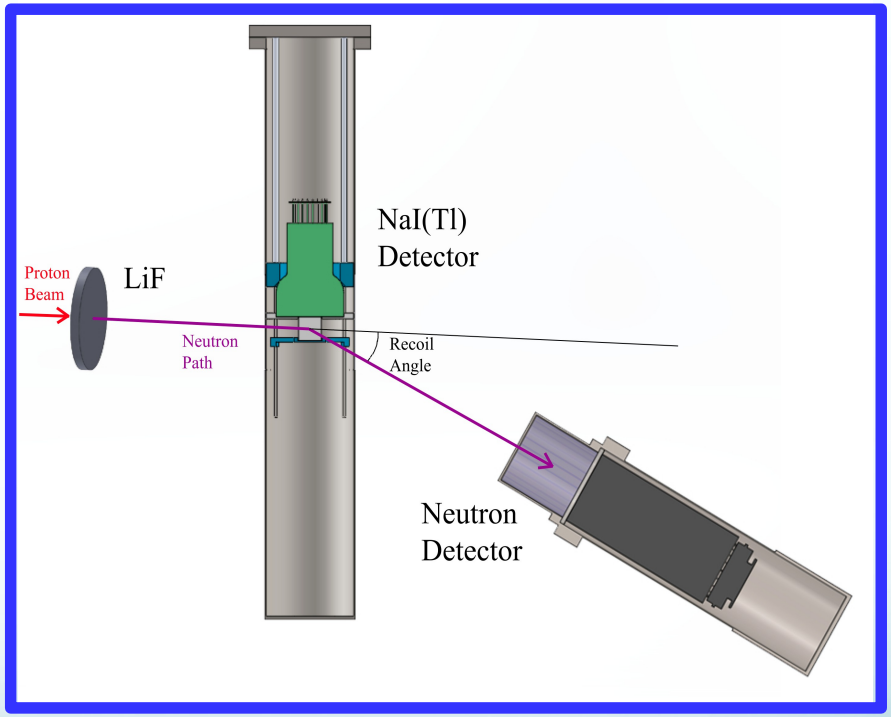


Detector-related uncertainties

Large NaI(Tl) crystals give high event rate but high uncertainty.

Uncertainty mitigations:

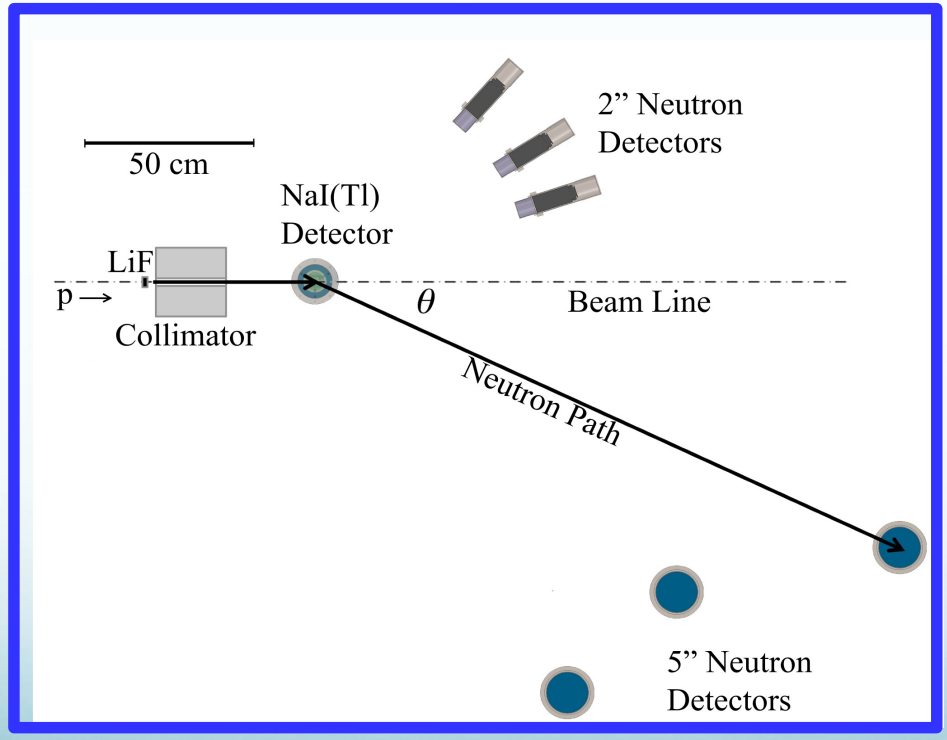
- 1” NaI(Tl) crystal
- 3” high Q.E. PMT
- High reflectivity reflectors
- Thin wall enclosure
- hollow supporting structure



Detector Layout uncertainties

Keep angular uncertainty at <5% while allowing high rate and TOF

- LiF – NaI(Tl) distance: 0.5m (1st run), 0.91m (2nd run)
- NaI(Tl) – nDet distance: ~0.5m (2” nDet) up to 2m (5” nDet)



Summary of Uncertainties

Uncertainties included in the final analysis:

1. Directly from spectral fit:

   ~1-3%

2. Varying spectral fit ranges:

   <3%

3. Light yield calibration:

   ~ 1.5% (57.6 keV ϒ)

4. Detector position:

   determined by kinematics, 3-12%

Overall uncertainty for Na recoil > 10 keVr: ~5% as expected

What we did right – Rate calculation

Factors to consider in the event rate calculation:

1. Proton beam luminosity, and pulse selector condition
2. Li(p,n)Be yield, LiF thickness
3. Li(p,n)Be neutron angular distribution
4. n – ^{23}Na scattering cross section
5. n – ^{23}Na scattering kinematics
6. LS detector neutron detection efficiency
7. Trigger/cut efficiencies

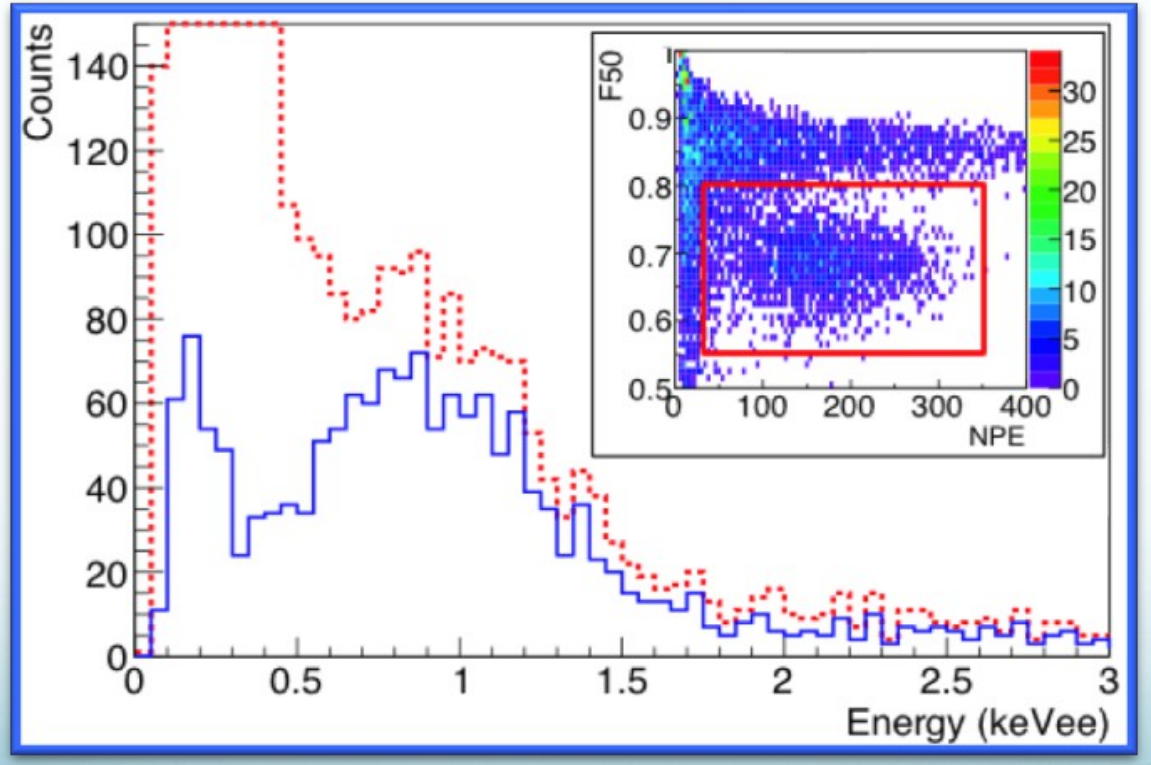
Our calculation was within a factor of 3 compared to observation!

We also managed to make the ~5% uncertainty measurement with 2 days of beam – a good compromise between rate and uncertainty.

What we did right – PSD in NDs

Low energy recoil spectrum suffers from noise.

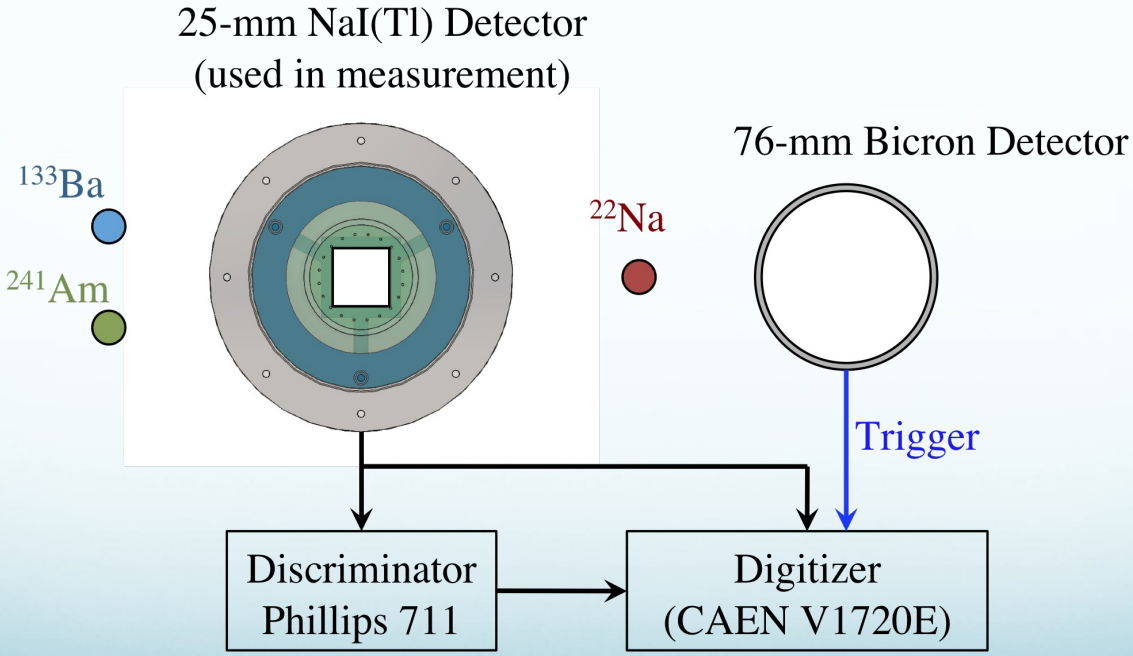
LS neutron detectors have good pulse shape discrimination capability!



What we did right – Trigger efficiency

Low energy events may not trigger the DAQ (~1.5 p.e. threshold)

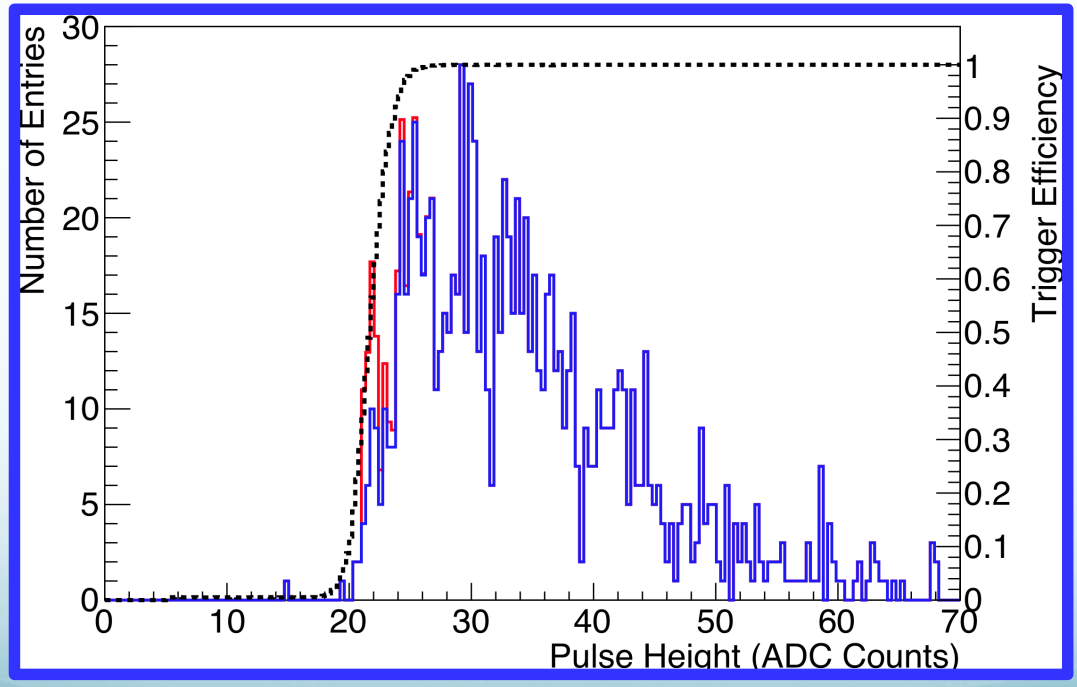
Method: to record NaI(Tl) pulses of variable heights together with the corresponding discriminator output.



What can be better – Trigger Threshold

Trigger threshold was limited by 1) low PMT gain (10 stage PMT chosen for high Q.E.) and 2) discriminator capability.

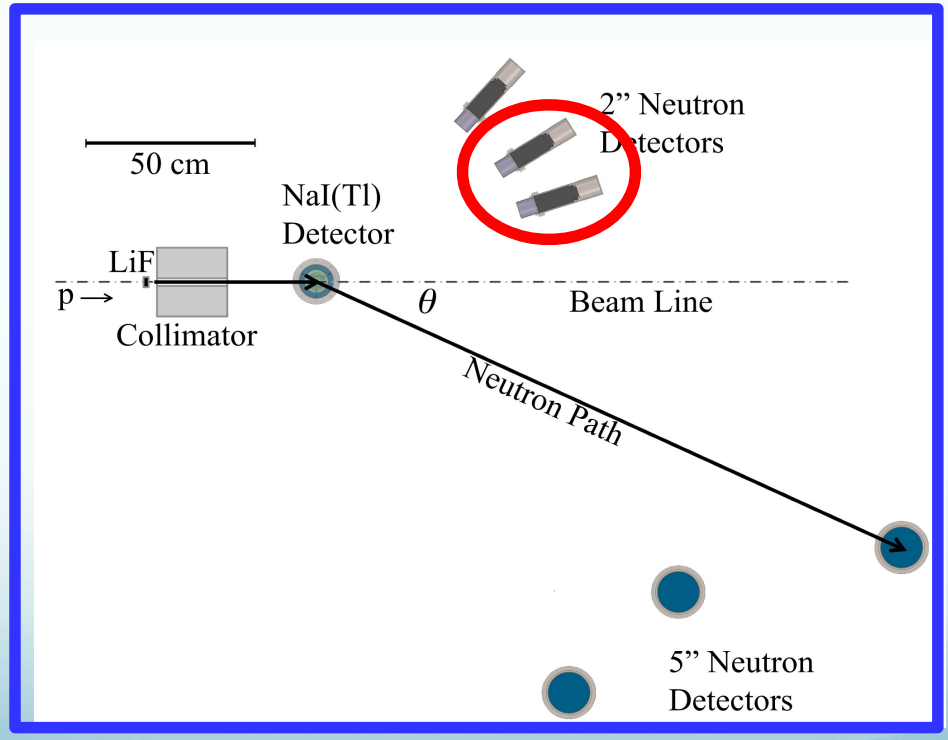
With a lower threshold, we may have observed 1) lower energy Na recoils, and 2) elastic I recoils (~5x lower recoil energy).



What can be better – Detector positions

Largest uncertainty in the measurement comes from

1. Uncertainties in the detector positions
2. Spread of scattering angle for small-angle scattering events



Conclusion

- Neutron scattering spectrometry is a powerful tool to calibrate detector response to nuclear recoils
- Neutron TOF is powerful in rejecting backgrounds
- Pulsed neutron facility can provide additional TOF
- Pulse shape analysis can select clean neutron events
- Multiple scattering needs to be suppressed as much as possible
- Monte Carlo simulations can be used to refine the kinematics

For more information, refer to:

Xu et al, Phys. Rev. C 92, 015807

http://dx.doi.org/10.1103/PhysRevC.92.015807

Backup Slides

Controversy about DAMA/LIBRA

Assumptions in standard WIMP sensitivity calculation:

- "Standard WIMP halo"
  - Local WIMP density ~0.3 GeV/cm^3 (perfect halo)
  - Only 1 WIMP species
  - Maxwellian velocity distribution (WIMPs in thermal equilibrium)
  - Galactic velocity (v_0~220 km/s, v_{esc}~600km/s)
  - …
- "Standard WIMP-nucleon interaction"
  - Equal cross section to protons and neutrons
  - May or may not have spin-exchange
  - Coherent scattering (nuclear form factor)
  - …

Which of these assumptions are known? NONE!

Model-independent test of DAMA/LIBRA is necessary.

Beam neutron generation

Database: Burke 1974 paper

1. Randomly sample proton energy and angle

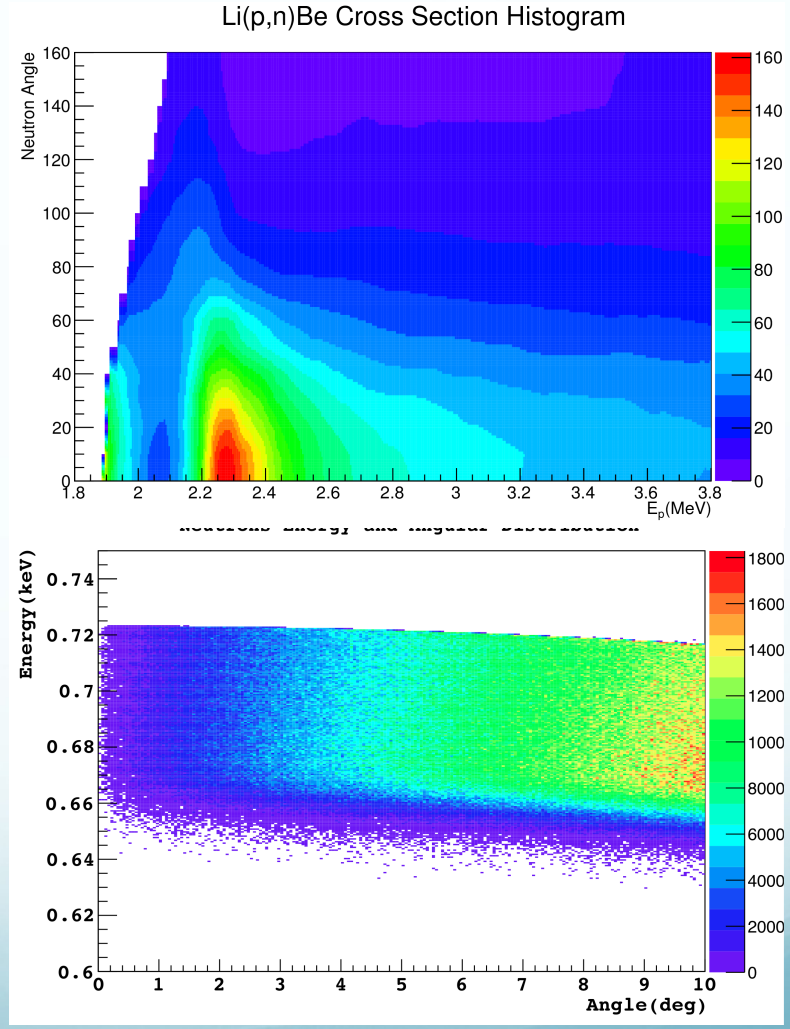
2. Randomly generate out-coming neutron angle

3. Calculate neutron energy

4. Weigh this neutron with the Li(p,n)Be cross section

Neutron energy has a similar ~70keV spread

Only simulate <4° neutrons (verified with simulations)



Electronics and DAQ

Trigger: NaI(Tl) && (Σ nDet)

Coincidence window: 400 ns, to include maximum TOF

Trigger threshold:

~1.5 photoelectron

Digitizer: CAEN V1720E, 250MS/s, 12 bit, loop buffer

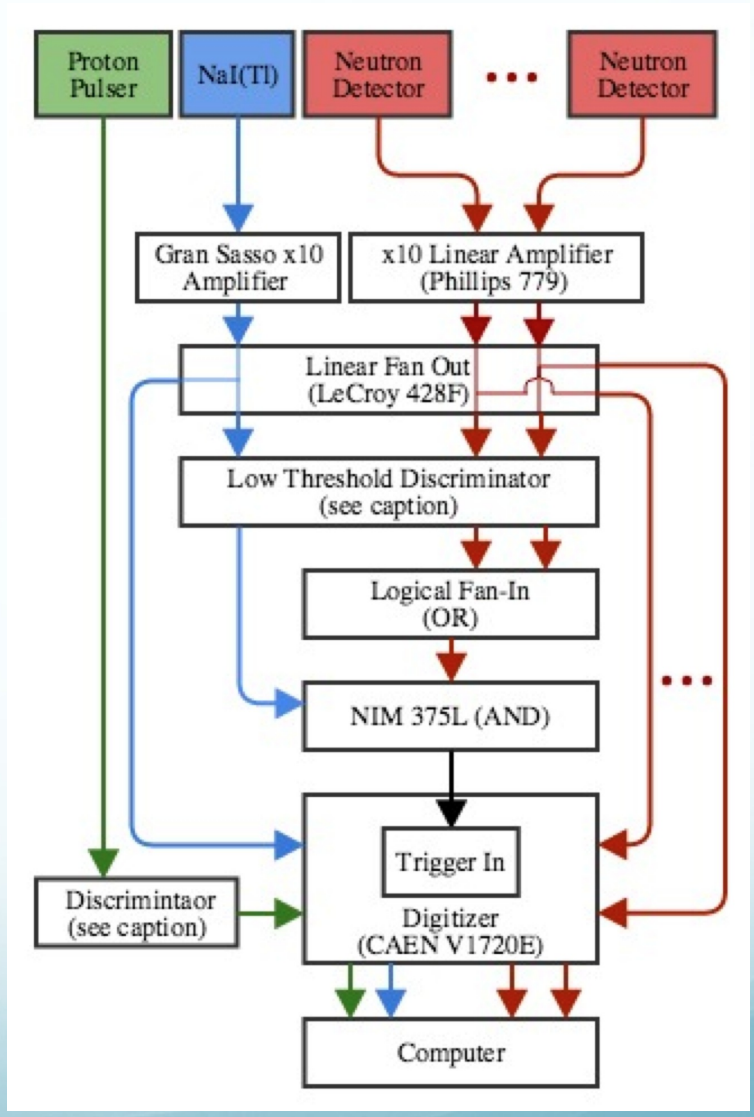
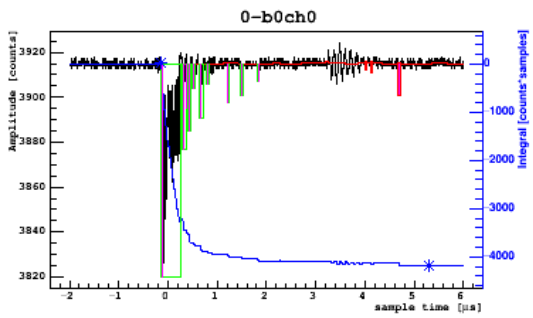
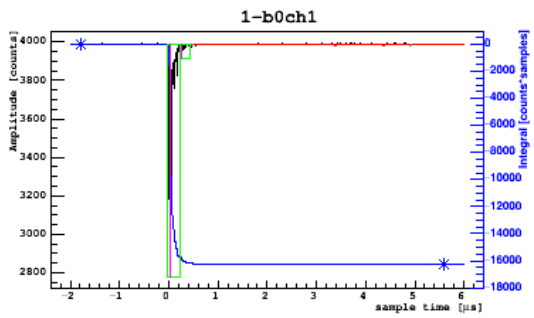
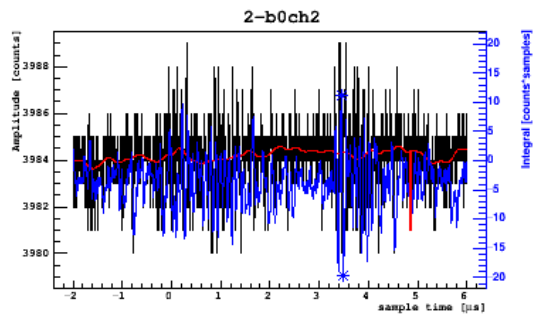
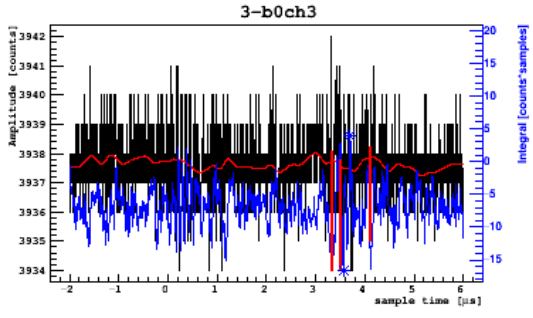
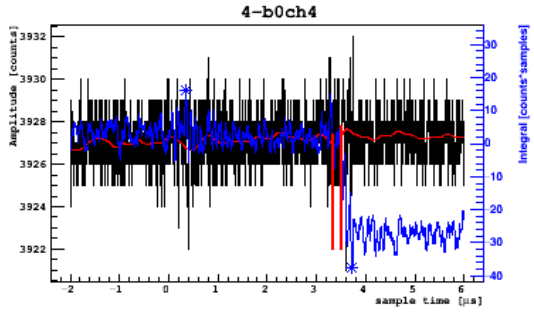
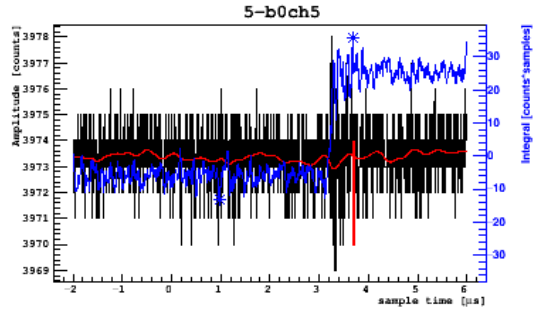
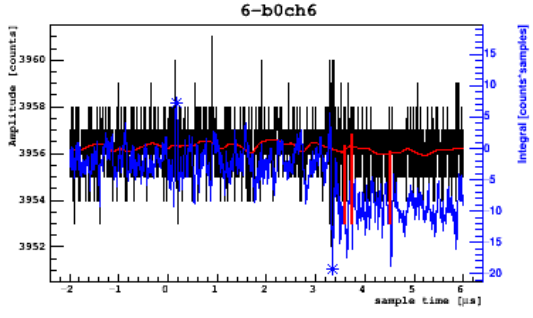
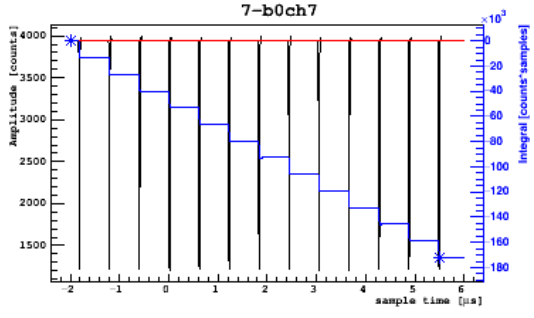
DAQ window: (-2, 6) μs

DAQ software: custom built

Online analysis:

TOF spectra

Energy spectra of coincidence events



Waveform example