WIMP's Search : the Saclay Program

presented by
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Abstract : this paper describes the various activities led by the Saclay group about WIMP's search. Results from the first dedicated Dark Matter search using Silicon by the UC Santa Barbara/ UC Berkeley/ LBL/ Saclay collaboration will be given. Most of the phase space available for vector coupling Cosmions is excluded by the data. Status of the feasability study of a Hydrogen Time Projection Chamber which could be sensitive to axial vector coupling Cosmions is briefly reported. Some details are given on results of the measurement of NaI response to Na recoils which suggest that NaI could also be used as a WIMP detector. Status of bolometric studies is sketched.

Introduction

"WIMP's" (Weakly Interacting Massive Particles) is the generic name of elementary particles which could solve the well known Dark Matter problem. Their mass (greater than one GeV) and their cross sections (equal to the weak cross section within a few orders of magnitude) are constrained by astrophysical and cosmological arguments. No known particle fits these requirements (light neutrinos are not WIMP's). Possible candidates within particle physics theories have seen their phase space sizeably reduced by the recent LEP results which rule out any neutral particle coupled to the Z^0 with a mass below 30-35 GeV.

However, the Dark Matter problem still remains and nature may choose more complicated theories than the minimal simple natural supersymmetric theory. Attempts to directly detect such particles is then a wise attitude for the time being.

Among WIMP's candidates, Cosmions are not issued from any particle physics theory but rather from some numerical coincidences which lead to the possibility of explaining both the Solar Neutrino deficit and the Dark Matter problem [1]. These particles captured in the core of the Sun would transport energy from the inner to the outer regions and then cool down the center by the amount needed to reduce the flux of ^8B neutrinos observed by the Chlorine experiment. This mechanism requires an admixture of Cosmions which is 10^{-11} of the 10^{57} baryons in the Sun. It turns out that the Sun, by sweeping the sea of Dark Matter particles of our galaxy during a few Gigayears could have indeed collected around 10^{46} of these by now, provided their interaction cross section with the proton and helium nuclei of the Sun is around 1 picobarn. This is also the right cross section to cool down the center of the Sun by the adequate amount.

Recent work has been performed to set precise constraints on Cosmions using a solar evolution code [2]; it shows that masses are constrained to lie in the 2-6 GeV range in order to produce a solar neutrino flux between 2 and 2.5 SNU's.

With a cross section around 10^{-36} cm^2, Cosmions lie in the upper part of the cosmological range of values, and are the "easiest" WIMP's to detect. They could be directly detected on Earth by measuring the recoiling energy of the nuclei with which they scatter elastically [3]. These energies are expected to be in the keV range [3,4].

The experimental event rates depend on the actual cross sections on nuclei. While the averaged cross section on the nuclei of the Sun is the only parameter fixed by the Cosmion model, actual cross sections on given nuclei depend on the exact nature of the interaction coupling.

In the case of vector coupling, cross sections increase roughly with the square of the number of nucleons (coherence effect). This characteristics makes detectors based on heavy nuclei well suited for this search. The first Dark Matter dedicated experimental search using Silicon as a semiconductor will be described in the following.

In the case of axial vector coupling, the coherence factor is replaced by a 'spin' factor λ^2 j (j+1) where j is the spin of the nucleon and λ a nuclear factor depending on the quark content of the nuclei. Nuclei with zero spin (like ^{28}Si or ^{76}Ge) will then have a null cross section while comparison of merits of various non zero spin nuclei is made difficult by the uncertainty in the 'spin' factor. There exist however calculations in some specific cases [5], and some more accurate determinations are currently being carried out [6]. The status of some studies made by the Saclay group on ionisation detectors using non zero spin nuclei will be given: one using low pressure hydrogen, the other using the NaI scintillator.

Last but not least, cryogenic bolometric detectors are not limited in their choice by semiconducting or scintillation properties of the crystals. Status of what has been done so far by the Saclay group will be summarised.

1 The Silicon experiment

Set up

The LBL/ UCSB/ UC Berkeley/ Saclay collaboration initiated two years ago from an idea described in references [7]. Particles more massive than 9 GeV/c^2 could be excluded by Germanium experiments, and the interest of replacing Germanium by Silicon was to push the mass range limit down to 3-4 GeV/c^2.

The experimental apparatus was located under 600 meter water equivalent overburden in the powerhouse of the Oroville dam in California. Four planar Si(Li) crystals of 17 g each were mounted inside a cavity formed by ten blocks of NaI of 15 cm thickness previously used for a search for ^{76}Ge double beta decay. This anticoincidence shield with a threshold of 30 keV was in turn inside a very pure lead shield of 20 cm thickness.

The present data has been obtained with unselected Silicon crystals with relatively large radioactive background used for a preliminary test run. However, data were good enough to get interesting limits given below.

The digitised pulse heights and arrival times of the signals from each of the four Si detectors, two remaining Germanium detectors, and each NaI scintillator were recorded for off-line analysis. One Si detector had both a lower threshold and less background than the others, and the data from that unique detector is reported here and used to set limits. Its energy spectrum, which has been normalised in energy by pulser information checked against known photopeaks is shown in Figure 1. The gaussian electronic noise (sigma = 0.22 keV) gives an effective threshold of about 1.1 keV, which is about a factor 3 lower than the threshold obtained with Ge. The background, however, is two orders of magnitude higher than that measured with the best Ge detectors. This background includes beta decay spectra from Tritium (18.6 keV, 12.3 y halflife), ^{32}Si (225 keV, 104 y halflife), and ^{210}Pb (63.1 keV, 22.3 y halflife). The main contribution at the lowest energy part of the spectrum comes from Tritium, a spallation product produced in the Si by cosmic rays when the crystal was at the ground level.

Calibration of Silicon nuclear recoil

Slow recoiling nuclei are expected to produce less ionisation than a Compton or photoelectron of the same energy. In the sixties, neutron nuclei elastic scattering was used to calibrate the response of Germanium [8] and Silicon [9] detectors. As the measurements did not extend down to the keV region interesting for Cosmion searches, we have performed an experiment where we have measured the response of a Si(Li) detector to nuclear Silicon recoils between 3.2 and 21 keV.

The method consists in sending neutrons on the Si(Li) detector which then scatter elastically on Si nuclei, and to measure the scattered neutron with a counter. The knowledge of the energy of the incident neutron and of the scattering angle completely determines the kinematics, and then the value of the expected recoil energy of the Silicon nucleus.

Neutrons are produced by the reaction $p + {}^7Li \Rightarrow {}^7Be + n$. To obtain neutrons with energies around 200 keV needed to produce Si recoil energies in the 3-20 keV range, protons of around 2 MeV are required. Such energies were obtained with a 4 MV Van de Graaf accelerator at Bruyères le Chatel. A very interesting feature of this machine is its ability to deliver a pulsed beam with nanosecond resolution; this allows to measure the time of flight of the neutron between its production at the Li target and the scattered neutron counter also with nanosecond resolution, independently of the actual time resolution of the Silicon detector. This provides a very efficient background rejection. Details on the set-up and on the method used for such a calibration can be found in ref [10].

Figure 2 shows the ratio between the observed energy and the energy deposited by an electron of the same energy as a function of the energy for the 8 Si recoil energies we measured. Also shown are the two lowest points obtained by Sattler [9]. The superimposed curve is taken from Lindhard et al.[11]. There is reasonable agreement between the theoretical calculations and the observed values (Lindhard et al. state that the assumptions made in their model may lead to errors of order 10 %). The ratio between the ionisation produced by a recoiling Silicon nucleus and an electron ranges from 0.25 at 3.4 keV up to 0.4 at 22 keV.

Results

To set limits on the Cosmion mass and cross-section on Silicon, the measured energy spectrum is compared with that expected from Cosmions. The expected spectrum has roughly an exponential shape (see Figure 1). Its mean value depends on various factors : the v_{rms} value of the assumed maxwellian Cosmion velocity taken to be 300 km/s, the velocity of the Earth around the galactic center estimated to be 230 km/s, the mass of the target Silicon nucleus (well known) and of course the mass of the Cosmion. The normalisation of this distribution varies with the Cosmion mean density at the Earth /Sun galactic radius, taken to be 0.3 $GeV/c^2/cm^3$ and with the Cosmion cross section, which is the second unknown. Those parameters reflect current estimates and the effect of the biggest uncertainties on the results is discussed below.

In Figure 3 is plotted the exclusion region for coherent vector coupling Cosmions. Masses and cross-sections on Silicon above and to the right of the dash-dotted line are excluded. The exclusion contour is obtained by two different procedures using maximum likelihood methods. One involves using the region 1.1-1.5 keV most sensitive to light Cosmions and fitting that small region with a straight line, then adding Dark Matter signal to the fit (allowing the parameters of the "background" line to change) until the fit can be rejected at a confidence level of 95 %. The other procedure uses a fit to a large region (up to 225 keV) of the data, including the shapes of known backgrounds. The final conclusion of the two analyses are in close agreement. Figure 3 also shows the contour obtained for a low value of 260 km/s for v_{rms}.

For the assumptions given above are also plotted the 2 SNU and 2.5 SNU curves obtained with the Saclay standard solar evolution code [2]. These curves represent the various mass and cross section combinations for which the Cosmion mechanism works and reduce the solar neutrino flux to the above quoted values while keeping the present observed characteristics of the Sun. Cosmions with coherent vector coupling become very unlikely, but are still not completely ruled out due to the uncertainties in the Dark Matter halo parameters, especially v_{rms}. More details on this analysis can be found in ref [12].

We are planning a new Si(Li) detector with lower threshold in order to have sensitivity below the remaining allowed mass region.

2 Axial Coupling Cosmions and the status of a Hydrogen TPC

Principle

For particles with spin-dependent couplings, suitable detectors do not exist yet. We have proposed [13] and are currently studying the use of a low pressure Hydrogen Time Projection Chamber (TPC) in a magnetic field.

A low pressure TPC provides in principle the imaging capacity for keV proton recoil tracks. A low pressure (20 torr) is necessary in order to obtain a track of a reasonable length (3 cm for 1 keV protons in hydrogen). The magnetic field can be adjusted so that keV electrons spiral while keV protons leave a rather straight track. This should allow the measurement of the direction of recoil protons. An observed correlation with the direction opposite to the Earth's movement relative to the center of the galaxy would be a beautiful signature for Dark Matter. A TPC of around 1 m^3 could be sensitive to Cosmions with an interaction cross-section of 4 pb at the level of 1 event/day, if the background can be kept low enough.

As for the question of the amount of ionisation produced by keV energy protons, proportional counters filled with hydrogen and methane are commonly used to measure neutron fluxes of energy between 1 keV and 1 MeV in experiments of material testing for breeder reactors. Protons down to 2 keV do produce electron-ion pairs in hydrogen with the same efficiency as electrons and higher energy protons (about 30 eV /ion-electron pair) [13].

Tests with a prototype

A.Breskin, a world expert in low pressure chambers, gave us one prototype which was no longer of use to his group. A series of measurements with a pulsed UV lamp convinced us that a second stage of amplification was needed in order to reach a reasonable gain and stable working conditions at the single electron level. With this set up, we measured longitudinal and transverse diffusions for different conditions in ethane and methane, and verified the results obtained previously by Breskin et al. We are now proceeding to measurements with hydrogen and hydrogen mixtures and results should come out soon. We also built a magnet (Helmholtz coils, 1kGauss) in which the chamber was installed in order to check the focalisation of drifting electrons in the magnetic field. Indeed the measured transverse diffusion is reduced according to expected factors.

To determine whether a 1 to 2 keV proton gives a recognizable track, we plan to use neutrons to induce proton recoils. We have installed the chamber with the magnet in the neutron beam of Bruyères-le Chatel for a test run. The multistep TPC is a very sensitive device and has difficulty operating in a large background environment. We have managed to shield the detector well enough that it could run reliably with standard beam luminosities.

Data is being analysed and we are hoping that the foreseen improvements (Flash ADC, better shielding and better alignment) will provide us in the next months the answers necessary for deciding if a 1 m^3 detector for Cosmion search is feasible.

Radioactive background study

An important effort on the choice of low radioactive material has been carried out by the double beta experiments. Many groups have built low radioactive drift chambers. Their experience is important for the final design of a Dark Matter TPC. The Orsay LAL group is helping us designing and building a low radioactivity Geiger tube detector with which we plan to measure the background rates and, if possible, identify their different origins. The test is planned for the fall 1990 in the Fréjus Tunnel, at the Modane Underground Laboratory (LSM).

3 Sodium Iodide NaI

Motivations

NaI is a scintillator well known for its high light yield, 2000 to 3000 p.e. (photoelectrons) per MeV with standard photo-multiplier tubes and reasonable light collection efficiency. This suggests that keV energies are reachable. Indeed, energies as low as 0.87 keV have been measured with NaI, corresponding to 3 detected p.e. [14].

Another interesting feature is that ^{23}Na and ^{127}I have non zero spins, which makes NaI well suited for axial vector coupling WIMP's search. However, it should be noted that natural Germanium is composed of a sizeable fraction (7.7 %) of a non zero spin isotope, ^{73}Ge, and limits can already been set on axial vector coupling WIMP's with data from existing double beta Germanium experiments. Keeping in mind the uncertainty in the calculation of axial vector coupling WIMP's cross sections with different nuclei (see introduction), one can roughly estimate the performances that a NaI detector should reach in terms of energy threshold and residual radioactive backgrounds to be competitive with ^{73}Ge, assuming equal spin factors; we found that the threshold should be as low as 4-5 keV with a residual background of 5 evts/kg/day/keV. These numbers are not out of reach, especially in view of the Na recoil measurement results reported below.

In any case, NaI is a more "convivial" detector than bolometers and is being investigated by various groups (Munich, Rome, Rutherford) and we found it worthwhile to study its response to nuclear recoils, a crucial point for WIMP's detection.

Na recoil response calibration

In the course of our Silicon calibration runs at Bruyères le Chatel (see section 1), we also measured the response of a small NaI crystal to recoils of Sodium nuclei of energies between 12 and 70 keV. The principle of the method is exactly the same as for the Silicon; some specific experimental details are given below.

The crystal used was 30 mm in diameter and 30 mm high. Double scattering of neutrons was limited to around 10 %. The crystal was coupled to a 2 " PMT via a plastic light guide 20 cm long. The energy calibration was done with the 60 keV line of a ^{241}Am source, corresponding to 120 p.e. detected, that is 2 p.e. per keV.

An advantage of the NaI over the silicon is its better time resolution which allows to keep the background due to accidental concidences very low, by proper time of flight selections.

As the NaI has a rather long light decay time (≈ 230 ns), one expects that for low energy events, the signal is not a nice exponential but a succession of single or few p.e. peaks (Figure 4). The first peak has then a non negligeable probability to be at the single p.e. level. In order to get the lowest energy threshold, the signal was discriminated at a small fraction of the single p.e. pulse height. In addition, not be overwhelmed by single p.e. triggers, the NaI trigger logic has been set up to accept only events with at least 3 discriminated pulses within 1 microsecond. The corresponding energy threshold was around 1.5 keV. This NaI trigger signal was then put in coincidence with the scattered neutron counter signal in order to generate the event trigger.

To measure the pulse height, the NaI analog signal was integrated during 1 μs and was also sent in a wave form digitiser (160 Mhz sampling) in order to study a possible shape difference between electron and nuclear recoil induced events.

The results presented here are preliminary as the data has been obtained recently and is still being analysed. They present interesting features worth being presented here.

Figure 5 shows the measured energy measured in the NaI as a function of the recoil energy of the Na nucleus. We infer that the recoil occurred on a Na nucleus rather than on a I nucleus from the expected kinematics : when a Na recoil of 30 keV is expected, for instance, the expected energy of the I recoil with the same set up is only 6 keV while the measured energy is 7.3 keV.

Signals can be measured down to recoil energies of 12 keV, and correspond to ratios $E_{\text{light recoil}}/E_{\text{recoil}}$ of 23-25 % compatible with being constant over the range 12-70 keV. It should be noted that the NaI response to electrons is not linear over this range [15], which makes a definition of the ratio $E_{\text{light recoil}}/E_{\text{light electron}}$, similar to the Silicon case, rather complicated. Not taking into account this effect of the order of 20 to 30 % , the ratio $E_{\text{light recoil}}/E_{\text{recoil}}$ appears smaller than for Silicon (35-40 %, see section 1) but definitely higher than for proton recoils in plastic scintillator (≈ 10 %) [16]. A measurement has been made for a Na recoil energy of 7 keV, but very few events were observed, which suggests some cut-off between 7 and 12 keV.

Measurements of the response of NaI to heavy nuclei of 200 kev to 1 MeV energy [17] also show a high light yield, suggesting reduced quenching effect .

Very interesting is the observation of different pulse shapes for Na recoil and X-ray induced events. Figure 6 shows pulse shapes summed over 50 events for 37 keV energy Na recoil events (10 keV mean observed energy) and for the 14-18 kev X-ray lines from a ^{241}Am source. The X-ray profile exhibits a longer decay time (exponential fitted value of 210 ns) than the nuclear recoil one (160 ns). However, the X-ray fit is much worse than the nuclear recoil one and the shape is probably more adequately represented by a plateau of 150 ns followed by a steeper exponential. More detailed analysis is going to be performed on this point. Surprisingly, the same behaviour difference has been noted by Birks [18] for MeV alpha's and MeV's photons.

The results are quite encouraging, but to get to a full scale D.M. detector, one obviously needs very pure materials and low radioactive background environments. Active shielding, low radioactivity PMT's and active light guide are presently being studied.

4 Bolometers

Bolometric devices could become the D.M detectors of the future as they can reach, in principle, resolutions well below 1 keV even for massive crystals, say 100-1000 g. On the other hand, simultaneous measurement of heat and ionisation or light should bring the capability of rejecting the radioactive background. State of the art is far from achieving such performances, but progress is being made quite rapidly (Munich, Berkeley, Paris, Milan).

We (M.C., G.C.) planned 2 years ago, starting from scratch, to reach a reasonable goal (1% resolution for 5 MeV's alpha's from ^{241}Am for a 1 g crystal) in a reasonable time scale (1-2 years). This goal has actually been fulfilled. In addition, we obtained a reasonable ($\approx$10%) energy resolution on 60 keV photons from ^{241}Am, a result indicating that keV resolutions on several gram crystals may be achieved relatively soon. The main experimental features are the followings.

The first characteristics is the use of commercial RuO_2 thick resistive films as the thermic sensor; their interest resides in the reproducibility of their impedance together with the possibility of intimate coupling to the crystal by melting. This melting of the RuO_2 powder on the substrate requires a high temperature (800 °C) and has been found to work well on Silicon and Al_2O_3. The present results have been obtained with a 10x10x1 mm Al_2O_3 crystal coupled to a 10 μ thickness film.

The second characteristic feature is the use of a quick handling dilution refrigerator requiring only 4 hours to reach its lowest temperature, 50 mK, starting from 300 K.

Performances of the described bolometer should be greatly improved by reducing the RuO_2 film thickness and using lower temperatures ($\approx$10 mK). Not only would this reduce the heat capacity of the film, found to be much larger than that of the crystal, but this would also allow a higher excitation voltage, and thus a higher signal/noise ratio. More details can be found in reference [19].

We are planning a calibration run with a cryostat and a diamond or silicon bolometer in a neutron beam at the end of June as well as the construction of a low radioactive cryostat for measurements in the Modane Underground Laboratory.

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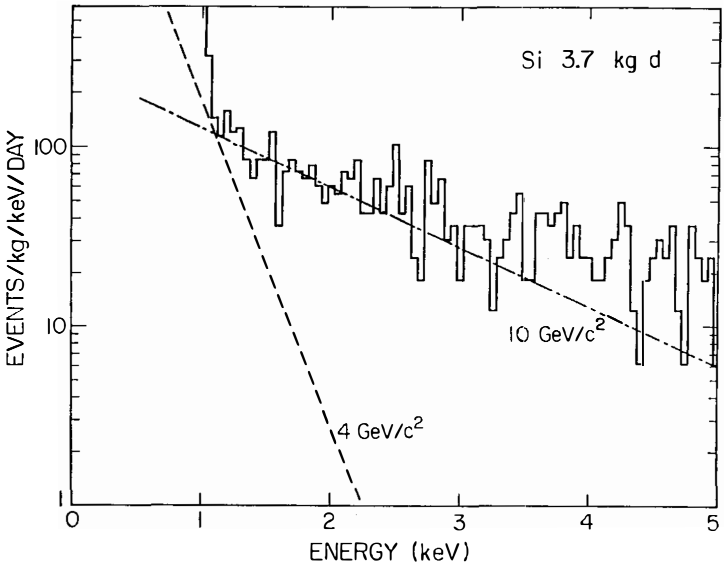

Figure 1 : Low energy region of the ionization detected in the 17 g Si(Li) detector for 3.7 kg.days of data. Also shown are the signals expected from 4 and 10 GeV/c^2 Cosmions with corresponding cross sections on the exclusion contour (v_{rms} = 300 km/s) of Figure 3.

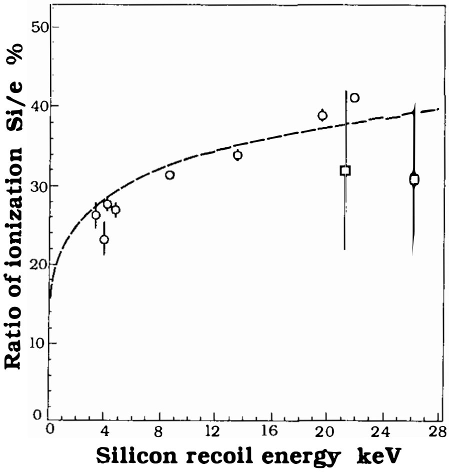

Figure 2: Ratio between the ionisation produced by a Si recoil and the ionisation produced by an electron of the same kinetic energy as a function of the kinetic energy. Circles are data points from the present experiment. Squares are from Sattler [9], the curve represent the prediction by Lindhard et al. [11].

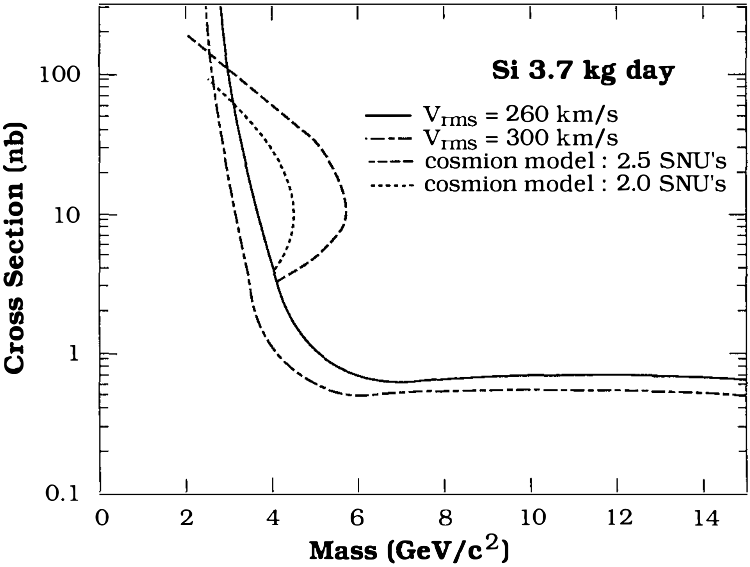

Figure 3 : Exclusion plots for two values of the velocity of Dark Matter particles as functions of their mass and elastic cross section on Silicon. Also shown are the expected curves where should lie the Cosmions for a resulting neutrino flux of 2 and 2.5 SNU's [2].

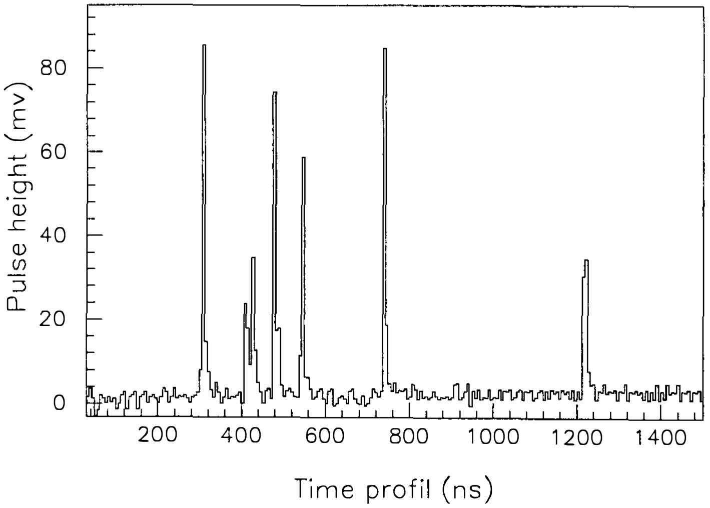

Figure 4 : Time profile of a single 4.7 keV energy Na recoil induced pulse (≈ 9 p.e.). The bin size is 6.25 ns. Individual p.e. peaks are clearly seen.

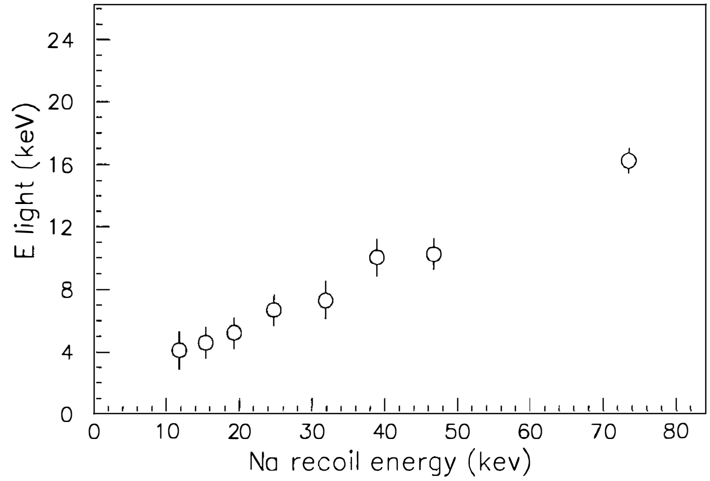

Figure 5: Mean observed luminous energy induced by Na recoils as a function of the Na recoil energy. The energy calibration was done with the 60 keV line of a ^{241}Am source.

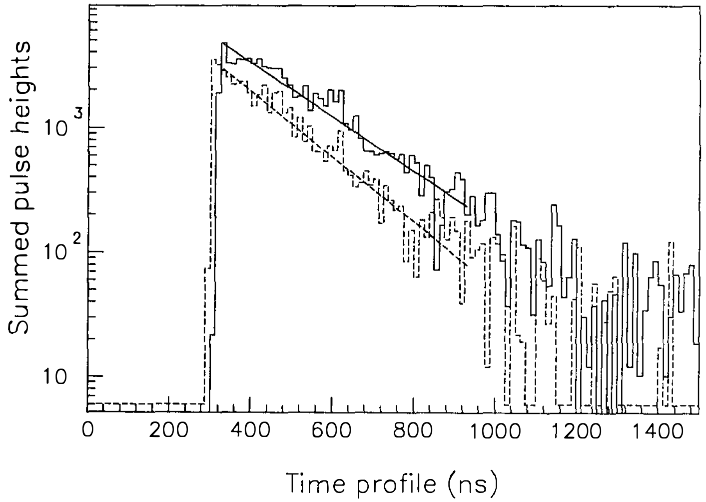

Figure 6 : Time profile summed over 50 events for 14-18 keV X ray (full line) and for Na recoils (dashed line). The straight lines are exponential fits which show the different decay times (see text for more details).