The Progress of the DAMA experiment

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The Dark Side of the Universe: experimental evidences ...

First evidence and confirmations:

1933  F. Zwicky: studying dispersion velocity of Coma galaxies
1936  S. Smith: studying the Virgo cluster
1974  two groups: systematical analysis of mass density vs distance from center in many galaxies

Other experimental evidences

✓ from LMC motion around Galaxy
✓ from X-ray emitting gases surrounding elliptical galaxies
✓ from hot intergalactic plasma velocity distribution in clusters

\[ M_{\text{visible Universe}} \ll M_{\text{gravitational effect}} \implies \text{about 90% of the mass is DARK} \]
Primordial Nucleosynthesis

∼ 90% of the matter in the Universe is non baryonic

A large part of the Universe is in form of non baryonic Cold Dark Matter particles

The Universe is flat

\[ \Omega = \Omega_M + \Omega_\Lambda = 1.02 \pm 0.02 \]

\[ \Omega_\Lambda \approx 0.73; \]

\[ \Omega_M \approx 0.27; \]

The baryons give “too small” contribution

\[ \Omega_b \sim 4\% \]

Non baryonic Cold Dark Matter is dominant

\[ \Omega_{CDM} \sim 23\% \]

\[ \Omega_{HDM,\nu} < 1\% \]

Observations on:
- light nuclei abundance
- microlensings
- visible light.

Structure formation in the Universe

Concordance model

WMAP

Supernovae IA
Relic CDM particles from primordial Universe

**Light candidates:** axion, axion-like produced at rest
(no positive results from direct searches for relic axions with resonant cavity)

**Heavy candidates:**
- In thermal equilibrium in the early stage of Universe
- Non relativistic at decoupling time $<\sigma v> \sim 10^{-26}/\Omega_{\text{WIMP}} h^2 \text{ cm}^3 \text{s}^{-1} \rightarrow \sigma_{\text{ordinary matter}} \sim \sigma_{\text{weak}}$
- Expected flux: $\Phi \sim 10^7 \cdot (\text{GeV}/m_W) \text{ cm}^{-2} \text{ s}^{-1} \ (0.2<\rho_{\text{halo}}<1.7 \text{ GeV cm}^{-3})$
- Form a dissipationless gas trapped in the gravitational field of the Galaxy ($v \sim 10^{-3}c$)
- neutral
- stable (or with half life ~ age of Universe)
- massive
  - weakly interacting

- **the sneutrino in the Smith and Weiner scenario**
- **self-interacting dark matter**
- **mirror dark matter**
- **Kaluza-Klein particles (LKK)**
- **heavy exotic candidates, as “4th family atoms”, ...**
- **even a suitable particle not yet foreseen by theories**

- **SUSY** (R-parity conserved $\rightarrow$ LSP is stable)
  - neutralino or sneutrino

- **a heavy $\nu$ of the 4-th family**

- **axion-like (light pseudoscalar and scalar candidate)**
Direct detection:
Various approaches and techniques (many still at R&D stage)
Various different target nuclei
Various different experimental site depths

Recently, another possibility has been considered:
the direct ionization/excitation in the detector by axion-like particles
A model independent signature is needed

**Directionality** Correlation of nuclear recoil track with Earth's galactic motion due to the distribution of Dark Matter particles velocities very hard to realize

**Nuclear-inelastic scattering** Detection of $\gamma$'s emitted by excited nucleus after a nuclear-inelastic scattering. very large exposure and very low counting rates hard to realize

**Diurnal modulation** Daily variation of the interaction rate due to different Earth depth crossed by the Dark Matter particles only for high $\sigma$

**Annual modulation** Annual variation of the interaction rate due to Earth motion around the Sun. at present the only feasible one
Investigating the presence of a Dark Matter particles component in the galactic halo by the model independent annual modulation signature

Requirements of the annual modulation

1) Modulated rate according cosine
2) In a definite low energy range
3) With a proper period (1 year)
4) With proper phase (about 2 June)
5) For single hit events in a multi-detector set-up
6) With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions, but it can be larger in case of some possible scenarios

\[ v_{\oplus}(t) = v_{\text{sun}} + v_{\text{orb}} \cos \gamma \cos[\omega(t-t_0)] \]

\[ S_k[\eta(t)] = \int \frac{dR}{dE_R} dE_R \approx S_{0,k} + S_{m,k} \cos[\omega(t-t_0)] \]

Expected rate in given energy bin changes because the annual motion of the Earth around the Sun moving in the Galaxy

To mimic this signature, spurious effects and side reactions must not only - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements
Competitiveness of NaI(Tl) set-up

• High duty cycle
• Well known technology
• Large mass possible
• “Ecological clean” set-up; no safety problems
• Cheaper than every other considered technique
• Small underground space needed
• High radiopurity by selections, chem./phys. purifications, protocols reachable
• Well controlled operational condition feasible
• Routine calibrations feasible down to keV range in the same conditions as the production runs
• Neither re-purification procedures nor cooling down/warming up (reproducibility, stability, ...)
• Absence of microphonic noise + effective noise rejection at threshold ($\tau$ of NaI(Tl) pulses hundreds ns, while $\tau$ of noise pulses tens ns)
• High light response (5.5 -7.5 ph.e./keV)
• Sensitive to SI, SD, SI&SD couplings and to other existing scenarios, on the contrary of many other proposed target-nuclei
• Sensitive to both high (by Iodine target) and low mass (by Na target) candidates
• Effective investigation of the annual modulation signature feasible in all the needed aspects
• PSD feasible at reasonable level
• etc.

A low background NaI(Tl) also allows the study of several other rare processes such as: possible processes violating the Pauli exclusion principle, CNC processes in $^{23}$Na and $^{127}$I, electron stability, nucleon and di-nucleon decay into invisible channels, neutral SIMP and nuclearites search, solar axion search, ...

High benefits/cost
DAMA: an observatory for rare processes @LNGS

Roma2, Roma1, LNGS, IHEP/Beijing

DAMA/LXe
DAMA/R&D
low bckg DAMA/Ge for sampling meas.

DAMA/NaI
DAMA/LIBRA

http://people.roma2.infn.it/dama
DAMA/LXe: results on rare processes

Dark Matter Investigation

- Limits on recoils investigating the DMp-\(^{129}\)Xe elastic scattering by means of PSD
- Limits on DMp-\(^{129}\)Xe inelastic scattering
- Neutron calibration
- \(^{129}\)Xe vs \(^{136}\)Xe by using PSD → SD vs SI signals to increase the sensitivity on the SD component

Other rare processes:

- Electron decay into invisible channels
- Nuclear level excitation of \(^{129}\)Xe during CNC processes
- N, NN decay into invisible channels in \(^{129}\)Xe
- Electron decay: \(e^- \rightarrow \nu_e \gamma\)
- \(2\beta\) decay in \(^{136}\)Xe
- \(2\beta\) decay in \(^{134}\)Xe
- Improved results on \(2\beta\) in \(^{134}\)Xe, \(^{136}\)Xe
- CNC decay \(^{136}\)Xe → \(^{136}\)Cs
- N, NN, NNN decay into invisible channels in \(^{136}\)Xe

DAMA/R&D set-up: results on rare processes

- Particle Dark Matter search with CaF\(_2\)(Eu)
- \(2\beta\) decay in \(^{136}\)Ce and in \(^{142}\)Ce
- \(2\beta\) decay in \(^{46}\)Ca and in \(^{40}\)Ca
- \(2\beta^+\) decay in \(^{106}\)Cd
- \(2\beta\) and \(\beta\) decay in \(^{48}\)Ca
- \(2\beta\) decay in \(^{136}\)Ce, in \(^{138}\)Ce and \(\alpha\) decay in \(^{142}\)Ce
- \(2\beta^+\) 0ν and EC \(\beta^+\) 0ν decay in \(^{130}\)Ba
- Cluster decay in LaCl\(_3\)(Ce)

References:


Foreseen/in progress


NIMA498(2003)352, INFN/EXP-08/03+NPA-II


DAMA/NaI(Tl) ~ 100 kg


Results on rare processes:

- Possible Pauli exclusion principle violation
- CNC processes
- Investigation on diurnal effect
- Exotic Dark Matter search
- Search for superdense nuclear matter
- Search for heavy clusters decays

Results on DM particles:

- PSD
- Investigation on diurnal effect
- Exotic Dark Matter search
- Annual Modulation Signature

Plotted papers:

PLB389(1996)757
PRL83(1999)4918


Data taking completed on July 2002

Total exposure collected in 7 annual cycles: 107,731 kg×d
Main Features of DAMA/NaI

• Reduced standard contaminants (e.g. U/Th of order of ppt) by material selection and growth/handling protocols.

• PMTs: Each crystal coupled - through 10 cm long tetrasil-B light guides acting as optical windows - to 2 low background EMI 9265BS3/FL (special development) 3” diameter PMTs working in coincidence.

• Detectors inside a sealed Cu box maintained in HP Nitrogen atmosphere in slight overpressure.

• Very low radioactive shields: 10 cm of Cu, 15 cm of Pb + shield from neutrons: Cd foils + polyethylene/paraffin+ ~ 1 m concrete moderator largely surrounding the set-up.

• Installation sealed: A Plexiglas box encloses the whole shield and is also maintained in HP Nitrogen atmosphere in slight overpressure. Walls, floor, etc. of inner installation sealed by Supronyl (2×10^{-11} cm²/s permeability). Three levels of sealing.

• Installation in air conditioning + huge heat capacity of shield.

• Calibration using the upper glove-box (equipped with compensation chamber) in HP Nitrogen atmosphere in slight overpressure calibration → in the same running conditions as the production runs.

• Energy and threshold: Each PMT works at single photoelectron level. Energy threshold: 2 keV (from X-ray and Compton electron calibrations in the keV range and from the features of the noise rejection and efficiencies). Data collected from low energy up to MeV region, despite the hardware optimization was done for the low energy.

• Pulse shape recorded over 3250 ns by Transient Digitizers.

• Monitoring and alarm system continuously operating by self-controlled computer processes.

Main procedures of the DAMA data taking for the DMp annual modulation signature

• data taking of each annual cycle starts from autumn/winter (when cosw(t-t_0)≈0) toward summer (maximum expected).

• routine calibrations for energy scale determination, for acceptance windows efficiencies by means of radioactive sources each ~ 10 days collecting typically ~10⁵ evts/keV/detector + intrinsic calibration from ^{210}Pb (~ 7 days periods) + periodical Compton calibrations, etc.

• continuous on-line monitoring of all the running parameters with automatic alarm to operator if any out of allowed range.
Final model independent result by DAMA/NaI

Experimental residual rate of the single hit events in 2-6 keV over 7 annual cycles

\[ A = (0.0200 \pm 0.0032) \text{ cpd/kg/keV} \]

Time (day)

P(A=0) = 7 \times 10^{-4}

Solid line: \( t_0 = 152.5 \text{ days}, \ T = 1.00 \text{ years} \)

from the fit:

\[ A = (0.0192 \pm 0.0031) \text{ cpd/kg/keV} \]

from the fit with all the parameters free:

\[ A = (0.0200 \pm 0.0032) \text{ cpd/kg/keV} \]

\[ t_0 = (140 \pm 22) \text{ d} \]

\[ T = (1.00 \pm 0.01) \text{ y} \]

All the peculiarities of the signature satisfied

model independent evidence of a particle Dark Matter component in the galactic halo at 6.3σ C.L.

Experimental residual rate of the multiple hit events (DAMA/NaI-6 and 7) in the 2-6 keV energy interval:

\[ A = -(3.9\pm7.9) \times 10^{-4} \text{ cpd/kg/keV} \]

Multiple hits events = Dark Matter particle “switched off”

No systematics or side reaction able to account for the measured modulation amplitude and to satisfy all the peculiarities of the signature

Experimental residual rate of the single hit events (DAMA/NaI-1 to 7) in the 2-6 keV energy interval:

\[ A = (0.0195 \pm 0.0031) \text{ cpd/kg/keV} \]

Principal mode

\[ \rightarrow 2.737 \times 10^{-3} \text{ d}^{-1} \approx 1 \text{ y}^{-1} \]

Running conditions stable at level < 1%

All the measured amplitudes well compatible with zero
+ none can account for the observed effect

(to mimic such signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also simultaneously satisfy all the 6 requirements)

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<table>
<thead>
<tr>
<th></th>
<th>DAMA/NaI-5</th>
<th>DAMA/NaI-6</th>
<th>DAMA/NaI-7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>(0.033 ± 0.008)°C</td>
<td>(0.021 ± 0.005)°C</td>
<td>(0.030 ± 0.008)°C</td>
</tr>
<tr>
<td>Flux</td>
<td>(0.03 ± 0.08) l/h</td>
<td>(0.07 ± 0.14) l/h</td>
<td>(0.07 ± 0.14) l/h</td>
</tr>
<tr>
<td>Pressure</td>
<td>(0.6 ± 1.7)10^-3 mbar</td>
<td>(0.5 ± 2.5)10^-3 mbar</td>
<td>(0.2 ± 2.3)10^-3 mbar</td>
</tr>
<tr>
<td>Radon</td>
<td>(0.00 ± 0.17) Bq/m^3</td>
<td>(0.00 ± 0.14) Bq/m^3</td>
<td>(0.02 ± 0.09) Bq/m^3</td>
</tr>
<tr>
<td>Hardware rate</td>
<td>(0.19 ± 0.17)10^-2 Hz</td>
<td>(0.09 ± 0.19)10^-2 Hz</td>
<td>(0.22 ± 0.19)10^-2 Hz</td>
</tr>
</tbody>
</table>

Summary of the results obtained in the investigations of possible systematics or side reactions

<table>
<thead>
<tr>
<th>Source</th>
<th>Main comment</th>
<th>Cautious upper limit (90%C.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RADON</td>
<td>Sealed Cu box in HP Nitrogen atmosphere, etc</td>
<td>$&lt;0.2% \ S_{m}^{obs}$</td>
</tr>
<tr>
<td>TEMPERATURE</td>
<td>Installation is air conditioned + detectors in Cu housings directly in contact with multi-ton shield → huge heat capacity + T continuously recorded</td>
<td>$&lt;0.5% \ S_{m}^{obs}$</td>
</tr>
<tr>
<td>NOISE</td>
<td>Effective noise rejection</td>
<td>$&lt;1% \ S_{m}^{obs}$</td>
</tr>
<tr>
<td>ENERGY SCALE</td>
<td>Periodical calibrations + continuous monitoring of $^{210}\text{Pb}$ peak</td>
<td>$&lt;1% \ S_{m}^{obs}$</td>
</tr>
<tr>
<td>EFFICIENCIES</td>
<td>Regularly measured by dedicated calibrations</td>
<td>$&lt;1% \ S_{m}^{obs}$</td>
</tr>
<tr>
<td>BACKGROUND</td>
<td>No modulation observed above 6 keV + this limit includes possible effect of thermal and fast neutrons + no modulation observed in the multiple-hits events in 2-6 keV region</td>
<td>$&lt;0.5% \ S_{m}^{obs}$</td>
</tr>
<tr>
<td>SIDE REACTIONS</td>
<td>Muon flux variation measured by MACRO</td>
<td>$&lt;0.3% \ S_{m}^{obs}$</td>
</tr>
</tbody>
</table>

+ even if larger they cannot satisfy all the requirements of annual modulation signature

Thus, they can not mimic the observed annual modulation effect
Can a hypothetical background modulation account for the observed effect?

Integral rate at higher energy (above 90 keV), $R_{90}$

- $R_{90}$ percentage variations with respect to their mean values for single crystal in the DAMA/NaI-5,6,7 running periods
  $\rightarrow$ cumulative gaussian behaviour with $\sigma \approx 0.9\%$, fully accounted by statistical considerations

- Fitting the behaviour with time, adding a term modulated according period and phase expected for Dark Matter particles:
  $\rightarrow$ consistent with zero + if a modulation present in the whole energy spectrum at the level found in the lowest energy region $\rightarrow R_{90} \sim$ tens cpd/kg $\rightarrow \sim 100 \sigma$ far away

<table>
<thead>
<tr>
<th>Period</th>
<th>Mod. Ampl.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAMA/NaI-5</td>
<td>(0.09±0.32) cpd/kg</td>
</tr>
<tr>
<td>DAMA/NaI-6</td>
<td>(0.06±0.33) cpd/kg</td>
</tr>
<tr>
<td>DAMA/NaI-7</td>
<td>-(0.03±0.32) cpd/kg</td>
</tr>
</tbody>
</table>

Energy regions closer to that where the effect is observed e.g.:

Mod. Ampl. (6-10 keV): -(0.0076 ± 0.0065), (0.0012 ± 0.0059) and (0.0035 ± 0.0058) cpd/kg/keV for DAMA/NaI-5, DAMA/NaI-6 and DAMA/NaI-7; $\rightarrow$ they can be considered statistically consistent with zero

In the same energy region where the effect is observed:
no modulation of the multiple-hits events (see elsewhere)

No modulation in the background: these results also account for the bckg component due to neutrons
Can a possible thermal neutron modulation account for the observed effect?

- Thermal neutrons flux measured at LNGS:
  \[ \Phi_n = 1.08 \times 10^{-6} \text{ n cm}^{-2} \text{ s}^{-1} \] (N.Cim.A101(1989)959)
  (cautiously adopted here and in all the DAMA calculations)

- Experimental limit on the neutrons flux “surviving” the neutron shield in the DAMA/Nal set-up:
    \[ \Phi_n < 5.9 \times 10^{-6} \text{ n cm}^{-2} \text{ s}^{-1} \]
  - more sensitive approach: studying triple coincidences able to give evidence for the possible presence of \(^{24}\text{Na}\) from neutron activation (derivable from EPJA24(2005)51):
    \[ \Phi_n < 4.0 \times 10^{-7} \text{ n cm}^{-2} \text{ s}^{-1} \]

Evaluation of the expected effect:

- Capture rate = \( \Phi_n \sigma_n N_T = 0.17 \text{ capture/d/kg} \cdot \Phi_n/(10^{-6} \text{ n cm}^{-2} \text{ s}^{-1}) \)
- For ex., neutron capture in \(^{23}\text{Na}\): \(^{23}\text{Na}(n,\gamma)^{24}\text{Na}; \(^{23}\text{Na}(n,\gamma)^{24m}\text{Na}\)

HYPOTHESIS: assuming very cautiously \( \Phi_n \approx 10^{-6} \text{ n cm}^{-2} \text{ s}^{-1} \) and a 10% thermal neutron modulation:

- \( S_m^{(\text{thermal n})} < 10^{-5} \text{ cpd/kg/keV} \) (< 0.05% \( S_m^{\text{observed}} \))

In all the cases of neutron captures (\(^{24}\text{Na}, ^{128}\text{I}, \ldots\)) a possible thermal n modulation induces a variation in all the energy spectrum

Already excluded also by \( R_{90} \) analysis
Can a possible fast neutron modulation account for the observed effect? NO

In the estimate of the possible effect of the neutron background cautiously not included the 1m concrete moderator, which almost completely surrounds (mostly outside the barrack) the passive shield.

**Measured fast neutron flux @ LNGS:**
\[ \Phi_n = 0.9 \times 10^{-7} \text{ n cm}^{-2} \text{ s}^{-1} \] (Astropart.Phys.4 (1995),23)

**By MC: differential counting rate above 2 keV \approx 10^{-3} \text{ cpd/kg/keV}**

**HYPOTHESIS:** Assuming - very cautiously - a 10% neutron modulation:
\[ S_m^{(\text{fast n})} < 10^{-4} \text{ cpd/kg/keV} \] (< 0.5% \( S_m^{\text{observed}} \))

Moreover, a possible fast n modulation would induce:
- a variation in all the energy spectrum (steady environmental fast neutrons always accompanied by thermalized component)
  already excluded also by \( R_{90} \)
- a modulation amplitude for multiple-hit events different from zero
  already excluded by the multiple-hit events (see also elsewhere)

Thus, a possible 5% neutron modulation (ICARUS TM03-01) cannot quantitatively contribute to the DAMA/NaI observed signal, even if the neutron flux would be assumed 100 times larger than measured by various authors over more than 15 years @ LNGS.
Summary of the DAMA/NaI Model Independent result

Presence of modulation for 7 annual cycles at $\sim 6.3\sigma$ C.L. with the proper distinctive features of the signature, all the features satisfied by the data over 7 independent experiments of 1 year each one

Absence of known sources of possible systematics and side processes able to account for the observed effect

No other experiment whose result can be directly compared in model independent way is available so far

To investigate the nature and coupling with ordinary matter of the possible DM candidate, an effective energy and time correlation analysis of the events has to be performed within given model frameworks

Corollary quest for a candidate

- the sneutrino in the Smith and Weiner scenario
- SUSY (R-parity conserved $\rightarrow$ LSP is stable)
  - neutralino or sneutrino
- a heavy $\nu$ of the 4-th family

- self-interacting dark matter
- mirror dark matter
- Kaluza-Klein particles
- heavy exotic candidates, as “4th family atoms”, ...
- axion-like (light pseudoscalar and scalar candidate)

astrophysical models: $\rho_{DM}$, velocity distribution and its parameters
nuclear Physics models
e.g. for WIMP class particles: nuclear and particle physics models: SI, SD, mixed SI&SD, preferred inelastic, scaling laws on cross sections, form factors and related parameters, spin factors, halo models, etc. etc.

THUS uncertainties on models and comparisons
**DM particle-nucleus elastic scattering**

**SI+SD differential cross sections:**

\[
\frac{d\sigma}{dE_R}(v, E_R) = \left( \frac{d\sigma}{dE_R} \right)_{SI} + \left( \frac{d\sigma}{dE_R} \right)_{SD} = \frac{2G_F^2m_N}{\pi v^2} \left\{ \left[ Zg_p + (A - Z)g_n \right] F^2_{SI}(E_R) + 8 \frac{J+1}{J} \left[ a_p \langle S_p \rangle + a_n \langle S_n \rangle \right] F^2_{SD}(E_R) \right\}
\]

**Generalized SI/SD DM particle-nucleon cross sections:**

\[
\begin{align*}
\sigma_{SI} &= \frac{4}{\pi} G_F^2 m_{wp}^2 g^2 \\
\sigma_{SD} &= \frac{32}{\pi} G_F^2 m_{wp}^2 \bar{a}^2
\end{align*}
\]

\[g = \frac{g_p + g_n}{2} \cdot \left[ 1 - \frac{g_p - g_n}{g_p + g_n} \left( 1 - \frac{2Z}{A} \right) \right]\]

where:

\[\bar{a} = \sqrt{a_p^2 + a_n^2} \quad tg\theta = \frac{a_n}{a_p}\]

**Differential energy distribution:**

\[
\frac{dR}{dE_R} = N_T \frac{\rho_W}{m_W} \int_{v_{min}(E_R)}^{v_{max}(E_R)} \frac{d\sigma}{dE_R}(v, E_R) v f(v) dv = N_T \frac{\rho_W m_N}{2 m_w m_{wp}} \cdot \Sigma(E_R) \cdot I(E_R)
\]

\[\Sigma(E_R) = \left\{ A^2 \sigma_{SI} F^2_{SI}(E_R) + \frac{4}{3} \frac{J+1}{J} \sigma_{SD} \left[ \langle S_p \rangle \cos\theta + \langle S_n \rangle \sin\theta \right] F^2_{SD}(E_R) \right\}\]

\[I(E_R) = \int_{v_{min}(E_R)}^{v_{max}(E_R)} \frac{f(v)}{v} dv \quad v_{min} = \sqrt{\frac{m_N E_R}{2 m_{WN}}} \]

- \(g_{p,n}(a_{p,n})\) effective DM particle-nucleon couplings
- \(\langle S_{p,n} \rangle\) nucleon spin in the nucleus
- \(F^2(E_R)\) nuclear form factors
- \(m_{wp}\) reduced DM particle-nucleon mass
- \(\rho_W\) energy density in the nucleus
- \(N_T\) number of target nuclei

\(f(v)\): DM particle velocity distribution in the Earth frame (**it depends on** \(v_e\))

\[v_e = v_{sun} + v_{orb}\cos\omega t\]

\(v_{max}\): maximal DM particle velocity in the Earth frame
The inelastic DM – nucleus interaction: \( W + N \rightarrow W^* + N \)

- DM particle candidate suggested by D. Smith and N. Weiner (PRD64(2001)043502)
- Two mass states \( \chi_+ , \chi_- \) with \( \delta \) mass splitting
- Kinematical constraint for the inelastic scattering of \( \chi_- \) on a nucleus with mass \( m_N \) becomes increasingly severe for low \( m_N \)

\[
\frac{1}{2} \mu v^2 \geq \delta \iff v \geq v_{\text{thr}} = \sqrt{\frac{2 \delta}{\mu}}
\]

**Differential energy distribution for SI interaction:**

\[
\frac{d\sigma}{d\Omega^*} = \frac{G_F^2 m_W^2}{\pi^2} \left[ Z g_p + (A - Z) g_n \right]^2 F_{SI}^2 (q^2) \cdot \sqrt{1 - \frac{v_{\text{thr}}^2}{v^2}}
\]

- \( g_{p,n} \) effective DM particle-nucleon couplings
- \( d\Omega^* \) differential solid angle in the DM-nucleon c.m. frame
- \( q^2 = \text{squared threee-momentum transfer} \)

**Nucleus recoil energy:**

\[
E_R = \frac{2m_{\text{WN}} v^2}{m_N} \cdot \frac{1 - \frac{v_{\text{thr}}^2}{v^2} - \sqrt{1 - \frac{v_{\text{thr}}^2}{v^2} \cdot \cos \theta^*}}{2}
\]

\[
\frac{d\sigma}{dE_R} = \frac{2G_F^2 m_N}{\pi v^2} \left[ Z g_p + (A - Z) g_n \right]^2 F_{SI}^2 (E_R)
\]

**Differential energy distribution:**

\[
\frac{dR}{dE_R} = N_T \frac{\rho_w}{m_w} \int_{v_{\text{min}}}^{v_{\text{max}}} d\sigma (v, E_R) v f(v) dv \quad v_{\text{min}} (E_R) = \sqrt{\frac{m_N E_R}{2m_{\text{WN}}}} \cdot \left( 1 + \frac{m_{\text{WN}} \delta}{m_N E_R} \right)
\]

Ex. \( m_W = 100 \text{ GeV} \)

<table>
<thead>
<tr>
<th>( m_N )</th>
<th>( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>41</td>
</tr>
<tr>
<td>130</td>
<td>57</td>
</tr>
</tbody>
</table>

\( S_m/S_0 \) enhanced with respect to the elastic scattering case
Examples of different Form Factor for $^{127}$I available in literature

- Take into account the structure of target nuclei.
- In SD form factor: no decoupling between nuclear and Dark Matter particles; dependence on nuclear potential.

Similar situation for all the target nuclei considered in the field.

Spin Independent

$A e^{-\alpha_1(qr_n)^2} + (1-A)e^{-\alpha_2(qr_n)^2}$

Spin Dependent

$e^{-\frac{(qr_n)^2}{5}}$

Helm charge spherical distribution

from Ressell et al., Astrop.Phys.6(1996) 87

from Helm

$e^{-\frac{(qr_n)^2}{5}}$

"thin shell" distribution

Smith et al., Astrop.Phys.6(1996) 87
**The Spin Factor**

Spin Factors for some target-nuclei calculated in simple different models

\[
\text{Spin factor} = \frac{\Lambda^2 J(J+1)}{a_x^2}
\]

\(a_x = a_n \text{ or } a_p \text{ depending on the unpaired nucleon}\)

Large differences in the measured counting rate can be expected:

- when using target nuclei sensitive to the SD component of the interaction (such as e.g. \(^{23}\text{Na}\) and \(^{127}\text{I}\)) with the respect to those largely insensitive to such a coupling (such as e.g. \(^{\text{nat}}\text{Ge},^{\text{nat}}\text{Si},^{\text{nat}}\text{Ar},^{\text{nat}}\text{Ca},^{\text{nat}}\text{W},^{\text{nat}}\text{O}\);)
- when using different target nuclei although all – in principle – sensitive to such a coupling, depending on the unpaired nucleon (compare e.g. odd spin isotopes of Xe, Te, Ge, Si, W with the \(^{23}\text{Na}\) and \(^{127}\text{I}\) cases).

<table>
<thead>
<tr>
<th>Target-Nucleus</th>
<th>single particle</th>
<th>odd group</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{29}\text{Si})</td>
<td>0.750</td>
<td>0.063</td>
<td>Neutron is the unpaired nucleon</td>
</tr>
<tr>
<td>(^{73}\text{Ge})</td>
<td>0.306</td>
<td>0.065</td>
<td></td>
</tr>
<tr>
<td>(^{129}\text{Xe})</td>
<td>0.750</td>
<td>0.124</td>
<td></td>
</tr>
<tr>
<td>(^{131}\text{Xe})</td>
<td>0.150</td>
<td>0.055</td>
<td></td>
</tr>
<tr>
<td>(^{1}\text{H})</td>
<td>0.750</td>
<td>0.750</td>
<td>Proton is the unpaired nucleon</td>
</tr>
<tr>
<td>(^{19}\text{F})</td>
<td>0.750</td>
<td>0.647</td>
<td></td>
</tr>
<tr>
<td>(^{23}\text{Na})</td>
<td>0.350</td>
<td>0.041</td>
<td></td>
</tr>
<tr>
<td>(^{27}\text{Al})</td>
<td>0.350</td>
<td>0.087</td>
<td></td>
</tr>
<tr>
<td>(^{69}\text{Ga})</td>
<td>0.417</td>
<td>0.021</td>
<td></td>
</tr>
<tr>
<td>(^{71}\text{Ga})</td>
<td>0.417</td>
<td>0.089</td>
<td></td>
</tr>
<tr>
<td>(^{75}\text{As})</td>
<td>0.417</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>(^{127}\text{I})</td>
<td>0.250</td>
<td>0.023</td>
<td></td>
</tr>
</tbody>
</table>

Spin Factors calculated on the basis of Ressell et al. for some of the possible \(\theta\) values considering some target nuclei and two different nuclear potentials

<table>
<thead>
<tr>
<th>Target-Nucleus / nuclear potential</th>
<th>(\theta=0)</th>
<th>(\theta=\pi/4)</th>
<th>(\theta=\pi/2)</th>
<th>(\theta=2.435) (pure (Z_0) coupling)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{23}\text{Na})</td>
<td>0.102</td>
<td>0.060</td>
<td>0.001</td>
<td>0.051</td>
</tr>
<tr>
<td>(^{127}\text{I}/\text{Bonn A})</td>
<td>0.134</td>
<td>0.103</td>
<td>0.008</td>
<td>0.049</td>
</tr>
<tr>
<td>(^{127}\text{I}/\text{Nijmegen II})</td>
<td>0.175</td>
<td>0.122</td>
<td>0.006</td>
<td>0.073</td>
</tr>
<tr>
<td>(^{129}\text{Xe}/\text{Bonn A})</td>
<td>0.002</td>
<td>0.225</td>
<td>0.387</td>
<td>0.135</td>
</tr>
<tr>
<td>(^{129}\text{Xe}/\text{Nijmegen II})</td>
<td>0.001</td>
<td>0.145</td>
<td>0.270</td>
<td>0.103</td>
</tr>
<tr>
<td>(^{131}\text{Xe}/\text{Bonn A})</td>
<td>0.000</td>
<td>0.046</td>
<td>0.086</td>
<td>0.033</td>
</tr>
<tr>
<td>(^{131}\text{Xe}/\text{Nijmegen II})</td>
<td>0.000</td>
<td>0.044</td>
<td>0.078</td>
<td>0.029</td>
</tr>
<tr>
<td>(^{129}\text{Te}/\text{Bonn A})</td>
<td>0.000</td>
<td>0.124</td>
<td>0.247</td>
<td>0.103</td>
</tr>
<tr>
<td>(^{129}\text{Te}/\text{Nijmegen II})</td>
<td>0.000</td>
<td>0.156</td>
<td>0.313</td>
<td>0.132</td>
</tr>
</tbody>
</table>
Quenching factors, \( q \), measured by neutron sources or by neutron beams for some detectors and nuclei

- Differences are often present in different experimental determinations of \( q \) for the same nuclei in the same kind of detector
- E.g. in doped scintillators \( q \) depends on dopant and on the impurities/trace contaminants; in LXe e.g. on trace impurities, on initial UHV, on presence of degassing/releasing materials in the Xe, on thermodynamical conditions, on possibly applied electric field, etc.
- Some time increases at low energy in scintillators (dL/dx)

<table>
<thead>
<tr>
<th>Nucleus/Detector</th>
<th>Recoil Energy (keV)</th>
<th>( q )</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaI(Tl)</td>
<td>(6.5-97)</td>
<td>(0.30 ± 0.01) for Na</td>
<td>[46]</td>
</tr>
<tr>
<td></td>
<td>(22-330)</td>
<td>(0.09 ± 0.01) for I</td>
<td>[46]</td>
</tr>
<tr>
<td></td>
<td>(20-80)</td>
<td>(0.25 ± 0.03) for Na</td>
<td>[119]</td>
</tr>
<tr>
<td></td>
<td>(40-100)</td>
<td>(0.08 ± 0.02) for I</td>
<td>[119]</td>
</tr>
<tr>
<td></td>
<td>(4-252)</td>
<td>(0.275 ± 0.018) for Na</td>
<td>[120]</td>
</tr>
<tr>
<td></td>
<td>(10-71)</td>
<td>(0.086 ± 0.007) for I</td>
<td>[120]</td>
</tr>
<tr>
<td></td>
<td>(5-100)</td>
<td>(0.4 ± 0.2) for Na</td>
<td>[121]</td>
</tr>
<tr>
<td></td>
<td>(40-300)</td>
<td>(0.05 ± 0.02) for I</td>
<td>[121]</td>
</tr>
<tr>
<td>CaF(_2)(Eu)</td>
<td>(30-100)</td>
<td>(0.06-0.11) for Ca</td>
<td>[120]</td>
</tr>
<tr>
<td></td>
<td>(10-100)</td>
<td>(0.08-0.17) for F</td>
<td>[120]</td>
</tr>
<tr>
<td></td>
<td>(90-130)</td>
<td>(0.049 ± 0.005) for Ca</td>
<td>[45]</td>
</tr>
<tr>
<td></td>
<td>(75-270)</td>
<td>(0.069 ± 0.005) for F</td>
<td>[45]</td>
</tr>
<tr>
<td></td>
<td>(53-192)</td>
<td>(0.11-0.20) for F</td>
<td>[122]</td>
</tr>
<tr>
<td></td>
<td>(25-91)</td>
<td>(0.09-0.23) for Ca</td>
<td>[122]</td>
</tr>
<tr>
<td>CsI(Tl)</td>
<td>(25-150)</td>
<td>(0.15-0.07)</td>
<td>[123]</td>
</tr>
<tr>
<td></td>
<td>(10-65)</td>
<td>(0.17-0.12)</td>
<td>[124]</td>
</tr>
<tr>
<td></td>
<td>(10-65)</td>
<td>(0.22-0.12)</td>
<td>[125]</td>
</tr>
<tr>
<td>CsI(Na)</td>
<td>(10-40)</td>
<td>(0.10-0.07)</td>
<td>[125]</td>
</tr>
<tr>
<td>Ge</td>
<td>(3-18)</td>
<td>(0.29-0.23)</td>
<td>[126]</td>
</tr>
<tr>
<td></td>
<td>(21-50)</td>
<td>(0.14-0.24)</td>
<td>[127]</td>
</tr>
<tr>
<td></td>
<td>(10-80)</td>
<td>(0.18-0.34)</td>
<td>[128]</td>
</tr>
<tr>
<td></td>
<td>(20-70)</td>
<td>(0.24-0.33)</td>
<td>[129]</td>
</tr>
<tr>
<td>Si</td>
<td>(5-22)</td>
<td>(0.23-0.42)</td>
<td>[130]</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>(0.32 ± 0.10)</td>
<td>[131]</td>
</tr>
<tr>
<td>Liquid Xe</td>
<td>(30-70)</td>
<td>(0.46 ± 0.10)</td>
<td>[72]</td>
</tr>
<tr>
<td></td>
<td>(40-70)</td>
<td>(0.18 ± 0.03)</td>
<td>[132]</td>
</tr>
<tr>
<td></td>
<td>(40-70)</td>
<td>(0.22 ± 0.01)</td>
<td>[133]</td>
</tr>
<tr>
<td>Bolometers</td>
<td>-</td>
<td>assumed 1 (see also NIMA507(2003)643)</td>
<td></td>
</tr>
</tbody>
</table>
Consistent Halo Models

- Isothermal sphere ⇒ very simple but unphysical halo model; generally not considered

Models accounted in the following


- Needed quantities
  - DM local density \( \rho_0 = \rho_{DM}(R_0 = 8.5 \text{ kpc}) \)
  - local velocity \( v_0 = v_{rot}(R_0 = 8.5 \text{kpc}) \)
  - velocity distribution \( f(v) \)

- Allowed ranges of \( \rho_0 \) (GeV/cm\(^3\)) have been evaluated for \( v_0 = 170, 220, 270 \) km/s, for each considered halo density profile and taking into account the astrophysical constraints:

  \[
  v_0 = (220 \pm 50) \text{km/s} \\
  1 \times 10^{10} M_\odot \leq M_{\text{vir}} \leq 6 \times 10^{10} M_\odot \\
  0.8 \cdot v_0 \leq v_{rot}(r = 100 \text{kpc}) \leq 1.2 \cdot v_0
  \]

  NOT YET EXHAUSTIVE AT ALL

<table>
<thead>
<tr>
<th>Class A: spherical ( \rho_{DM} ), isotropic velocity dispersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
</tr>
<tr>
<td>A1</td>
</tr>
<tr>
<td>A2</td>
</tr>
<tr>
<td>A3</td>
</tr>
<tr>
<td>A4</td>
</tr>
<tr>
<td>A5</td>
</tr>
<tr>
<td>A6</td>
</tr>
<tr>
<td>A7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Class B: spherical ( \rho_{DM} ), non–isotropic velocity dispersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Osipkov–Merrit, ( \beta_0 = 0.4 ))</td>
</tr>
<tr>
<td>B1</td>
</tr>
<tr>
<td>B2</td>
</tr>
<tr>
<td>B3</td>
</tr>
<tr>
<td>B4</td>
</tr>
<tr>
<td>B5</td>
</tr>
<tr>
<td>B6</td>
</tr>
<tr>
<td>B7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Class C: Axisymmetric ( \rho_{DM} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
</tr>
<tr>
<td>C2</td>
</tr>
<tr>
<td>C3</td>
</tr>
<tr>
<td>C4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Class D: Triaxial ( \rho_{DM} ) [107] (( q = 0.8, p = 0.9 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
</tr>
<tr>
<td>D2</td>
</tr>
<tr>
<td>D3</td>
</tr>
<tr>
<td>D4</td>
</tr>
</tbody>
</table>
Few examples of corollary quests for the WIMP class


DM particle with elastic SI&SD interactions
(Na and I are fully sensitive to SD interaction, on the contrary of e.g. Ge and Si)
Examples of slices of the allowed volume in the space $(\xi_{\sigma_{SI}}, \xi_{\sigma_{SD}}, m_W, \theta)$ for some of the possible $\theta$ ($\tan \theta = a_n / a_p$ with $0 \leq \theta < \pi$) and $m_W$.

DM particle with preferred inelastic interaction:
$W + N \rightarrow W^* + N$ ($S_{\pi}/S_0$ enhanced): examples of slices of the allowed volume in the space $(\xi_{\sigma_p}, m_W, \delta)$ [e.g. Ge disfavoured].

DM particle with dominant SI coupling
Region of interest for a neutralino in supersymmetric schemes where assumption on gaugino-mass unification at GUT is released and for “generic” DM particle

Model dependent lower bound on neutralino mass as derived from LEP data in supersymmetric schemes based on GUT assumptions (DPP2003)

Higher mass region allowed for low $v_0$, for every set of parameters’ values and the halo models: Evans’ logarithmic C1 and C2 co-rotating, triaxial D2 and D4 non-rotating, Evans power-law B3 in setA.

Most of these allowed volumes/regions are unexplorable e.g. by Ge, Si, TeO2, Ar, Xe, CaWO4 targets.

Not exhaustive + different scenarios?
An example of the effect induced by a non-zero SD component on the allowed SI regions

- Example obtained considering Evans’ logarithmic axisymmetric C2 halo model with $v_0 = 170$ km/s, $\rho_0$ max at a given set of parameters
- The different regions refer to different SD contributions with $\theta = 0$

A small SD contribution $\Rightarrow$ drastically moves the allowed region in the plane ($m_W$, $\xi\sigma_{SI}$) towards lower SI cross sections ($\xi\sigma_{SI} < 10^{-6}$ pb)

- There is no meaning in bare comparison between regions allowed in experiments sensitive to SD coupling and exclusion plots achieved by experiments that are not.
- The same is when comparing regions allowed by experiments whose target-nuclei have unpaired proton with exclusion plots quoted by experiments using target-nuclei with unpaired neutron where $\theta \approx 0$ or $\theta \approx \pi$. 

Similar effect for whatever considered model framework
Supersymmetric expectations in MSSM

• Assuming for the neutralino a dominant purely SI coupling

• when releasing the gaugino mass unification at GUT scale: $M_1/M_2 \neq 0.5 (<)$;

(Where $M_1$ and $M_2$ U(1) and SU(2) gaugino masses)

low mass configurations are obtained

scatter plot of theoretical configurations vs DAMA/NaI allowed region in the given model frameworks for the total DAMA/NaI exposure (area inside the green line);

(for previous DAMA/NaI partial exposure see PRD68(2003)043506)
## DAMA/NaI vs some others

<table>
<thead>
<tr>
<th>DAMA/NaI</th>
<th>CDMS-II</th>
<th>Edelweiss-I</th>
<th>Zeplin-I</th>
<th>Cresst-II</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signature</strong></td>
<td>annual modulation</td>
<td>none</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td><strong>Targets</strong></td>
<td>$^{23}$Na, $^{127}$I</td>
<td>$^{nat}$Ge</td>
<td>$^{nat}$Ge</td>
<td>$^{nat}$Xe</td>
</tr>
<tr>
<td><strong>Technique</strong></td>
<td>widely known</td>
<td>poorly experienced (known just by Edelweiss)</td>
<td>poorly experienced (known just by CDMS)</td>
<td>liq/gas optical interface (light collected from top)</td>
</tr>
<tr>
<td><strong>Target mass</strong></td>
<td>$\approx 100$ kg</td>
<td>0.75 kg</td>
<td>0.32 kg</td>
<td>$\approx 3$ kg</td>
</tr>
<tr>
<td><strong>Used exposure</strong></td>
<td>$(1.1 \times 10^5)$ kg $\times$ day (RivNCim 26 n1(2003)1-73)</td>
<td>19.4 kg $\times$ day (astro-ph/0405033)</td>
<td>30.5 kg $\times$ day (NDM03)</td>
<td>280 kg $\times$ day (Moriond03)</td>
</tr>
<tr>
<td><strong>Expt. depth</strong></td>
<td>1400 m</td>
<td>780 m</td>
<td>1700 m</td>
<td>1100 m</td>
</tr>
<tr>
<td><strong>Neutron shield</strong></td>
<td>~1m of concrete + 10/40 cm polyethylene/paraffin + 1.5 mm Cd</td>
<td>50 cm polyethylene</td>
<td>30 cm paraffin</td>
<td>---</td>
</tr>
<tr>
<td><strong>Energy threshold</strong></td>
<td>2 keVee (5.5 - 7.5 p.e./keV)</td>
<td>10 keVee</td>
<td>20 keVee</td>
<td>2 keVee (but: $\sigma/E=100%$) and 1 p.e./keVee!!! (IDM02) (2.5 p.e./keVee; Moriond03)</td>
</tr>
<tr>
<td><strong>Quenching factor</strong></td>
<td>measured</td>
<td>assumed 1</td>
<td>measured (see also NIMA507(2003)643)</td>
<td>measured</td>
</tr>
<tr>
<td><strong>Measured evt rate in low energy range</strong></td>
<td>~1 cpd/kg/keV</td>
<td>??(claimed $\gamma$ than CDMS-I) $\sim 10^4$ events total where ~60 cpd/kg/keV, $10^5$ events</td>
<td>~100 cpd/kg/keV (IDM02) (??)</td>
<td>6 cpd/kg/keV above 35 keVee</td>
</tr>
<tr>
<td><strong>Claimed evts after rejection procedures</strong></td>
<td>0 o 1</td>
<td>2 (claimed taken in a noisy period!)</td>
<td>16</td>
<td>~20-50 cpd/kg/keV after filtering (?) and ?? after PSD (Moriond03, IDM02)</td>
</tr>
<tr>
<td><strong>Evts satisfying the signature in DAMA/NaI</strong></td>
<td>modulation amplitude integrated over the given exposure some $10^3$ evts</td>
<td>insensitive</td>
<td>insensitive</td>
<td>insensitive</td>
</tr>
<tr>
<td><strong>Expected number of evts from DAMA/NaI effect</strong></td>
<td>from few down to zero depending on the model frameworks (and on quenching factor)</td>
<td>from few down to zero depending on the model framework (and on quenching factor)</td>
<td>depends on the model framework, also zero</td>
<td>from few down to zero depending on the model framework (and on quenching factor)</td>
</tr>
</tbody>
</table>
FAQ:

... DAMA/NaI “excluded” by CDMS-II (and others)?

OBVIOUSLY NO

They give a single model dependent result using natGe target
DAMA/NaI gives a model independent result using 23Na and 127I targets

Even assuming their expt. results as they give them ...

• In general? OBVIOUSLY NO

The different sensitivities to the various kinds of candidates, interactions and particle mass,
the accounting for realistic and consistent halo models and accounting for existing parameters
uncertainties, FFs and/or SF and existing uncertainties on related parameters, different
scaling laws than assumed (possible even for the neutralino candidate), their proper
accounting for experimental parameters and related uncertainties, the many possible
scenarios, etc. fully “decouple” the results.

• At least in the purely SI coupling they only consider? OBVIOUSLY NO

they give a single result fixing all the astrophysical, nuclear and particle physics assumptions
and all the expt. and theor. parameters values .....; moreover, they usually quote in an
uncorrect, partial and unupdated way the implications of the DAMA/NaI model independent
result...; see above, etc.

(see also in Riv. N. Cim. 26 n. 1(2003)1-73 and JUMPD13(2004)2127,
various papers in literature, astro-ph/0511262)
Hints from indirect searches and not in conflict with DAMA/NaI for the WIMP class candidate

Some measurements performed by indirect search experiments have pointed out the presence of antiparticles and photons which could be ascribed to some classes of Cold Dark Matter particles annihilating in the halo.

Example of joint analysis of DAMA/NaI and positron/gamma's excess in the space.

In next years new data from DAMA/LIBRA and indirect searches from Agile, Glast, Ams2, Pamela, ...
Axion-like particles: similar phenomenology with ordinary matter as the axion, but significantly different values for mass and coupling constants are allowed.

A wide literature is available and various candidate particles have been and can be considered.

The detection is based on the total conversion of the absorbed bosonic mass into electromagnetic radiation.

In these processes the target nuclear recoil is negligible and not involved in the detection process (i.e. signals from these candidates are lost in experiments applying rejection procedures of the electromagnetic contribution)

A complete data analysis of the total 107731 kgxday exposure from DAMA/NaI has been performed for pseudoscalar (a) and scalar (h) candidates in some of the possible scenarios.

They can account for the DAMA/NaI observed effect as well as candidates belonging to the WIMPs class.

Main processes involved in the detection:

- Compton-like
- Axioelectric or Photoelectric-like
- Primakoff

<table>
<thead>
<tr>
<th></th>
<th>( S_0 )</th>
<th>( S_0, S_m )</th>
<th>( S_0, S_m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>h</td>
<td>( S_0, S_m )</td>
<td>( S_0 )</td>
<td>( S_0, S_m )</td>
</tr>
</tbody>
</table>
The pseudoscalar case

Axioelectric contribution dominant in all “natural” cases → allowed region almost independent on the other fermion coupling values

Also this can account for the DAMA/NaI observed effect
1) electron coupling does not provide modulation
2) from measured rate: $g_{\text{hee}} < 3 \times 10^{-16}$ to $10^{-14}$ for $m_h \approx 0.5$ to 10 keV
3) coupling only to hadronic matter: allowed region in $g_{hNN}$ vs. $m_h$

$(3\sigma$ C.L.)

Also this can account for the DAMA/NaI observed effect.
As a result of a second generation R&D for more radiopure NaI(Tl) by exploiting new chemical/physical radiopurification techniques (all operations involving crystals and PMTs - including photos - in HP Nitrogen atmosphere)

The new LIBRA set-up ~250 kg NaI(Tl) (Large sodium Iodide Bulk for RAre processes) in the DAMA experiment

PMT +HV divider

Cu etching with super- and ultra-pure HCl solutions, dried and sealed in HP N₂

storing new crystals

etching staff at work in clean room

improving installation and environment
DAMA/LIBRA in data taking since March 2003, waiting for a larger exposure than DAMA/NaI.
DAMA/LIBRA performance: energy scale and calibrations

$^{241}$Am routine calibrations
(all the detectors together)

$\sigma_E(60keV) = 7.4\%$

Stability of the high energy calibration factors (ADCs)
March 2003 – April 2005

Stability of the low energy calibration factors (TDs)
Period: March 2003 – August 2005

$\sigma = 0.4\%$

$\sigma = 0.5\%$

$\langle \alpha \rangle \approx 2$

$\sigma = 0.9\%$
Example of the stability of the high energy rate, $R_{90}$, (above 90 keV)

- $R_{90}$ percentage variations with respect to their mean values for single crystal

$\sigma = 1.2\%$

DAMA/LIBRA
(from March 2003 – August 2004)
... other astrophysical scenarios?

Possible non-thermalized multicomponent galactic halo? In the galactic halo, fluxes of Dark Matter particles with dispersion velocity relatively low are expected:

- Possible contribution due to the tidal stream of Sagittarius Dwarf satellite galaxy of Milky Way
- Possible presence of caustic rings ⇒ streams of Dark Matter particles

K. Freese et al. astro-ph/0309279

Fu-Sin Ling et al. astro-ph/0405231

Interesting scenarios for DAMA

- Effect on $|S_m/S_o|$ respect to “usually” adopted halo models?
- Effect on the phase of annual modulation signature?

Other dark matter stream from satellite galaxy of Milky Way close to the Sun?

.....very likely....

Can be guess that spiral galaxy like Milky Way have been formed capturing close satellite galaxy as Sgr, Canis Major, ecc…

Canis Major simulation: astro-ph/0311010

Position of the Sun: (-8,0,0) kpc
An example of possible signature for the presence of streams in the Galactic halo

The effect of the streams on the phase depends on the galactic halo model.

Expected phase in the absence of streams $t_0 = 152.5 \text{ d (2nd June)}$

Evans’log axisymmetric non-rotating, $v_0=220\text{km/s, } R_c = 5\text{kpc, } \rho_0 \text{max} + 4\% \text{ Sgr}$

NFW spherical isotropic non-rotating, $v_0=220\text{km/s, } \rho_0 \text{max} + 4\% \text{ Sgr}$

The higher sensitivity of DAMA/LIBRA will allow to more effectively investigate the presence or contributions of streams in the galactic halo.

DAMA/NaI results:
(2-6) keV $t_0 = (140 \pm 22) \text{ d}$
DAMA/LIBRA perspectives

DAMA/LIBRA (\sim 250\text{kg NaI(Tl)}), running since March 2003, can allow to:

- achieve higher C.L. for the annual modulation effect (model independent result)
- investigate many topics on the corollary model dependent quests for the candidate particle (continuing and improving past and present efforts on the data of the previous DAMA/NaI experiment):
  
  + on different astrophysical scenarios
  + on different dark matter particles distributions
  + on different scaling laws
  + on different possible CDM candidates
  + on different couplings
  
  ...and more

- competitive limits on many rare processes can also be obtained
  
  ...wait for an exposure larger than DAMA/NaI

...and beyond?

- R&D-III approved and funded by INFN towards a possible multi-purpose NaI(Tl) ton set-up we proposed in 96 » work in progress

- new ideas to fully exploit Cold Dark Matter particle signal peculiarities and halo features under study
Summary

DAMA/NaI data show a $6.3 \sigma$ C.L. model independent evidence for the presence of a Dark Matter particle component in the galactic halo.

This evidence allows to investigate new physics beyond the Standard Model:

**Corollary model dependent quest for the candidate particle:**

- WIMP particles with $m_w \sim$ (few GeV to TeV) with coupling pure SI or pure SD or mixed SI/SD as well as particles with preferred inelastic scattering
  

- several other particles suggested in literature by various authors
  
  (see literature)

- bosonic particles with $m_a \sim$ keV having pseudoscalar, scalar coupling
  
  (astro-ph/0511262, IJMPA, in press)

DAMA/LIBRA will allow to further restrict the nature of the candidate and to investigate the phase space structure of the dark halo.