DAMA investigations on Dark Matter at Gran Sasso: results and perspectives

Zaragoza, Oct. 2006

R. Bernabei
Universita’ & INFN – Roma “Tor Vergata”
Roma2, Roma1, LNGS, IHEP/Beijing
(+ in some small scale expts and by-products results:)
+ in the framework of MAE activ. for studies on
double positron decays:
+ neutron measurements:

DAMA/R&D
DAMA/LXe
low bckg DAMA/Ge
for sampling meas.
meas. with $^{100}$Mo

DAMA/LIBRA

http://people.roma2.infn.it/dama
Investigations on rare processes

An interdisciplinary field

Particle Physics
Study of the Nature on small scale

Cosmology
Study of the Nature on large scale

Primordial Universe

Particle Accelerator of fundamental potentialities?

Searches for rare exotic nuclear processes:

- Double beta decays: $\beta^-\beta^-$, $\beta^+\beta^-$, $EC\beta^+$, $2EC$ in several isotopes;
- Electron stability;
- CNC processes;
- Nucleon instabilities into invisible channels;
- Possible Pauli exclusion principle violation;
- Electron and non-paulian transitions;
- Solar axions;
- Exotic Matter;
- Superdense nuclear matter;
- Heavy clusters decays

Possibility to investigate the Particle Physics beyond the Standard Model
DAMA/LXe: recent results on rare processes

**Dark Matter Investigation**
- Limits on recoils investigating the DMp-129Xe elastic scattering by means of PSD
- Limits on DMp-129Xe inelastic scattering
- Neutron calibration
- 129Xe vs 136Xe by using PSD \( \rightarrow \) SD vs SI signals to increase the sensitivity on the SD component

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

**DAMA/R&D set-up: recent results on rare processes**
- Particle Dark Matter search with CaF\(_2\)(Eu)
- 2\( \beta \) decay in 136Ce and in 142Ce
- 2EC\( \nu \) 40Ca decay
- 2\( \beta \) decay in 46Ca and in 40Ca
- 2\( \beta^+ \) decay in 106Cd
- 2\( \beta \) and \( \beta \) decay in 48Ca
- 2EC\( \nu \) in 136Ce, in 138Ce and \( \alpha \) decay in 142Ce
- 2\( \beta^+ 0\nu \) and EC \( \beta^+ 0\nu \) decay in 130Ba
- Cluster decay in LaCl\(_3\)(Ce)
- CNC decay of 139La into 139Ce

NIMA482(2002)728


DAMA results on $\beta\beta$ decay

Experimental limits on $T_{1/2}$ obtained by DAMA (red) and by previous experiments (blue)

(all the limits are at 90% C.L. except for $2\beta^+0\nu$ in $^{136}\text{Ce}$ and $2\beta^-0\nu$ in $^{142}\text{Ce}$ - 68% C.L.)

Now in progress measurement on $2\beta^2\nu$ decay in $^{100}\text{Mo}$ to the first excited $0^+$ level of $^{100}\text{Ru}$ by using ~1 kg of Molybdenum enriched in $^{100}\text{Mo}$ at 99.5% inserted in a 4 HP Ge detector array
Investigation on $\beta\beta$ decay in $^{136}$Xe and in $^{134}$Xe

Total Statistics: 8823.54 h $\rightarrow$ 68.8% in $^{136}$Xe (4.5 kg$\times$y $^{136}$Xe), 17.1% in $^{134}$Xe (1.1 kg$\times$y $^{134}$Xe)

Joint analysis of the $0\nu\beta\beta$ decay mode in $^{134}$Xe and $^{136}$Xe carried out as suggested by F. Simkovic et al., hep-ph/0204278:

1) Backgr estimated excluding the energy regions of $0\nu\beta\beta(0^+\rightarrow0^+)$ decays in $^{134}$Xe and $^{136}$Xe.

2) Fit on residuals with linear combination of the expected signal from $0\nu\beta\beta(0^+\rightarrow0^+)$ processes in $^{134}$Xe and $^{136}$Xe (other approaches considered as cross check)

Analysing the single processes:

$^{134}$Xe $0\nu\beta\beta(0^+\rightarrow0^+)$: $T_{1/2} > 5.8 \times 10^{22}$ y (90%CL)

$^{136}$Xe $0\nu\beta\beta(0^+\rightarrow0^+)$: $T_{1/2} > 1.2 \times 10^{24}$ y (90%CL)
Other $\beta\beta$ decay modes in $^{136}$Xe investigated

$2\beta^-0\nu M(0^+\rightarrow0^+)$
Excluding energy region 1.00-2.35 MeV (containing ~84% of the expected signal) an estimate of the background compatible with the previous one has been obtained; fitting residuals:

$T_{1/2} > 5.0 \times 10^{23} \text{ y}$
(90% C.L.):

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<tr>
<td>$\langle g_M \rangle \times 10^{-5}$</td>
<td>&lt; 2.0</td>
<td>&lt; 2.1</td>
<td>&lt; 2.4</td>
<td>&lt; 5.3</td>
<td>&lt; 7.5</td>
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$2\beta^-2\nu(0^+\rightarrow0^+)$; $2\beta^-2\nu(0^+\rightarrow2^+)$
Expected signal do not present peculiar structure in the energy region of the analysis.
Obtained limits without background subtraction (90% C.L.):

$2\beta^-2\nu(0^+\rightarrow0^+): \quad T_{1/2} > 1.0 \times 10^{22} \text{ y}$
$2\beta^-2\nu(0^+\rightarrow2^+): \quad T_{1/2} > 9.4 \times 10^{21} \text{ y}$

The obtained limit for $(0^+\rightarrow0^+)$ decay mode is lower than the theoretical value of [A. Staudt et al., Europhys. Lett. 13 (1990) 31]: $2\cdot10^{22} \text{ y}$, ruling out other theoretical estimations. This has also been confirmed recently by the Xenon exp. at Baksan.
Search for $^{100}\text{Mo}$ $2\beta$ decay to the first excited $0^{+}_{1}$ level of $^{100}\text{Ru}$ (Armonia coll.)

Previous results by Barabash et al.:
1) Soudan mine, 1 kg $^{100}\text{Mo}$, 114 cm$^3$ HP Ge, 9960 h [PLB345(1995)408]
   $T_{1/2} = 6.1 \times 10^{20}$ y
2) Modane, 17 different $^{100}\text{Mo}$ samples with HP Ge
   $T_{1/2} = 9.3 \times 10^{20}$ y
3) Low Bck. Facility of TUNL, 2 HP Ge 280 cm$^3$ in coinc.
   [PRL86(2001)3510]
   $T_{1/2} = 5.9 \times 10^{20}$ y
4) NEMO-3 detector, 6.9 kg $^{100}\text{Mo}$, 2 $e^{-}$ and 2 $\gamma$’s
   [NPAE2006 Conference]
   $T_{1/2} = 5.7 \times 10^{20}$ y

However:
5) NEMO Coll., 1 kg $^{100}\text{Mo}$, HP Ge 100 cm$^3$
   $T_{1/2} > 1.2 \times 10^{21}$ y
   [PLB275(1992)506]

1 kg $^{100}\text{Mo}$ of INR-Kiev
LNGS 4 HP Ge detectors 255 cm$^3$ each

Preliminary measurements (1927 h)
540 keV peak: $T_{1/2} \sim 3 \times 10^{20}$ y
591 keV peak: $T_{1/2} > 6 \times 10^{20}$ y

• Further efforts on $^{100}\text{Mo}$ purification
• Increasing the exposure
DAMA/Ge

Low background Ge for sample measurements

in operation deep underground in the low backg. facility of LNGS since early 90’s

It has the lowest background for high energy than others in the LNGS facility (data by Junker at GS workshop on $\beta\beta$ expts few years ago) and is probably the most sensitive at low energy for external radiation for sample measurements having a low Z window (originally Be, than modified in special plastic)

**work done:**
qualifications of powders and other materials
for RD-I, for RD-II, for some other scintillator materials and for some of the RDs on PMTs

**work to be done on long term:**
qualifications of powders and other materials for RD-III, for RDs on PMTs and of other scintillator materials + other measurements on materials
The Dark Side of the Universe: experimental evidences ...

From larger scale ...

“Precision” cosmology supports:

Flat Universe:

\[ \Omega = 1.02 \pm 0.02 \]

“Concordance” model:

\[ \Omega_\Lambda \sim 73\% \]
\[ \Omega_{CDM} \sim 23\% \]
\[ \Omega_b \sim 4\% \]
\[ \Omega_\nu < 1\% \]

Evidence for dark matter at large and small scales since 70 years (luminous matter less than 1%)

... to galaxy scale

- Composition?
- Right halo model and parameters?
- Multicomponent also in the particle part?
- Related nuclear and particle physics?
- Non thermalized components?
- Caustics and clumpiness?
- ...............
Relic DM particles from primordial Universe

**Light candidates:** axion, sterile neutrino, axion-like particles cold or warm DM
(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 \(<\sigma_{\text{ann}}\cdot v> \sim 10^{-26}/\Omega_{\text{WIMP}} h^2 \text{ cm}^3\text{s}^{-1} \rightarrow \sigma_{\text{ordinary matter}} \sim \sigma_{\text{weak}}\)
- 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 \(\sim\) age of Universe)
- massive
- weakly interacting

- 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 (LKK)
- axion-like (light pseudoscalar and scalar candidate)
- heavy exotic candidates, as “4th family atoms”, ...
- even a suitable particle not yet foreseen by theories
- etc…
Direct detection of Dark Matter particles in the galactic halo

Various approaches and techniques (many still at R&D stage)

Various different target nuclei

Various different experimental site depths

Direct detection processes:

- scattering on nuclei
  → detection of nuclear recoil energy

- conversion of particle into electromagnetic radiation
  → detection of $\gamma$, X-rays, $e^-$

- excitation of bound electrons in scatterings on nuclei
  → detection of recoil nuclei + e.m. radiation

**Ionization:** Ge, Si

**Bolometer:** TeO$_2$, Ge, CaWO$_4$, ...

**Scintillation:** NaI(Tl), LXe, CaF$_2$(Eu), ...

NOTE: signals from these candidates are lost in experiments based on rejection procedures of the electromagnetic events
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 γ'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 σ.

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

With the present technology, the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small, a suitable large-mass, low-radioactive set-up with an efficient control of the running conditions would point out its presence.

Drukier, Freese, Spergel PRD86
Freese et al. PRD88

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

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

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

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 (τ of NaI(Tl) pulses hundreds ns, while τ 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 $^{23}\text{Na}$ and $^{127}\text{I}$, electron stability, nucleon and di-nucleon decay into invisible channels, neutral SIMP and nuclearites search, solar axion search, ...

High benefits/cost
Results on DM particles:
- PSD
- Investigation on diurnal effect
- Exotic Dark Matter search
- Annual Modulation Signature

Results on rare processes:
- Possible Pauli exclusion principle violation
- CNC processes
- Electron stability and non-paulian transitions in Iodine atoms (by L-shell)
- Search for solar axions
- Exotic Dark Matter search
- Search for superdense nuclear matter
- Search for heavy clusters decays

Performances:
- EPJC18(2000)283
- IJMPD13(2004)2127

data taking completed on July 2002
(still producing results)

**DAMA/NaI(Tl)~100 kg**

**107731 kg×d**

Total exposure collected in 7 annual cycles
Main Features of DAMANaI

- Reduced standard contaminants (e.g. U/Th of order of ppt) by material selection and growth/handling protocols.
- **PMTs**: Each crystal coupled - through 10cm long tetrasil-B light guides acting as optical windows - to 2 low background EMI9265B53/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 highly radiopure Cu, 15 cm of highly radiopure 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} cm^2/s permeability). Three levels of sealing from environmental air.
- **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. + electronics and DAQ fully renewed in summer 2000

**Main procedures of the DAMA data taking for the DMP annual modulation signature**

- **data taking of each annual cycle** starts from autumn/winter (when \( \cos \omega (t-t_0) = 0 \)) toward summer (maximum expected).
- **routine calibrations** for energy scale determination, for acceptance windows efficiencies by means of radioactive sources each ~ 10 days collecting typically ~10^5 evts/keV/detector + intrinsic calibration from \(^{210}\text{Pb}\) (~ 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.
The model independent result

Annual modulation of the rate: DAMA/NaI 7 annual cycles

The data favor the presence of a modulated behavior with proper features at 6.3σ C.L.

Absence of modulation? No
χ²/dof=71/37 → P(A=0)=7⋅10⁻⁴

fit: A = (0.0210 ± 0.0038) cpd/kg/keV

fit (all parameters free):
A = (0.0200 ± 0.0032) cpd/kg/keV;
t₀ = (140 ± 22) d ;  T = (1.00 ± 0.01) y

2-4 keV

Acos[ω(t-t₀)] ; continuous lines: t₀ = 152.5 d, T = 1.00 y

2-5 keV

2-6 keV
Low energy vs higher energy

Single-hit residual rate as in a single annual cycle $\approx 10^5$ kg $\times$ day

Power spectrum of single-hit residuals

Treatment of the experimental errors and time binning included here

- Clear modulation present in the lowest energy region: from the energy threshold, 2 keV, to 6 keV.
  - Fixing $t_0 = 152.5$ day and $T = 1.00$ y, the modulation amplitude:
    - $A = (0.0195 \pm 0.0031)$ cpd/kg/keV
    - $A = -(0.0009 \pm 0.0019)$ cpd/kg/keV

- No modulation found:
  - in the 6-14 keV energy regions
  - in other energy regions closer to that where the effect is observed e.g.:
    - mod. ampl. (6-10 keV): $-(0.0076 \pm 0.0065), (0.0012 \pm 0.0059)$
    - and $(0.0035 \pm 0.0058)$ cpd/kg/keV for DAMA/NaI-5, DAMA/NaI-6 and DAMA/NaI-7; statistically consistent with zero
  - in the integral rate above 90 keV, e.g.:
    - mod. ampl.: $(0.09 \pm 0.32), (0.06 \pm 0.33)$ and $-(0.03 \pm 0.32)$ cpd/kg for DAMA/NaI-5, DAMA/NaI-6 and DAMA/NaI-7; statistically 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

Principal mode in the 2-6 keV region
$\rightarrow 2.737 \cdot 10^{-3} \text{ d}^{-1} \approx 1 \text{ y}^{-1}$

Not present in the 6-14 keV region (only aliasing peaks)
Statistical distribution of the modulation amplitudes ($S_m$)

\[ (S_m - \langle S_m \rangle) / \sigma \]

\begin{enumerate}
\item $S_m$ for each detector, each annual cycle and each considered energy bin (here 0.25 keV)
\item $\langle S_m \rangle = \text{mean values over the detectors and the annual cycles for each energy bin}; \sigma = \text{error associated to the } S_m$
\end{enumerate}

Individual $S_m$ values follow a normal distribution since \( (S_m - \langle S_m \rangle) / \sigma \) is distributed as a Gaussian with a unitary standard deviation

$S_m$ statistically well distributed in all the crystals, in all the data-taking periods and energy bins
Multiple-hits events in the region of the signal

- In DAMA/NaI-6 and 7 each detector has its own TD (multiplexer system removed)
  → pulse profiles of multiple-hits events (multiplicity > 1) also acquired (total exposure: 33834 kg d).
- The same hardware and software procedures as the ones followed for single-hit events
  → just one difference: events induced by Dark Matter particles do not belong to this class of events, that is: multiple-hits events = Dark Matter particles events “switched off”

- 2-6 keV residuals

\[
\text{Mod ampl.} = -(3.9 \pm 7.9) \cdot 10^{-4} \text{ cpd/kg/keV}
\]

Residuals for single-hit events (DAMA/NaI 7 annual cycles)

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

This result offers an additional strong support for the presence of Dark Matter particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background.
Running conditions

Pressure
Temperature
Nitrogen Flux

Radon outside the shield

Distribution of some parameters

Hardware rate

Running conditions stable at level < 1%

Modulation amplitudes obtained by fitting the time behaviours of main running parameters, acquired with the production data, when including a modulation term as in the Dark Matter particles case.

<table>
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<tr>
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<th>DAMA/NaI-5</th>
<th>DAMA/NaI-6</th>
<th>DAMA/NaI-7</th>
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<tbody>
<tr>
<td>Temperature</td>
<td>$-(0.033 \pm 0.090)^\circ$C</td>
<td>$(0.021 \pm 0.095)^\circ$C</td>
<td>$-(0.038 \pm 0.098)^\circ$C</td>
</tr>
<tr>
<td>Flux</td>
<td>$(0.03 \pm 0.08)$ l/h</td>
<td>$(0.06 \pm 0.14)$ l/h</td>
<td>$(0.07 \pm 0.14)$ l/h</td>
</tr>
<tr>
<td>Pressure</td>
<td>$-(0.6 \pm 1.7)10^{-3}$ mbar</td>
<td>$(0.5 \pm 2.5)10^{-3}$ mbar</td>
<td>$(0.2 \pm 2.3)10^{-3}$ mbar</td>
</tr>
<tr>
<td>Radon</td>
<td>$-(0.09 \pm 0.17)$ Bq/m$^3$</td>
<td>$(0.09 \pm 0.14)$ Bq/m$^3$</td>
<td>$-(0.02 \pm 0.03)$ Bq/m$^3$</td>
</tr>
<tr>
<td>Hardware rate</td>
<td>$(0.19 \pm 0.17)10^{-2}$ Hz</td>
<td>$(0.09 \pm 0.19)10^{-2}$ Hz</td>
<td>$-(0.22 \pm 0.19)10^{-2}$ Hz</td>
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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)

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:
  
  → consistent with zero + if a modulation present in the whole energy spectrum at the level found in the lowest energy region → $R_{90} \sim$ tens cpd/kg → $\sim 100 \sigma$ far away

<table>
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<tr>
<th>Period</th>
<th>Mod. Ampl.</th>
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<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>
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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; → 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/NaI 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 = \( \Phi_n \sigma_n N_T = 0.17 \text{ capture/d/kg} \times \Phi_n/(10^{-6} \text{ n cm}^{-2} \text{ s}^{-1}) \)
- 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 \( \Phi_n = 10^{-6} \text{ n cm}^{-2} \text{ s}^{-1} \) 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 R90 analysis
Can a possible fast neutron modulation account for the observed effect?

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 $\approx 10^{-3}$ cpd/kg/keV**

HYPOTHESIS: Assuming - very cautiously - a 10% neutron modulation:

$S_{m}^{(\text{fast n})} < 10^{-4}$ 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.
What we can also learn from the multiple/single hit rates. A toy model

\[ R_{\text{mult}} = R_{\text{single}} \cdot \left( \frac{N_T \sigma_T}{4\pi r^2} \right) \]

What about the nuclear cross sections of the particle \((A)\) responsible of the modulation in the single-hit rate and not in the multiple-hit rate?

\[ N_T \sigma_T = N_{Na} \sigma_{Na} + N_I \sigma_I = N \cdot (\sigma_{Na} + \sigma_I) \]

The 8 NaI(Tl) detectors in (anti-)coincidence have \(3.1 \times 10^{26}\) nuclei of Na and \(3.1 \times 10^{26}\) nuclei of Iodine. \(N = 3.1 \times 10^{26}\)

\[ R_{\text{mult}} \approx R_{\text{single}} \cdot \frac{N \cdot (\sigma_{Na} + \sigma_I)}{4\pi \cdot r_{\text{med}}^2} \quad r_{\text{med}} \sim 10-15\text{ cm} \]

Therefore, the ratio of the modulation amplitudes is:

\[ \frac{A_{\text{mult}}}{A_{\text{single}}} \approx \frac{N \cdot (\sigma_{Na} + \sigma_I)}{4\pi \cdot r_{\text{med}}^2} \]

From the experimental data: \(A_{\text{mult}} \approx -(4 \pm 8) \times 10^{-4}\) cpd/kg/keV < \(10^{-3}\) cpd/kg/keV;

\(A_{\text{single}} \approx 2 \times 10^{-2}\) cpd/kg/keV;

Hence:

\[ \frac{A_{\text{mult}}}{A_{\text{single}}} < 5 \times 10^{-2} \]

In conclusion, the particle \((A)\) responsible of the modulation in the single-hit rate and not in the multiple-hit rate must have:

\(\sigma_{Na} + \sigma_I < 0.2\text{ barn}\)

Since for fast neutrons the sum of the two cross sections (weighted by \(1/E\), ENDF/B-VI) is about 4 barns:

It \((A)\) cannot be a fast neutron
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% $S_m^{\text{obs}}$</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% $S_m^{\text{obs}}$</td>
</tr>
<tr>
<td>NOISE</td>
<td>Effective noise rejection</td>
<td>&lt;1% $S_m^{\text{obs}}$</td>
</tr>
<tr>
<td>ENERGY SCALE</td>
<td>Periodical calibrations + continuous monitoring of $^{210}$Pb peak</td>
<td>&lt;1% $S_m^{\text{obs}}$</td>
</tr>
<tr>
<td>EFFICIENCIES</td>
<td>Regularly measured by dedicated calibrations</td>
<td>&lt;1% $S_m^{\text{obs}}$</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% $S_m^{\text{obs}}$</td>
</tr>
<tr>
<td>SIDE REACTIONS</td>
<td>Muon flux variation measured by MACRO</td>
<td>&lt;0.3% $S_m^{\text{obs}}$</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
Summary of the DAMA/NaI Model Independent result

Presence of modulation for 7 annual cycles at ~6.3σ 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 quantitatively account for the observed effect and to contemporaneously satisfy the many peculiarities of the signature

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(s), effective energy and time correlation analysis of the events has to be performed within given model frameworks

**Corollary quests for candidate(s)**

- astrophysical models: \( \rho_{DM} \), velocity distribution and its parameters
- nuclear and particle Physics models
- experimental parameters
- e.g. for WIMP class particles: SI, SD, mixed SI&SD, preferred inelastic, scaling laws on cross sections, form factors and related parameters, spin factors, halo models, etc.
- + different scenarios
- + multicomponent?

THUS uncertainties on models and comparisons
**First case:** the case of DM particle scatterings on target-nuclei. The recoil energy is the detected quantity.

**DM particle-nucleus elastic scattering**

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

Note: not universal description. Scaling laws assumed to define point-like cross sections from nuclear ones. Four free parameters: \( m_W \), \( \sigma_{SI} \), \( \sigma_{SD} \), \( \tan \theta = \frac{a_n}{a_p} \).

**Preferred inelastic DM particle-nucleus scattering: \( \chi^-+N \rightarrow \chi^++N \)**

- 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 \( m_N \):

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

Three free parameters: \( m_W \), \( \sigma_p \), \( \delta \)

Differential energy distribution depends on the assumed scaling laws, nuclear form factors, spin factors, free parameters (→ kind of coupling, mixed SI&SD, pure SI, pure SD, pure SD through \( Z_0 \) exchange, pure SD with dominant coupling on proton, pure SD with dominant coupling on neutron, preferred inelastic, ...), on the assumed astrophysical model (halo model, presence of non-thermalized components, particle velocity distribution, particle density in the halo, ...) and on instrumental quantities (quenching factors, energy resolution, efficiency, ...)

**SI+SD differential cross sections:**

\[
g_{p,n}(a_{p,n}) \text{ effective DM particle-nucleon couplings} \\
\langle S_{p,n} \rangle \text{ nucleon spin in the nucleus} \\
F^2(E_R) \text{ nuclear form factors} \\
m_{Wp} \text{ reduced DM particle-nucleon mass}
\]
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

<table>
<thead>
<tr>
<th>Spin Independent</th>
<th>Spin Dependent</th>
</tr>
</thead>
<tbody>
<tr>
<td>from Helm</td>
<td>from Ressell et al.</td>
</tr>
<tr>
<td>$Ae^{-\alpha_1(qr_n)^2} + (1-A)e^{-\alpha_2(qr_n)^2}$</td>
<td>$e^{-(qr_n)^2/5}$</td>
</tr>
</tbody>
</table>

$e^{-(qr_n)^2/5}$ charge spherical distribution

$e^{-(qr_n)^2/5}$ “thin shell” distribution

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
The Spin Factor

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

<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>

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

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

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>$^{125}\text{Te}/\text{Bonn A}$</td>
<td>0.000</td>
<td>0.124</td>
<td>0.247</td>
<td>0.103</td>
</tr>
<tr>
<td>$^{125}\text{Te}/\text{Nijmegen II}$</td>
<td>0.000</td>
<td>0.156</td>
<td>0.313</td>
<td>0.132</td>
</tr>
</tbody>
</table>

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. natGe, natSi, natAr, natCa, natW, natO);
- 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).
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 ($dL/dx$)

Ex. of different $q$ determinations for Ge

<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>25-252</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>assumed 1 (see also NIMA507(2003)643))</td>
<td></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 $\rho_0 = \rho_{\text{DM}} (R_0 = 8.5 \text{ kpc})$
  → local velocity $v_0 = v_{\text{rot}} (R_0 = 8.5 \text{kpc})$
  → velocity distribution $f(\vec{v})$

- 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:

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

  NOT YET EXHAUSTIVE AT ALL

<table>
<thead>
<tr>
<th>Class A: spherical $\rho_{\text{DM}}$, 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 $\rho_{\text{DM}}$, non–isotropic velocity dispersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Osipkov–Merrit, $\rho_0 = 0.4$)</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 $\rho_{\text{DM}}$</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 $\rho_{\text{DM}}$ [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 in given scenarios  

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 \((\xi \sigma_{\text{SI}}, \xi \sigma_{\text{SD}}, m_W, \theta)\) 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: \(W + N \rightarrow W^* + N\) \((S_m/S_0\) enhanced): examples of slices of the allowed volume in the space \((\xi \sigma_{\text{p}}, m_W, \delta)\) [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 \(v_0\), 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

DM particle with dominant SD coupling

volume allowed in the space \((m_W, \xi \sigma_{\text{SD}}, \theta)\); here example of a slice for \(\theta = \pi/4\) (\(0 \leq \theta < \pi\))

Regions above 200 GeV allowed for low \(v_0\), for every set of parameters’ values and for Evans’ logarithmic C2 co-rotating halo models

Already 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 $\theta \approx \pi$. 
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 image]

figure taken from PRD69(2004)037302

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)
In supersymmetric models, the one-nucleon current generically produces roughly equal SI couplings to the proton and neutron \cite{5}, which results in a SI amplitude that is proportional to the atomic number of the nucleus. Inclusion of the two-nucleon contributions could change this picture since such contributions might cancel against the one-nucleon contributions. If the ratio of the two-nucleon matrix element to the atomic number varies from one nucleus to the next so will the degree of the cancellation. Thus, when the two-current contribution is taken into account, a dark-matter candidate that appears in DAMA but not in other searches \cite{14} is conceivable for a WIMP with SI interactions even within the framework of the MSSM…

Prezeau, Kamionkowski, Vogel et al., PRL91(2003)231301

\[ \sigma_A \propto \mu^2 A^2 (1+\varepsilon_A) \]

\[ \varepsilon_A = 0 \quad \text{“usually”} \]

\[ \varepsilon_A \approx \pm 1 \quad \text{here in some nuclei?} \]

Different scaling laws for a DM particle with SI interactions even within the framework of the MSSM? + Different Form Factors, e.g. the recently proposed by Gondolo et al. hep-ph/0608035
Some open scenarios on astrophysical aspects

In the galactic halo, fluxes of Dark Matter particles with dispersion velocity relatively low are expected:

some relics of the hierarchical assembly of the Milky Way are already observed in the visible: Sagittarius dwarf galaxy since 1994, Canis Major galaxy early discovered...

This scenario foreseen streams of Dark Matter particles with low velocity dispersion, very interesting for direct detection: $S_m/S_0$ enhanced in A.M., new signature for streams
... investigating halo substructures by underground expt through annual modulation

Possible contributions due to the tidal stream of Sagittarius Dwarf satellite (SagDEG) galaxy of Milky Way

Examples of the effect of SagDEG tail on the phase of the signal annual modulation

$V_{8*}$, from 8 local stars: PRD71(2005)043516
Investigating the effect of SagDEG contribution for WIMPs

DAMA/NaI: seven annual cycles 107731 kg d
for different SagDEG velocity dispersions (20-40-60 km/s)

$\rho_{\text{SagDEG}} < 0.1$ GeV cm$^{-3}$ (bound by M/L ratio considerations)

mixed SI&SD case

green area: no SagDEG

pure SI case

pure SD case
Constraining the SagDEG stream by DAMA/NaI

for different SagDEG velocity dispersions (20-40-60 km/s)

This analysis shows the possibility to investigate local halo features by annual modulation signature already at the level of sensitivity provided by DAMA/NaI, allowing to reach sensitivity to SagDEG density comparable with M/L evaluations.

The higher sensitivity of DAMA/LIBRA will allow to more effectively investigate the presence and the contributions of streams in the galactic halo.
... other astrophysical scenarios?

Possible other (beyond SagDEG) non-thermalized component in the galactic halo? In the galactic halo, fluxes of Dark Matter particles with dispersion velocity relatively low are expected:

Possible presence of caustic rings

⇒ streams of Dark Matter particles

P. Sikivie, 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
a viable signature for DM streams in the solar neighborhood...

the periodical Earth orbit crossing of a caustic region can be investigate by underground direct detection experiment as DAMA/LIBRA

an example:

\[ V_{\text{flux}} \sim 300 \text{ km/s} ; \sigma_v \sim 70 \text{ km/s} \]

Earth orbit within 10° from “spike”
sensibility to \( \rho_{\text{flux}} > \text{few} \% \rho_0 \)
What about the indirect searches of DM particles in the space?

It was already noticed in 1997 that the EGRET data showed an excess of gamma ray fluxes for energies above 1 GeV in the galactic disk and for all sky directions.

The EGRET Excess of Diffuse Galactic Gamma Rays

Hints from indirect searches are not in conflict with DAMA/NaI for the WIMP class candidate

In next years new data from DAMA/LIBRA (direct detection) and from Agile, Glast, Ams2, Pamela, ... (indirect detections)
... not only neutralino, but also e.g. ...

... sneutrino, ...

... or Kaluza-Klein DM

PLB536(2002)263

PRD70(2004)115004

... or neutrino of 4th family

Example of joint analysis of DAMA/NaI and positron/gamma’s excess in the space in the light of two DM particle components in the halo

hep-ph/0411093
many possible Dark Matter Particle candidates (+ multicomponent?):

**WIMP class:**
Detection by elastic scattering on nuclei:
- Spin Independent coupling,
- Spin Dependent coupling,
- SI&SD mixed coupling,
(+ e.m. contribution from excitation of bound electrons in scatterings on nuclei to be considered)
Detection by preferred inelastic scattering:

**WIMP-like class (different particles with “similar” phenomenologies):**
Subdominant heavy 4th neutrino and sterile dominant component
(see the analysis including the results of the indirect search in hep-ph/0411093)
Lightest Kaluza Klein Particle,
Self Interacting Dark Matter Particle: (SIMP + SIDM model)
Mirror Dark Matter,
etc…

**BOSONIC class (axion-like, Majoron, sgoldstino, familon, pseudo Nambu-Goldstone bosons, Kaluza Klein axions, etc):** very different detection processes and phenomenologies

IJMPD 13 (2004) 2127)

Ex: Lightest Susy Particle as neutralino, heavy 4-family neutrino, etc..

<table>
<thead>
<tr>
<th>Detection by preferred inelastic scattering:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ex: sneutrino Smith &amp; Weiner</td>
</tr>
<tr>
<td>Phys.Rev. D64 (2001) 043502</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>&amp; BOSONIC class (axion-like, Majoron, sgoldstino, familon, pseudo Nambu-Goldstone bosons, Kaluza Klein axions, etc)</th>
</tr>
</thead>
</table>

... every case within its specific features and uncertainties ...

IJMPA21(2006)1445

... and more
Another class of DM candidates: light bosonic particles

The detection is based on the total conversion of the absorbed 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, as CDMS, Edelweiss, CRESST, WARP, Xenon,…)

Axion-like particles: similar phenomenology with ordinary matter as the axion, but significantly different values for mass and coupling constants allowed.

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

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.

![Diagram of detection processes]
Some examples of axion-like particles:

... in general any PGB Pseudo-Goldstone boson, such as familon, majoron, sgoldstino...

Many other “exotic” axion models exist (hep-ph/0507236, astro-ph/0009290), etc...

In axion models the couplings are related to the mass (by model).

“Heavy” axion are strongly coupled (thus excluded)

But many configurations in \( g_{\gamma\gamma} \) vs \( m_a \) plane are unexplored

Astrophysical or semi-astrophysical limits are quite model dependent.

- keV KK axions can explain some X-ray astrophysical observations: (Di Lella & Zioutas AP19(2003)45)
- keV majoron as DM: (Akhmedov,Berezhiani,Mohapatra,Senjanovi hep-ph/9209285)
- keV DM majoron can explain galactic scale: (Berezinsky & Valle PLB318(1993)360)
- keV axion-like hypothesized for UHECR: (Gorbunov, Raffelt & Semikoz PRD64(2001)096005)

They can be cold or warm DM
Pseudoscalar case:

Analysis of 107731 kg day exposure from DAMA/NaI.

DAMA/NaI allowed region in the considered framework.

All these configurations are allowed by DAMA/NaI depending on the relative contributions of charged fermion couplings.

Maximum allowed photon coupling

Region almost independent on other fermion coupling values.

Also this can account for the DAMA/NaI observed effect

coupling to photons vanish at first order:

\[ a_{\gamma\gamma} \approx \frac{\alpha}{\pi} \left[ g_{a\pi e} \frac{1}{m_e} + 3 \frac{g_{a\bar{d}d}}{m_d} + 3 \frac{g_{a\bar{u}u}}{m_u} \right] \approx 0 \]

\[ \left( \frac{g_{a\pi e}}{m_e}, \frac{g_{a\bar{d}d}}{m_d}, -\frac{g_{a\bar{u}u}}{m_u} \right) \propto \tau_3 \]

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Also this can account for the DAMA/NaI observed effect

Majoron as in PLB 99 (1981) 411

axion-like, some astrophysical hint (1):

Hypothesis: $\sim$ keV axion-like (K.K. axion) trapped in the Sun neighborhood and $\gamma\gamma$ decay.

- solar corona problem
- X-ray from dark side of the Moon
- soft X-ray background radiation
- “diffuse” soft X-ray excess
- warm dark matter?

Di Lella & Zioutas
AP19(2003)45

Solar corona problem:
Scalar case:

Analysis of 107731 kg day exposure from DAMA/NaI.

- DAMA/NaI allowed region in the considered framework.

\[ g_{h\gamma\gamma} \approx \sum_q -\frac{2}{3} \frac{\alpha^2}{\pi} \frac{g_{h\gamma q}}{m_q} \approx -2 \frac{\alpha}{\pi} \left[ \frac{\beta g_{h\mu u}}{m_u} + \frac{\gamma g_{h\mu d}}{m_d} \right] \]

\[ g_{hNN} = (g_{h\mu u} + 2g_{h\mu d}) + \frac{Z}{A} (g_{h\mu u} - g_{h\mu d}) \]

- Annual modulation signature present for a scalar particle with pure coupling to hadronic matter (possible gluon coupling at tree level?).
- Compton-like to nucleus conversion is the dominant process for particle with cosmological lifetime.

Just an example: all the couplings to quarks of the same order \( \leftrightarrow \) lifetime dominated by u & d loops.

Also this can account for the DAMA/NaI observed effect.

Many other configurations of cosmological interest are possible depending on the values of the couplings to other quarks and to gluons….

- Allowed by DAMA/NaI (for \( m_h > 0.3 \) keV)
- \( \tau_h > 15 \) Gy (lifetime of cosmological interest)
- \( m_u = 3.0 \pm 1.5 \) MeV, \( m_d = 6.0 \pm 2.0 \) MeV

Considered dark halo models as in ref:

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FAQ: ... DAMA/NaI “excluded” by others?

OBVIOUSLY NO

They give a single **model dependent** result using other target
dAMa/NaI gives a **model independent** result using $^{23}$Na and $^{127}$I targets

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

**Case of DM particle scatterings on target-nuclei**

- In general? **OBVIOUSLY NO**

  The results are fully “decoupled” either because of the different sensitivities to the various kinds of candidates, interactions and particle mass, or simply taking into account the large uncertainties in the astrophysical (realistic and consistent halo models, presence of non-thermalized components, particle velocity distribution, particle density in the halo, ...), nuclear (scaling laws, FFs, SF) and particle physics assumptions and in all the instrumental quantities (quenching factors, energy resolution, efficiency, ...) and theor. parameters.

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

  still room for compatibility either at low DM particle mass or simply accounting for the large uncertainties in the astrophysical, nuclear and particle physics assumptions and in all the expt. and theor. parameters.

**Case of bosonic candidate (full conversion into electromagnetic radiation)**

- These candidates are lost by these expts. **OBVIOUSLY NO**

  (they usually quote in an uncorrect, partial and unupdated way the implications of the DAMA/NaI model independent result; they release orders of magnitude lower exposures, etc.)

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No direct model independent comparison possible
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 DAMA/LIBRA set-up ~250 kg NaI(Tl) (Large sodium Iodide Bulk for RAre processes)

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

improving installation and environment

etching staff at work in clean room

storing new crystals
installing DAMA/LIBRA detectors during installation; in the central and right up detectors the new shaped Cu surrounding light guides (acting also as optical windows) was not yet applied.
Main Features of DAMALIBRA

- **Reduced standard contaminants** by material selection, purification and growth/handling protocols.
- **PMTs**: Each crystal coupled - through 10 cm long suprasil light guides acting as optical windows - to 2 low background 3” diameter PMTs working in coincidence.
- **25 Detectors** inside a sealed Cu box maintained in HP Nitrogen atmosphere in slight overpressure.
- **Very low radioactive shields**: highly radiopure Cu shield shaped for PMTs, >10 cm of highly radiopure Cu, 15 cm of highly radiopure Pb + shield for neutrons: Cd foils + 10-40 cm 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); HP nitrogen released in inner barrack (oxygen alarm operating). Three levels of sealing from environmental air.
- **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 of the experiment: 1-2 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 is done for the low energy.
- **Pulse shape** in normal run recorded up to about 80 keV over 2048 ns by Transient Digitizers Tektronix TVS641A (one channel for each PMT). Total energy spectrum up to very HE by ADCs.
- **Monitoring and alarm system** continuously operating by self-controlled computer processes.
- **DAQ**: Compaq Workstation with Intel processor (1 GHz) with SUSE Linux operating system, MXI-2 and GPIB buses, VXI and CAMAC standards.

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

- **data taking of each annual cycle** starts from autumn/winter (when cos(ω(t-t₀))≈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 ²¹⁰Pb (~ 7 days periods) + periodical Compton calibrations, etc.
- **continuous on-line monitoring of all the running parameters** with automatic alarm if any out of allowed range.
Environment, alarms and N\textsubscript{2} flux systems: implemented

Dismounting/Installing protocol:

It was used a "Scuba" system (a self-contained underwater breathing apparatus) modified in order to avoid that the entire breath is expelled into the surrounding air when the operator exhales. The cylinders were kept five meters away. Output two meters away.

Air conditioners: devoted line equipped with new chiller and UPS system + freon conditioning

Electronics: new implementation, as for DAMA/NaI, under air conditioner in sealed environment

DAQ: new implementation
Few examples of operational features (here from March 2003 to August 2005):

- 241Am routine calibrations (all the detectors together)
  \[ \frac{\sigma}{E}(60\,keV) = 7.4\% \]
  \[ E \,(keV) \]

- Stability of the low energy calibration factors
  \[ \sigma = 0.4\% \]
  \[ \frac{\\langle \text{ideal} \rangle - \langle \text{ideal} \rangle}{\langle \text{ideal} \rangle} \]
  \[ \langle \alpha \rangle \approx 2 \]

- Stability of the high energy calibration factors
  \[ \sigma = 0.9\% \]
  \[ \frac{f_{HE} - \langle f_{HE} \rangle}{\langle f_{HE} \rangle} \]
Few examples of the stability parameters: the first year

in air conditioning (double system) + huge heat capacity of shield

Outside the Plexiglas box enclosing the whole shield and maintained in the HP Nitrogen atmosphere in slight overpressure. In the center of the shield there is the sealed Cu box housing the detectors and also maintained in HP Nitrogen atmosphere in slight overpressure.

N.B. Walls, floor, etc. of inner installation sealed by Supronyl (2×10^{-11} cm^{2}/s permeability); HP nitrogen released there.
DAMA/LIBRA in operation since March 2003

e.g. up to March 2006:
exposure: of order of $10^5$ kg x d
overall sources’ data: of order of $4 \times 10^7$ events
Summary

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

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
  
  (IJMPA21(2006)1445)

- halo substructures (SagDEG) effects (EPJC47(2006)263)

- and more in progress on halo models, candidates, type of interactions...

The presently running DAMA/LIBRA will allow to further increase the C.L. of the model independent result, and will allow to restrict the nature of the candidate and to investigate the phase space structure of the dark halo.

- a new R&D towards a possible ton set-up we proposed in 1996 in progress

  ... wait for more in the near future

- many other measurements in progress with the other set-ups