WIMP dark matter searches by measuring X rays and γ rays

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For ICRR Seminar in March 7th

Thanks Prof. Moriyama


1. Search for WIMPs
2. X ray measurements
3. Gamma ray measurements
4. Concluding remarks
A view from the Ejiri-weekend house

DM WIMP's

- Dark energy 70%, DM 30 %, Baryonic matter 5 %.

$$\Omega_b = 0.0456 \pm 0.0015, \qquad \Omega_{\mathrm{CDM}} = 0.228 \pm 0.013, \qquad \Omega_\Lambda = 0.726 \pm 0.015$$

DM : mainly of cold DM WIMP's

- LSP Lightest SUSY Particle. Neutralino

DM WIMP's detection

- Detection of WIMP's is extremely hard.
-
- A. Cross sections & fluxes are small. $\sigma < 10^{-43} cm^2$
- SI Spin Independent σ(coherent) = A^2
- SD Spin dependent σ(coherent) = 1

B. Energy signals of recoil nuclei are low and smooth as BG/noise.

- Recoil E ~ 50 keV.
- Detected E ~ 2 keV with quenching.

Event properties for WIMPs and DBD

	DM WIMP 100 GeV	DBD ν 30 meV M=1.5
σ Xe	σ_p 10^{-45} cm^2 Low luminosity	σ 10^{-73} cm^2 High Luminosity
Rate (>Eth)	170 (40)/ t y	2.5 /t y
E(Quenched)	0-50 keV(1-2keV)*	2500 keV
Spectrum	Continuum*	Peak
Solar ν BG	1 /t y	0.6/t y if ΔE=50 keV
BG required	< 10/t y at a few KeV	0.5 / t y at a few MeV

New points: non-quenched & discrete peak

Noble methods to study low and rare WIMPs

- * Annular modulation of E-spectra :
- Small (% order) and subject to annular BG modulation

* Direction of recoil: Ton-scale detectors are hard：(Emulsion).

- * Present; X –γ rays from inelastic/elastic scatterings
-
- Non-quenched and descrete line spectrum
- .
-

A: Atomic electrons & X-rays with nuclear recoils

following WIMP/LSP nuclear interaction

H. Ejiri, Ch. C. Moustakidis, J.D. Vergados, PL. B639, 06, 218,

The role of ionization electrons in direct neutralino detection.

J.D. Vergados and H. Ejiri, PL B606 (2005) 305.

B: Nuclear inelastic γ SD Spin dependent WIMPs

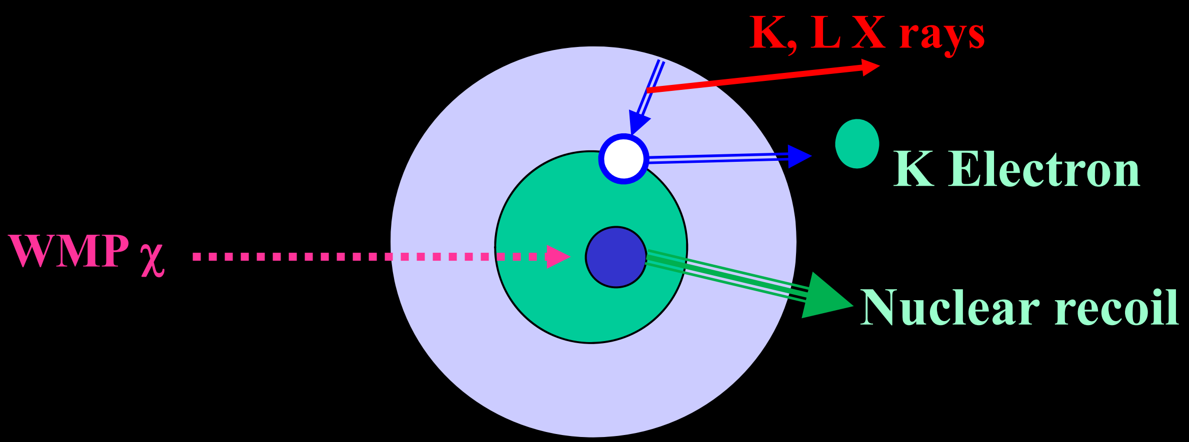
H.Ejiri, K. Fushimi, H. Ohsumi, Phys. Lette. B317 1993 14

J. Vergados, H. Ejiri , K.G. Savvidy Nucl. Phys. B 877 2013 36

2. X ray measurements

A sun rise view from the Ejiri-Yokohama

X ray opens a new experimental window



(i) inner-shell electrons are well excited through WIMPs nuclear interactions,

(ii) hard X-rays are emitted when inner-shell holes thus created are filled by outer-shell electrons and

(iii) exclusive measurements of such X-rays provide new excellent opportunities for high-sensitivity studies of WIMPs.

The differential cross section for the LSP nucleus scattering leading to the emission of electrons in the case of non-relativistic neutralino takes the form [25]

$$d\sigma(\mathbf{k}) = \frac{1}{\upsilon}\frac{m_e}{E_e}|M|^2 \frac{d\mathbf{q}}{(2\pi)^3}\frac{d\mathbf{k}}{(2\pi)^3}(2\pi)^3 \frac{1}{2(2l+1)} \times \sum_{nlm} p_{nl}\left[\tilde{\phi}_{nlm}(\mathbf{k})\right]^2 2\pi\delta\left(T_\chi + \epsilon_{nl} - T - \frac{q^2}{2m_A} - \frac{(\mathbf{p}_\chi - \mathbf{k} - \mathbf{q})^2}{2m_\chi}\right) \quad (1)$$

where υ, T_χ and $\mathbf{p}_\chi$ are the oncoming LSP velocity, energy and momentum distribution, while $\mathbf{q}$ is the momentum transferred to the nucleus. M is the invariant amplitude, known from the standard neutralino nucleus cross section, T and $\mathbf{k}$ are the kinetic energy and the momentum of the outgoing electron and ϵ_{nl} is the energy of the initial electron, which is, of course, negative. $\tilde{\phi}_{nlm}(\mathbf{k})$ is the Fourier transform of the bound electron wave function, i.e., its wave function in momentum space. p_{nl} is the probability of finding the electron in the n, l orbit. In the expression above and in what follows our normalization will consist of one electron per atom, to be compared with the cross section per nucleus of the standard experiments.

T is a function of k, thus Eq.1. gives a relation of q and k for given T and P of initial DM. Then one get k and T as a function of q

Unique features of X rays

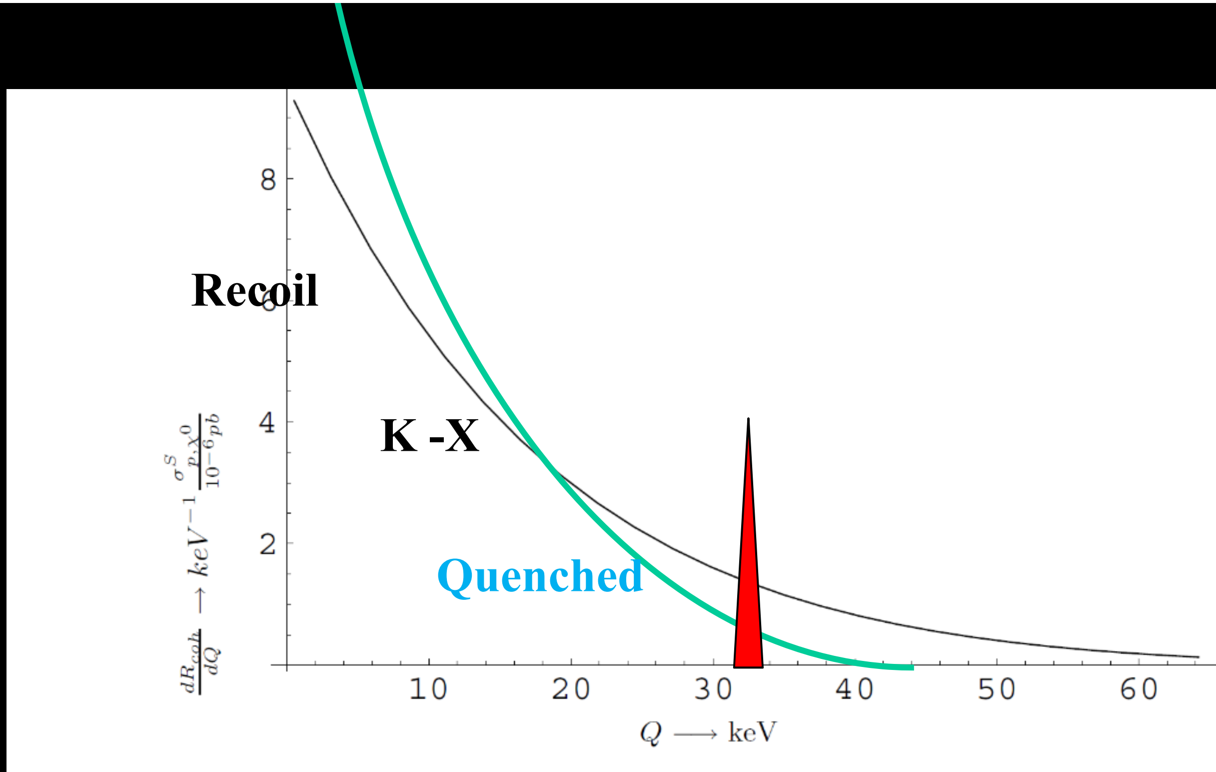


FIG. 2: We show the differential event rate dR_{coh}/dQ for the coherent process , as a function transfer, for a WIMP mass, m_χ, of 100 GeV in the case of ^{131}Xe.

1. Descrete line, non-quenched , at E(X) ~ 30 keV.
2. Well above E(threshold)~1-2 keV.
3. Peak yield is much larger than the continuum one spread over .
4. Production depends only on the WIMP recoil/momentum, not on the nuclear structure and WIMP properties of SI/SD.
5. Exclusive coincidence studies with recoil to be free from BG

Cross section ratios in case of 1 electron and Z=54 e in Xe for L/M/H=30 GeV, 100 GeV, and 300 GeV

Table 1
The binding energies and the inner-shell ionization ratios in WIMP nuclear interactions for ^{131}Xe. The inner-shell ionization rates, normalized to one electron per atom, relative to the nuclear recoil rates are given in the 3–5 columns, and the inner-shell cross-sections relative to the nuclear recoil cross-sections are in the 6–8 columns

$n\ell$	$-\epsilon_{n\ell}$ keV	$[\frac{\sigma_{n\ell}}{\sigma_r}]_L$	$[\frac{\sigma_{n\ell}}{\sigma_r}]_M$	$[\frac{\sigma_{n\ell}}{\sigma_r}]_H$	$[\frac{Z\sigma_{n\ell}}{\sigma_r}]_L$	$[\frac{Z\sigma_{n\ell}}{\sigma_r}]_M$	$[\frac{Z\sigma_{n\ell}}{\sigma_r}]_H$
1s	34.56	0.0006	0.0041	0.0047	0.034	0.221	0.255
2s	5.45	0.0224	0.0271	0.0271	1.211	1.461	1.463
2p	4.89	0.0703	0.0834	0.0836	3.796	4.506	4.513
3p	0.96	0.1017	0.1050	0.1050	5.492	5.670	5.670
3d	0.68	0.1734	0.1775	0.1775	9.364	9.585	9.585

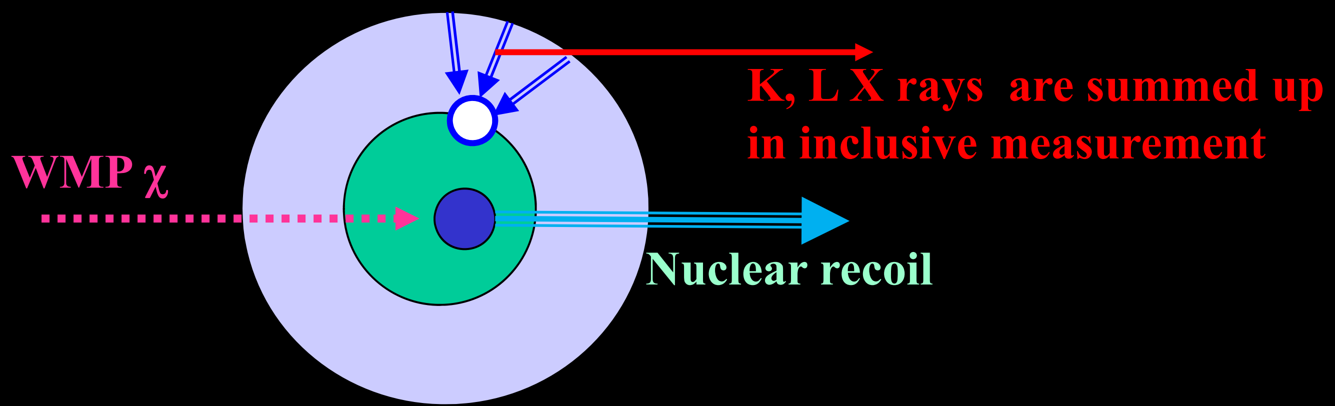
Large number of inner-shell holes/X-rays, K=2 and L=6 .
K X rays if K hole is not 0 and 2s-2p electrons are not 0.

Table 2

K X-ray rates and energies in WIMPs nuclear interactions with ^{124}Xe. $[\sigma_K/\sigma_r]_L$, $[\sigma_K/\sigma_r]_M$ and $[\sigma_K/\sigma_r]_H$ are the ratios for light (30 GeV), medium (100 GeV) and heavy (300 GeV) WIMP's.

K X-ray	$E_K(K_{ij})$ keV	$B_K(K_{ij})$	$[\frac{\sigma_K(K_{ij})}{\sigma_r}]_L$	$[\frac{\sigma_K(K_{ij})}{\sigma_r}]_M$	$[\frac{\sigma_K(K_{ij})}{\sigma_r}]_H$
$K_{\alpha 2}$	29.5	0.284	0.0086	0.0560	0.0645
$K_{\alpha 1}$	29.8	0.527	0.0160	0.1036	0.1196
$K_{\beta 1}$	33.6	0.154	0.0047	0.0303	0.0350
$K_{\beta 2}$	34.4	0.034	0.0010	0.0067	0.0077

Sum of 4 K X-rays after fluorescence ratio of 89 %are 0.025 for 30 GeV and 0.22 for 300 GeV



Experiment inclusive

B. Recoil and K shell ionization 5-20 % for 50-300 GeV

E=Er + Ek, Ek=K shell binding energy ~30 keV

Measured E=QEr+Ek Q=Quenching factor

= Q(E-Ek) +Ek = QE + Ek(1-Q) shift

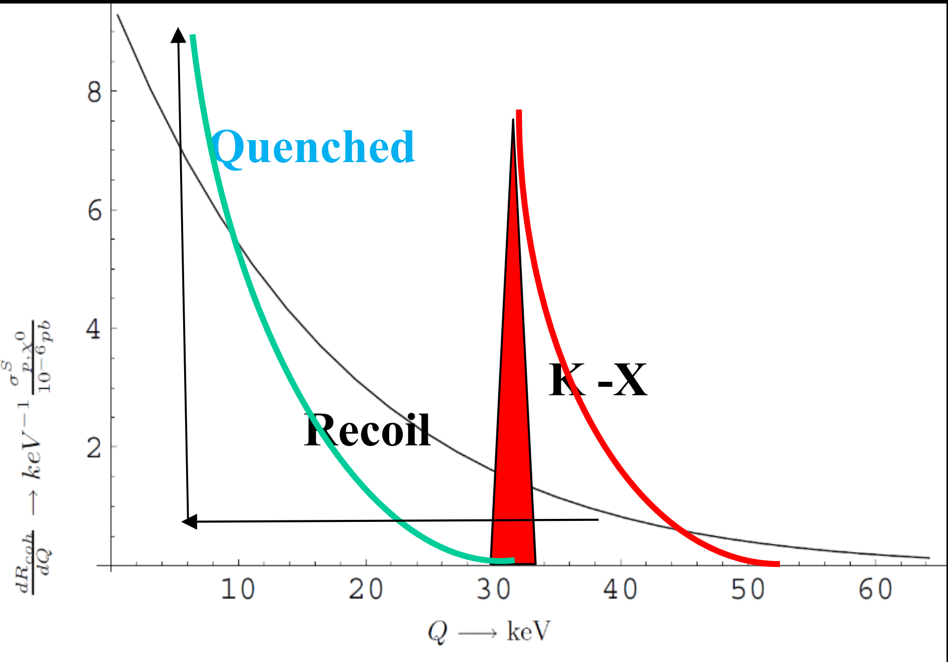


FIG. 2: We show the differential event rate dR_{coh}/dQ for the coherent process , as a function transfer, for a WIMP mass, m_χ, of 100 GeV in the case of ^{131}Xe.

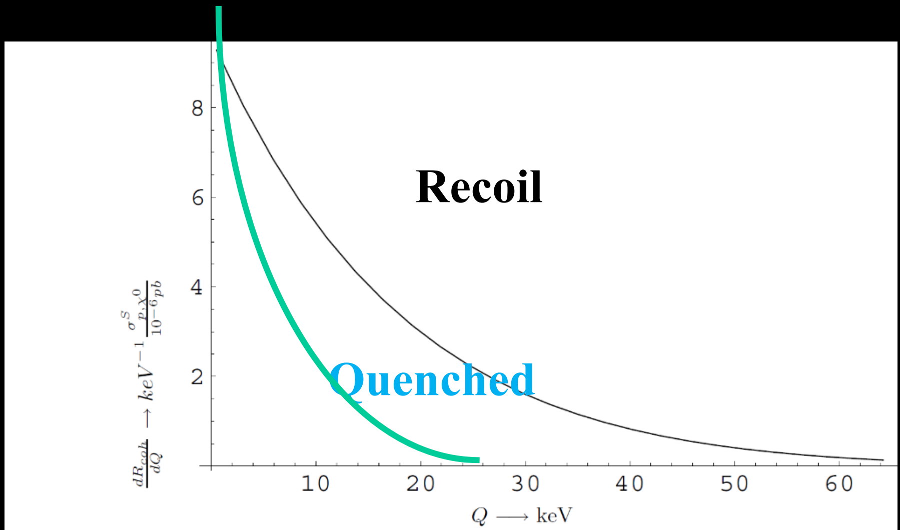
Experiment (exclusive)

B. Recoil and K shell ionization

E=Er + Ek, Ek=K shell binding energy

E=QEr and Ek Q=Quenching factor Er is small by Ek

Emulsion, Tracking chamber, Plastic fiber, ets



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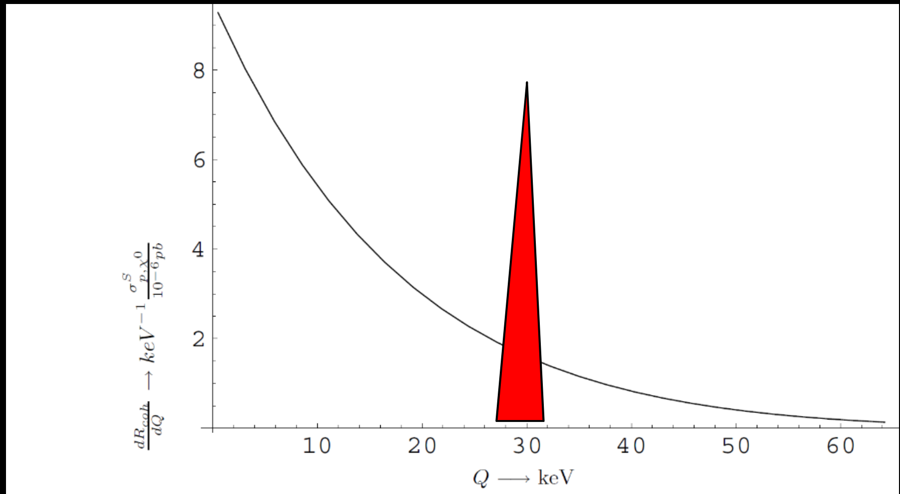


FIG. 2: We show the differential event rate dR_{coh}/dQ for the coherent process , as a function transfer, for a WIMP mass, m_χ, of 100 GeV in the case of ^{131}Xe.

BG consideration

1. Solar ν : Same, but more for lighter DM with smller recoils.

   Solar ν recoil + K X ray

2. Neutrons: Same , but fast neutrons are by active PL shield

   Neutron recoil + K Xray

3. RI β–γ continuum: No sharp rise at E(K)

Solar ν

Vergados Ejiri
Nucl. Phys. B
804 2008 144

Comparison of the event rates for boron solar neutrino detection with those of WIMP detection rate latter we assumed a nucleon cross section independent of the mass. The kinematics were obtained as masses, namely 100 and 300 GeV. NoFF means that the nuclear form factor was neglected

Target	$R_\chi\,(\text{kg yr}) \times \frac{\sigma_N}{10^{-9}\text{ pb}}$ $m_\chi = 100$ GeV	$R_\chi\,(\text{kg yr}) \times \frac{\sigma_N}{10^{-9}\text{ pb}}$ $m_\chi = 300$ GeV	R_ν (kg yr)
Full range			
^{131}Xe	0.167	0.060	0.934×10^{-3}
^{32}S	0.033	0.014	0.167×10^{-3}
$2\text{ keV} \leqslant T_A \leqslant 4\text{ keV}$			
^{131}Xe	0.018	0.010	0.308×10^{-5}
^{32}S	0.0012	0.0006	0.367×10^{-4}

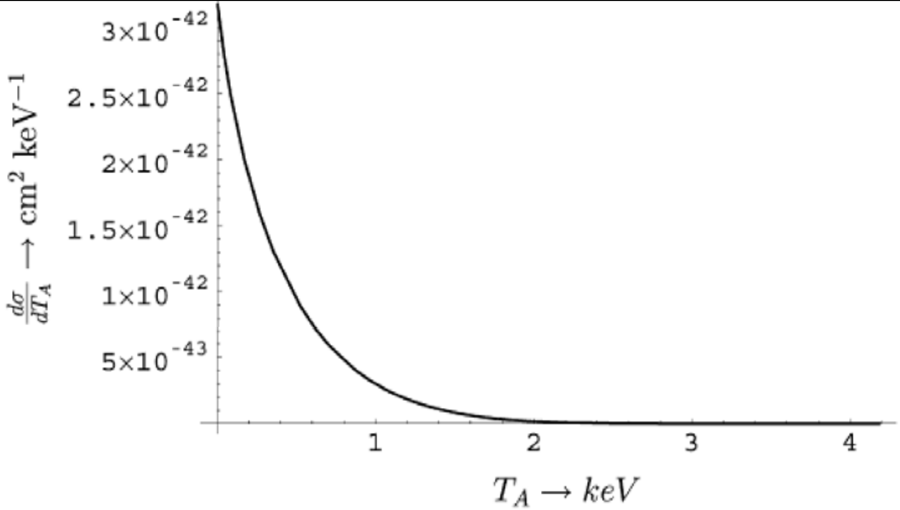


Fig. 5.12. The neutrino induced differential cross section in units $\text{cm}^2\,\text{keV}^{-1}$ as a function of the recoil energy in keV in the case of the target ^{131}Xe. Note that essentially all the contribution comes from the recoil energy region $0 \leqslant T_A \leqslant 1$ keV. The effect of the form factor is invisible in the figure.

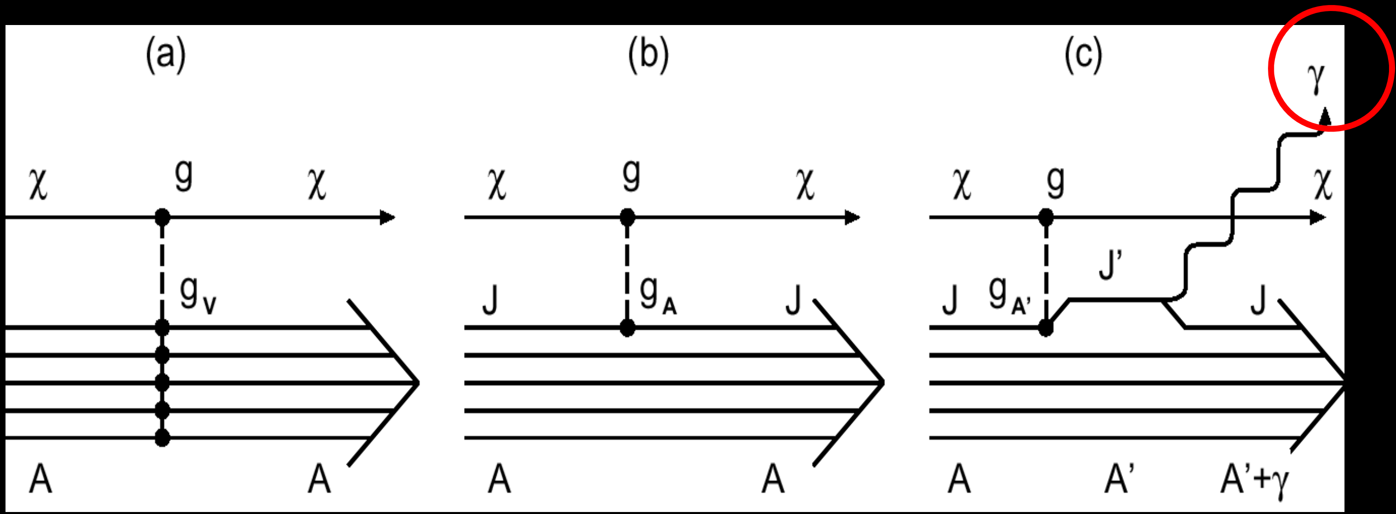
Gamma rays from inelastic WIMP scattering

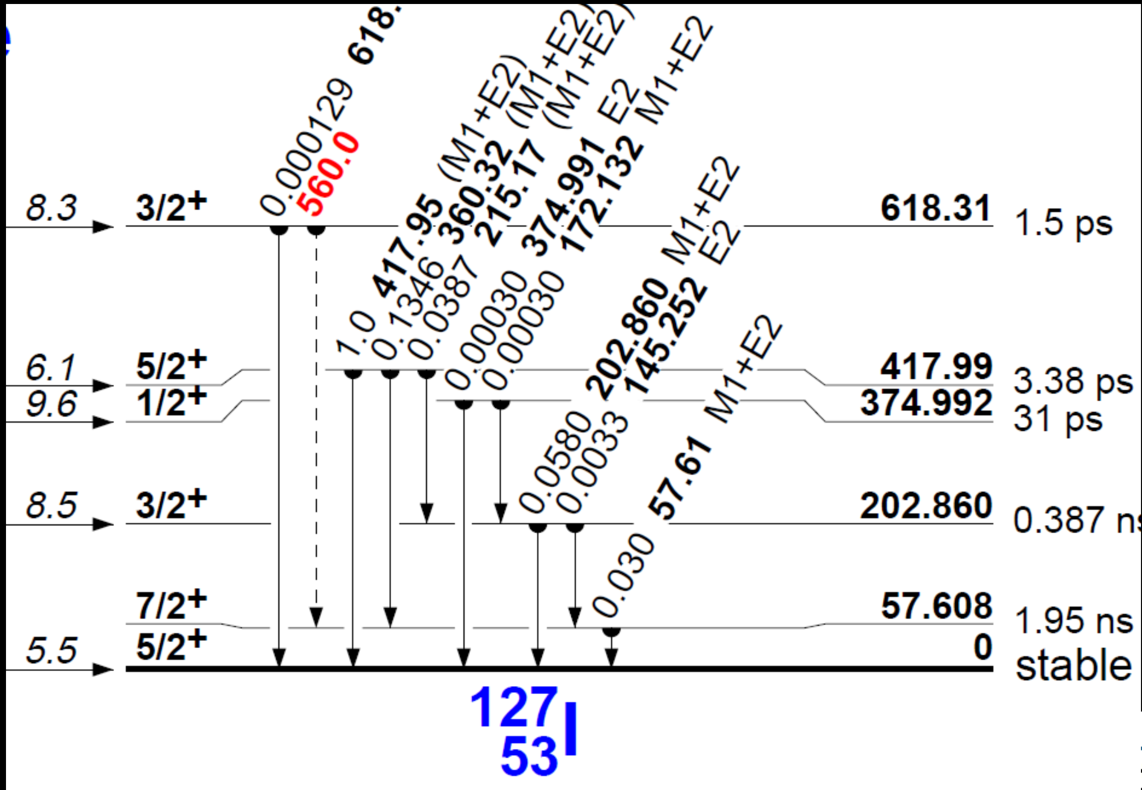
II. Nuclear inelastic γ rays

H.Ejiri, K. Fushimi, H. Ohsumi, Phys. Lette. B317 1993 14

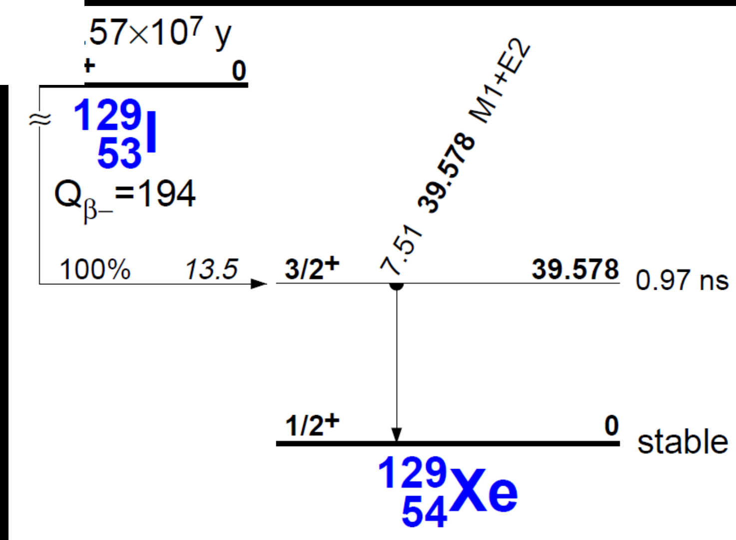
J. Vergados, H. Ejiri , K.G. Savvidy Nucl. Phys. B 877 2013 36

1. Larger signals~ 50 keV than quenched recoil signals
2. Sharp peak at $E\gamma$=58 keV and 40 keV in case of ^{127}I and ^{129}Xe.
3. Incoherent much smaller (10^{-5}) cross-section for spin-coupled DM





100 %



26.4 %

Inelastic NMEs : Toivanen Kotelainen Suhonen
Int. J. mod. Phys. E 14 (2005) 751

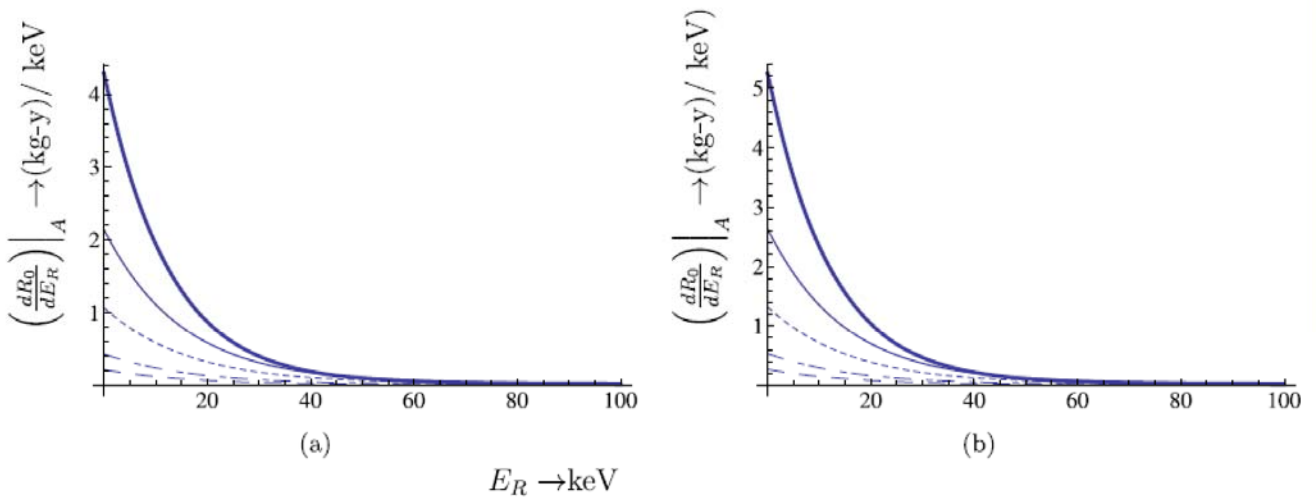


Fig. 2. We show the time average differential rate $\frac{dR_0}{dE_R}|_A$, as a function of the recoil energy E_R in keV for elastic scattering. These results correspond to the spin mode in the case of ^{127}I (a) and ^{129}Xe (b). The graphs from top to bottom correspond to WIMP masses (50, 100, 200, 500, 1000) GeV. The escape velocity was taken to be $\upsilon_{\rm esc} = 2.8\upsilon_0$. The effect of quenching has not been included.

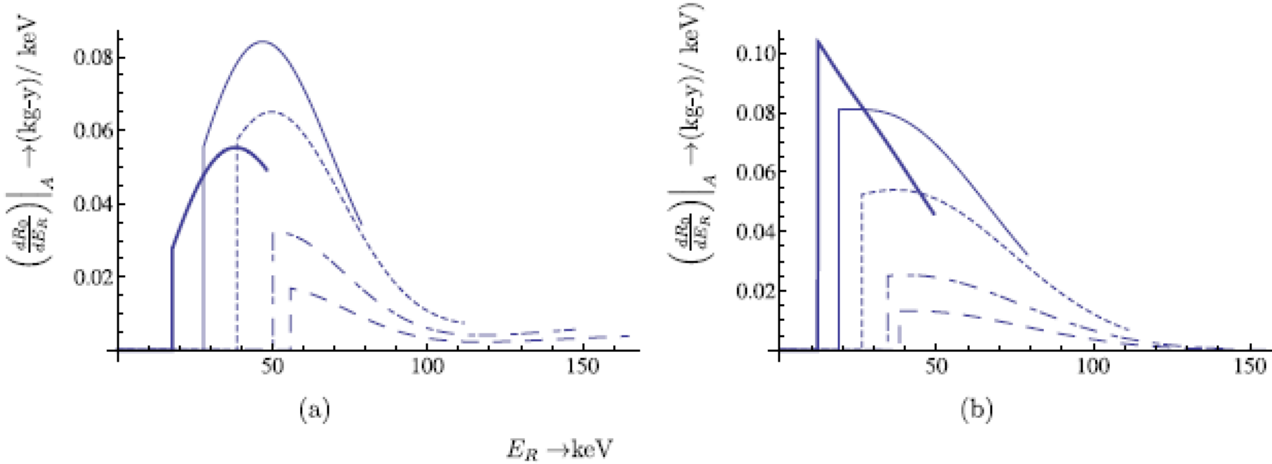


Fig. 4. The same as in Fig. 2 in the case of the inelastic scattering.

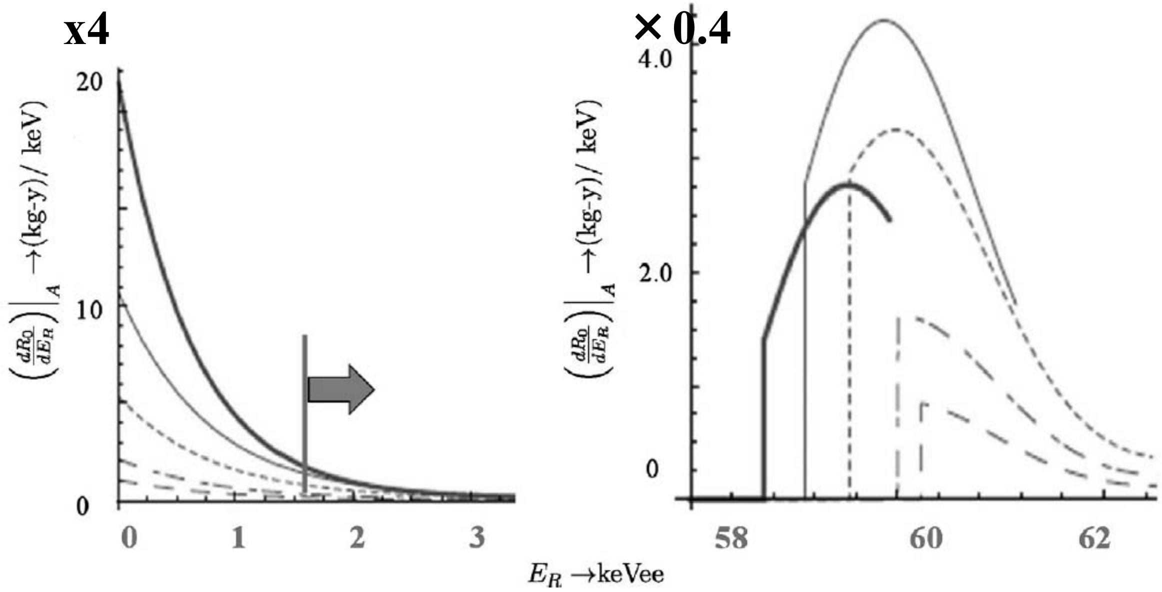
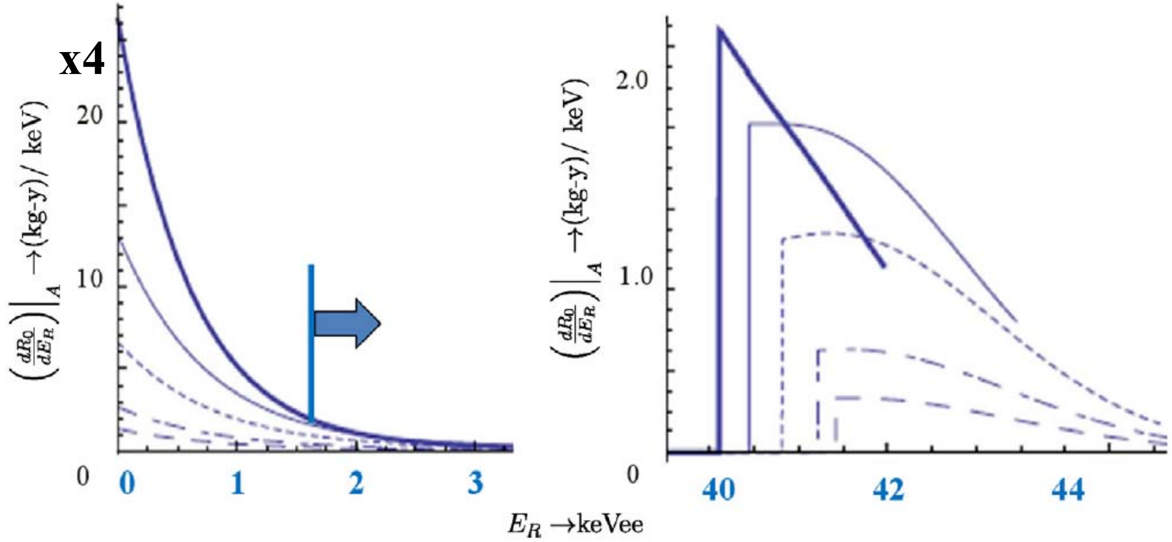
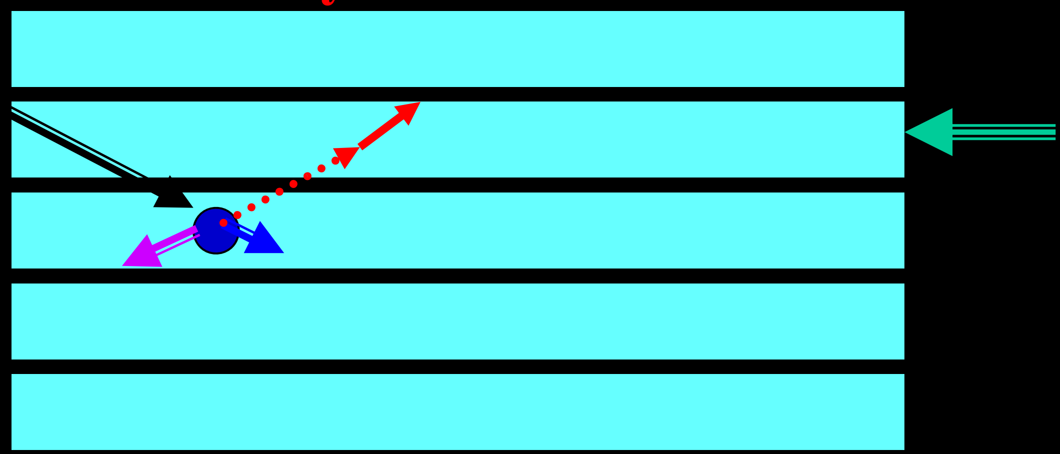


Fig. 8. Energy spectrum for WIMP ^{127}I elastic scattering (left panel) and that for the 57.6 keV excited state inelastic scattering (right panel). The quenching factor is $Q = 0.05$ and the energy threshold is $E(th) = 1.6$ keV. The x and y scales are the electron-equivalent energy and the rate per unit electron equivalent energy.



Exclusive study of X rays in coincidence with nuclear recoil



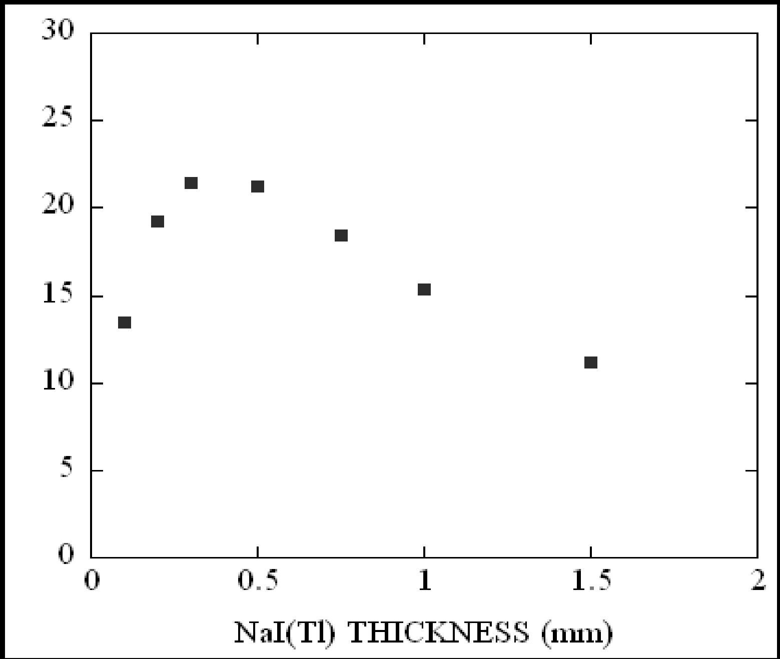
Long flight pass, K: 0.1 gr, L: 0.01 gr.

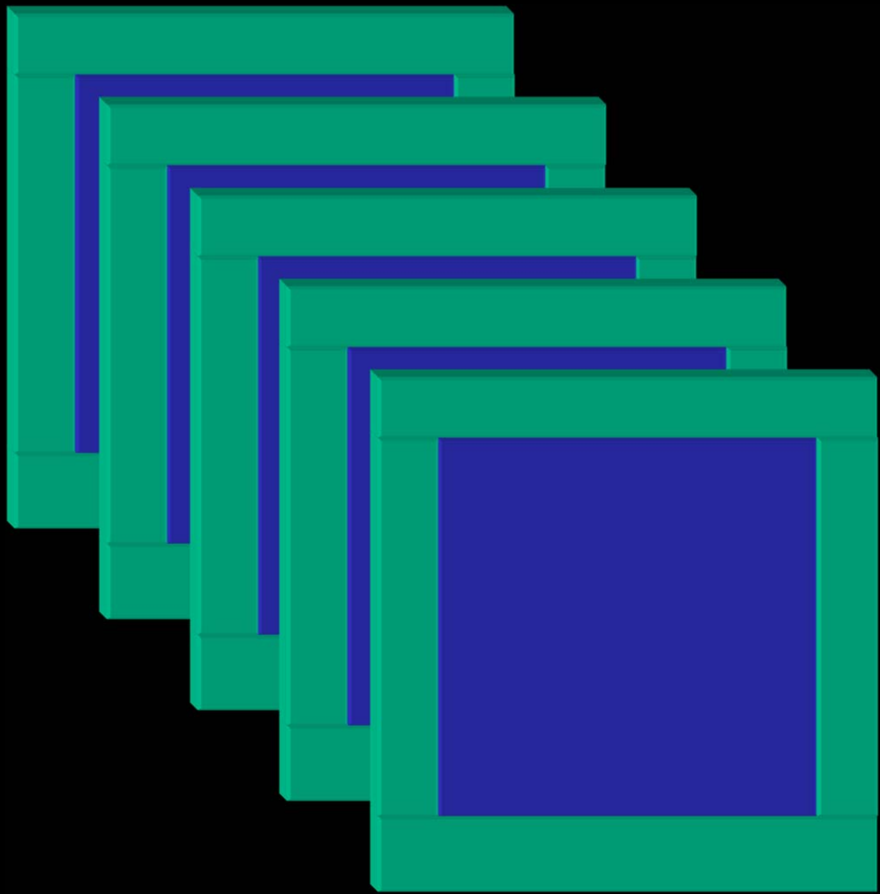
Exclusive coincidence measurements of X-rays and nuclear recoils.

Muliti-layers of thin NaI plates

Fushimi et al Tokushima Osak

- NaI 500 μm x 50 mm x 50 mm
- LG 500 μm x 60 mm x 60 mm
- 16 modules (phase 1 present)
- 256 modules (phase 2)
- Sensitivity ~ 1 GeV /cc
- one order improvement.





57 keV γ efficiency at n+1 th NaI when recoil at n th NaI

Concluding Remarks

1. E-spectrum of nuclear recoils from WIMPs (LSP) is of low-E continuum like BG, being hardly identified by inclusive studies.
2. Atomic electron ionization in WIMP nuclear interactions provides noble methods for high-sensitive WIMP studies.

   The ionized electrons with E ~ keV can be studied in TPC.
3. K X-rays with 30 keV in I-Xe detectors are measured exclusively in coincidence with nuclear recoils by a multi-layer thin (~300 μ m) NaI array.
4. The inclusive measurement of the E-shifted sharp-rise spectrum is a new high sensitivity WIMP search.
5. Exclusive and inclusive measurements of γ following inelastic scattering of WIMPs are very sensitive for SI.

6. MOON (Multi-later NaI-scitillators Observatory Of Neutralinos)
   MOON(Multi-layer PL-scintillator Observatory Of Neutrinos) f


Thank you for your attention
Ejiri-weekend house at Shounan