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THE SCINTILLATING CRYSTAL DETECTOR
FOR THE DARK MATTER SEARCHES
(Proposal)

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Protvino 2002

Abstract

Akopdzhanov G.A., Blick A.M., Kozelov A.V. et al. The Scintillating Crystal Detector for the Dark Matter Searches. (Proposal): IHEP Preprint 2002–31. – Protvino, 2002. – p. 7, figs. 2, refs.: 16.

The study of the crystal scintillating detector (based on pure CsI) is proposed with the aim of use in future Dark Matter searches. The planned energy range of the recoil nuclei detection between 2 and 40 keV allows to register neutralino interactions with masses up to 100 GeV/c^2.

Аннотация

Акопджанов Г.А., Блик А.М., Козелов А.В. и др. Детектор на сцинтилляционных кристаллах для поисков темной материи. (Предложение): Препринт ИФВЭ 2002–31. – Протвино, 2002. – 7 с., 2 рис., библиогр.: 16.

Предлагается исследовать сцинтилляционный детектор на основе чистого CsI для дальнейшего использования в поисках темной материи. Планируемый энергетический диапазон регистрации ядер отдачи от 2 до 4 кэВ позволит детектировать взаимодействия нейтралино с массами до 100 ГэВ/с^2.

Short review of the Dark Matter search experiments

Recent astrophysical studies indicate that the part of the matter in the Universe is of a non-baryonic nature. The cosmological models give satisfactory description of the formation process of the spiral galaxies under assumption that nearly 70% of its mass is due to the so called "Cold Dark Matter" (CDM). It is generally assumed that the dark matter halo is present in our Galaxy with the density around 0.3 GeV/cm^3 in the vicinity of the Solar System. It is usually assumed that the invisible dark matter forms a nonrotating spherically symmetric cloud in the center of the Galaxy with the Maxwellian distribution of the velocities.

The most probable candidates for such dark matter halo are Weakly Interacting Massive Particles ($WIMP's$), predicted in supersymmetric models. The recent searches of these particles in the frame of the Minimal Supersymmetric Model (MSSM) at the Tevatron and LEP colliders still have no positive results. An upper limit for the mass of the lightest neutralino (a mixture of photino, zino and higgsino) is $m_{\chi_1^0} > 32.5 \ GeV$ [1].

In addition to the accelerator experiments one can look for elastic and inelastic interactions of the relic $WIMP's$ with the detectors material. Under the different assumptions the collision frequency can vary from 0.001 to 1 $\frac{events}{kg \cdot day}$ [2].

Around twenty neutralino search experiments are now working or under the planning. There are two different groups of the experiments. The low mass detectors look for the scatterings on detector nuclei which are not explained by the background radiation. The high mass detectors look for the seasonal variations of the counting rates possibly connected with the Earth circulation around the Sun.

The value of the minimum collision frequency can give us the estimation of the background conditions for an "ideal" neutralino registering detector. Let us assume that background and useful event rates are equal, this gives the background rate level around 0.00001 $\frac{events}{kg \cdot day \cdot keV}$ in the $\sim 100 \ keV$ recoil nuclei energy range. Surely this background level rate is unreachable.

The data analysis of the current experiments shows that the main background contributions are radioactive admixtures in detector materials and its surrounding and also neutrons in the MeV-range originating from high energy interactions of cosmic muons. The low background setup needs special conditions — underground laboratories, very low radioactivity of the materials in use, powerful cosmic radiation shielding, etc. Various physical methods of background rejection are also used.

One of the ways to discriminate the background is to use the different ionization losses of electrons and recoil nuclei in the same dense materials. For instance an electron signal in a Ge–counter exceeds several times a signal given by recoil nucleus. As a rule, the phonon signal depends on the total energy release of a particle. Such a method of the background suppression with the Ge–detector at mK–temperatures was used in the CDMS [3] setup, where authors found 3 events treated as CDM elastic scattering.

It should be be stressed that the background level achieved for low mass detectors is of the order $0.01 \frac{events}{kg\cdot day\cdot keV}$ [4] for recoil nuclei energy $10-100 \ keV$. This background sharply increases if one register particles with energies less than $5 \ keV$. The better background rejection than indicated above is planning to achieve in the DRIFT setup [5]. This experiment is starting in the nearest time with the aim to look for $WIMP's$ with masses $\sim 1000 \ GeV$.

Among the current experiments the highest mass of the active detector medium is used by the DAMA ($\sim 100 \ kg$) [6,7] and ELEGANT V (662 kg) [8] experiments (they used crystals of $NaI(Tl)$). Other experiments using the same technique have much smaller weight of crystals. The main goal of these experiments is to measure recoil nuclei energy spectra which can be used for extracting of the neutralino interaction cross–section and mass. The signature of Dark Matter in these experiments is the seasonal modulation of the signal.

The total background level of such detectors is usually two order of magnitude more than compared to cryogenic experiments, but it can be significantly lowered using extremely pure materials. The special technique is used to reduce the natural radioactivity of crystals and photomultipliers (PMT). Each crystal of the DAMA detector ($\sim 10 \ kg$) is viewed by two photomultipliers from opposite sides (the noise frequency of each PMT is about $0.1 \ kHz$). During the data taking the pulse shape of each PMT is stored with the following discrimination. The discrimination is based on the fact that the recoil nucleus have a much shorter scintillating time than the electrons. The high temperature stability is required to analyze the pulse shape — it is better than $1°C$ in the DAMA detector. In the latest DAMA publications $2 \ keV$ energy threshold for X-rays is given (taking into account quencher-factor the threshold for recoil nuclei is about $10 \ keV$). One should mention that they don't present analysis of the efficiency of the pulse shape discrimination near the registration threshold. Using seasonal variations analysis they obtain neutralino mass equal to $40 \div 50 \ GeV$ and cross-section $5 \div 7 \ pb$ per nucleon [7].

Experiment ELEGANT V has made one year exposure of the $NaI(Tl)$ crystal setup. Some modulation at the level of statistical fluctuations has been observed [9]. The main background in this experiment is due to the high concentration of the ^{222}Rn in the underground laboratory. It is planned to move the setup to the new underground hall with a lower radon contamination.

Another high mass detector experiment of the CRESST [10] collaboration is planning to carry out one year exposure of the "heavy" scintillator $CaWO_4$ (total weight 100 kg) at the liquid helium temperature $12 \ mK$. Each crystal is viewed by both a photodetector and a bolometer to obtain a sufficient background rejection. The background rejection of electrons of $\sim 99.9\%$ at the $15 \ keV$ is planned. This experiment is expected to provide the background rate level about $1 \frac{events}{kg\cdot day\cdot keV}$.

The main advantage of using the scintillating crystals ($NaI(Tl)$, $CsI(Tl)$ etc.) in dark matter search experiments is relatively low cost and simplicity of setup. This gives a possibility to construct an apparatus with larger working mass. From our point of view there are two significant drawbacks in the existing experiments (DAMA, ELEGANT V). One of them is their inability of full background rejection in the experiment. Another one is a relatively high energy registration threshold if compared with Ge detectors. For example, usage of only two PMTs for

the large ($10 \times 10 \times 100 \ cm^3$) scintillating crystal in ELEGANT V leads to a high threshold because geometric acceptance is significantly less than 4π. Random coincidences of PMT signals during luminescence decay time give contribution into the background even with a low single electron PMT noise level and their suppression decreases the efficiency of low-energy recoil nuclei registration.

It should be mentioned that in cryogenic detectors (where ionization and thermal signals are compared) the registration threshold is about several hundreds eV, but electrons and recoil nuclei could not be distinguished at $\sim 3 \ keV$ and reliable discrimination in different setups starts only at $10 - 15 \ keV$.

Also the recoil discrimination by the electronic analysis of the pulse shape, as used in the DAMA experiment, is questionable for small signals. Indeed, let us assume that the scintillator with PMT is exposed to the pulsed neutron and gamma ray sources and the pulse shape is registered (triggering from the pulsed source). With the signal level around 10^3 photoelectrons per pulse we have for nuclei and for electrons two different luminescence decay times of the scintillator. In another extreme case when the signal level is about one photoelectron per pulse of the source and measuring arrival times of the photoelectrons we need near 10^3 pulses in order to measure just the same curves. This simple example shows that for the luminescence decay times of the scintillator and the real integration times of PMT signals the pulse shape discrimination works only above some threshold number of photoelectrons (or above some threshold recoil energy).

So, some progress in the experimental searches of the Dark Matter in the mass region below $100 \ GeV$ can be achieved with cryogenic devices (as CRESST for instance), or using increased detecting mass in DAMA, or a more background rejection in ELEGANT V. If seasonal variations are not detected, using detector mass and background level one could set an upper limit for the neutralino interaction cross-section. The ambitious solution for the determination of the upper limit of the cross-section is proposed in project with one tonne of enriched ^{76}Ge as working material [4]. Another way of solution of this problem is the construction of a high-precision setup with a cheaper detecting material.

Main goals of the project

We propose to build a relatively inexpensive detector with pure CsI for the relict neutralino detection.

CsI could be used because of nonhydroabsorbtion, easy mechanics operations, smaller quenching-factor and the sharp dependence of light yield on the temperature of a crystal. At the temperature of liquid nitrogen its light yield is increased by a factor of 10 with simultaneous increase of light decay time [11,12]. Moreover, CsI crystals have better radioactive background rejection [13] when compared to $NaI(Tl)$, i.e. are more suitable for the detection of recoil nuclei at low energies. Because almost equal atomic weights of Cs and I there is a possibility that their quenching-factors are close, and Monte-Carlo simulation of energy spectra of these nuclei could be simplified.

The energy spectrum of recoil nuclei in the neutralino elastic scattering on the CsI for several values of $WIMP's$ masses with Maxwellian velocity spectrum is shown in Fig. 1. One can observe that quite good efficiency (or number of photoelectrons per 1 keV of the absorbed energy) and recoil nuclei discrimination must be reached in the recoil energy region lower 40 keV.
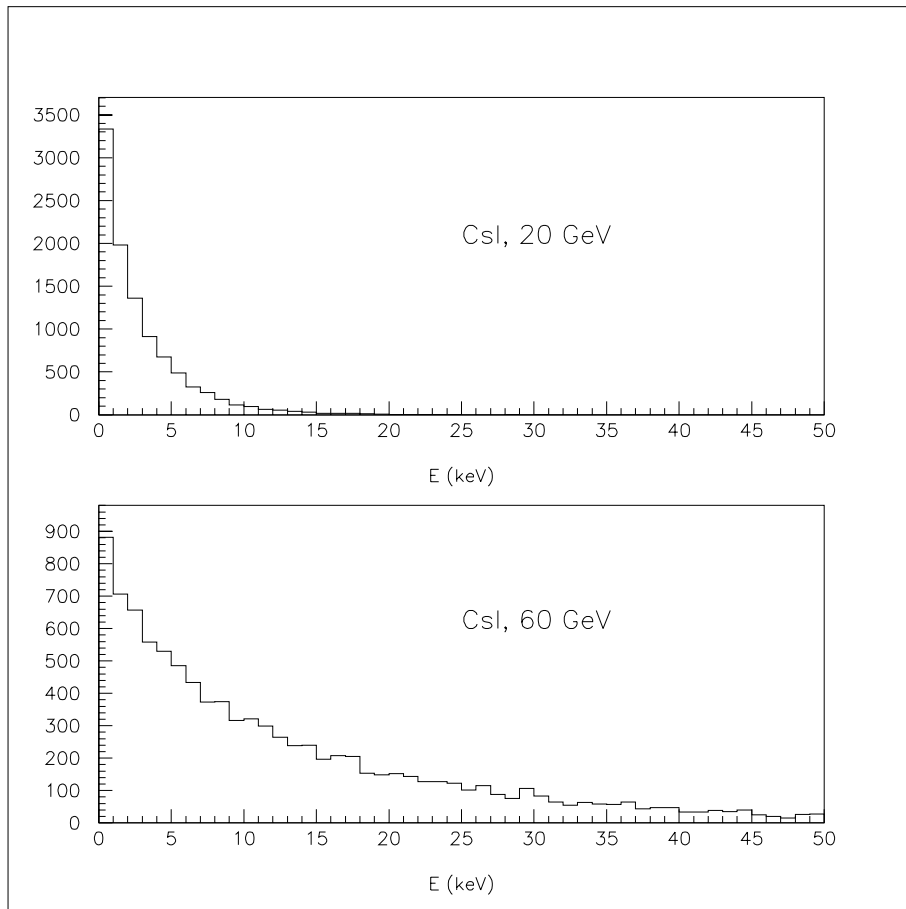
Fig. 1. The energy spectrum of recoil nuclei in the neutralino elastic scattering on the CsI.

During detector design we take into account the following considerations. For the rough estimation we take mean energy for one photoelectron production $\sim 1.5\ keV$. In this case the upper registration limit is about 30 photoelectron. Therefore, optimal detection mode is measurement of arrival times of single photoelectron pulses and their subsequent summation. The upper registration threshold will approximately correspond to energy deposition of a single X-ray quant with energy of 5.9 keV from ^{55}Fe source. Signals larger than this threshold are treated as the background and rejected during data processing.

We suppose to reach good efficiency using optimal choice of crystal size ($\sim 10 \times 10 \times 10\ cm^3$) and geometric acceptance about 4π. Therefore we choose the following design of the modular detector. Planes of a scintillating crystal are observed by six PMTs via quartz light guides. Crystal and PMT input windows are situated inside a copper cassette cooled to the liquid nitrogen temperature. The cassette is put into the center of a shielding box, the function of which is to protect from the surrounding natural radiation.

The employment of six PMTs per crystal increases registration efficiency and simplifies time analysis of single photoelectron signals. The detector cooling reduces PMT thermoemission noise and the frequency of random coincidences is decreased in spite of increased number of PMTs. The PMT noise due to extract of group of photoelectrons from the photocathode could be rejected by the amplitude analysis.

We estimated the production energy of a single photoelectron at the temperature of liquid nitrogen as 500 eV for recoil nucleus (taking into account the rise of quencher-factor with the decrease of recoil nucleus energy [13]). Four detected photoelectrons correspond to recoil nucleus energy about 2 keV. This is the lower limit of the measured recoil nucleus energy.

The 40 kev upper limit means that the electrons and γ-quanta from the external radiation with energy deposition in crystal less than 6 keV will simulate neutralino interactions and give the main contribution into the background. Another background source is interactions of neutrons from the surrounding with the scintillator.

We propose to take into account the background from the external radiation using a background detector. To make a such detector we simply replace the CsI crystal by a plastic scintillator. In this case we can separate to a certain degree interactions of neutrons and γ-quanta. A neutron slowing down in the scintillator could produce two light pulses which correspond to interactions with plastic. The time between pulses is in accordance with the free flight time at a given energy. As plastic light decay time at the liquid nitrogen temperature decreases to several nanoseconds, a possibility of separation will appear. The shortening of the light decay time and the decrease of the PMT noise reduce the probability of accidental coincidence. In this case the total time spectrum of six PMTs of the background detector is the sum of the PMT noise spectra and signals caused by interactions of low-energy electrons and neutrons with the plastic scintillator.

It would be ideal to achieve the equal light yields from the CsI crystals and plastic scintillator for electrons with energies lower than 6 keV by variation of the detector temperature. But even if this goal could not be achieved, the measurements of energy losses of γ-quanta in the organic scintillator will give a possibility to reconstruct energy spectrum of the external γ background. To achieve this goal characteristics of both modules should be almost identical.

The time spectra of all PMTs with tight photocathodes are measured before and after the measurements.

In energy region of neutralino registration there is also a background originating form nuclear transitions in scintillating crystal leading to the production of radioactive isotopes, X-rays and Auger electrons. Careful measurements of crystals in this energy range are required to identify the isotopes. However, the knowledge of some background conditions is an advantage of the proposed detector when compared to the existing setups for dark matter searches.

The counting rate of each PMT (less than 1000 Hz) defines requirements for electronics. A common timer with time resolution 1 ns is used. Fast amplifiers are installed on the PMT base to amplify anode and last dynode signals. The anode signals are digitized flash ADC. The dynode signal is used to form a logic signal and their arrival times are digitized also.

It should be mentioned that after measurements of real time spectra the electronics could be optimized.

There is a plan to research the temperature dependence of light yields due to recoil nuclei, electrons and neutrons in the CsI and organic scintillator. The calibration of the detecting crystal could be performed with the γ-quanta from ^{55}Fe source (energies are 5.9 keV and 2.5 keV). For CsI in the single photoelectron mode one should observe two peaks in energy spectrum.

The disadvantages of the proposed detector are a relatively small scintillator mass and six PMTs per module. The PMTs with small content of radioactive materials are required, and their cost will define the cost of the whole detector. It could also turned out that natural radioactivity of PMT's is one of the main sources of the background. As for the scintillating

crystals, available crystals have various shapes and cutting them to the cubic shape will lead to the loss of scintillating material. Besides it's desirable to have a crystal of the largest possible weight.

For large crystals it will be very promising to use gas electronic multipliers (GEM) instead of PMTs. Classic schematics of GEM by F.Sauli is presented in Fig. 2 [14].
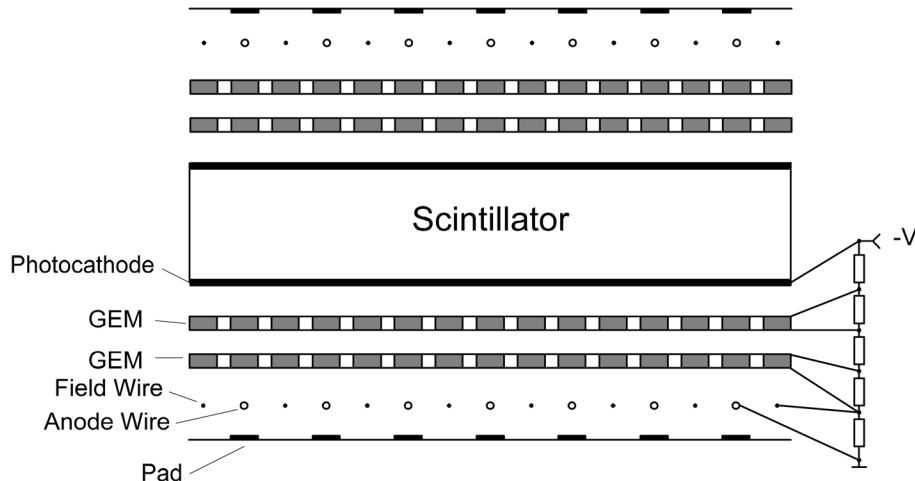

Fig. 2.   Schematics of the scintillating crystal with GEM photomultiplier.

Let us consider $10 \times 10 \times 100 \ cm^3$ scintillating crystal. Usually crystals of such a shape are viewed by two PMTs on small edges. We propose to glue thin quartz plates with visible light photocathodes to two opposite large edges. After the gas gap two GEMs with total amplification about 100 are situated. The amplifier consists of a capton film with small holes in which gas amplification takes place. Film thickness is 50 μm and its production is organized at CERN. The main amplification takes place near anode wires. Signals from wires and pads are registered. Gas mixture works in the limited proportional mode (when there is no transition between the limited mode and Self Quenching Streamer mode). In this case we will have anode signals with the amplitude about 30 mV and length $\sim 30 \ ns$ at 50Ω load [15].

For the background detector with PMTs the pile-up of signals from neutrons with small free flight times is very probable. A better spatial resolution of GEM could eliminate this problem.

Several groups carry out researches of visible light photocathodes which will be stable at normal atmosphere conditions. The best result for quantum sensitivity is ~ 0.03 [16]. It's about ten times worse than for PMTs but this loss will be compensated by better light collection efficiency.

Replacement of PMTs to GEMs in dark matter detector has obvious advantages - miserable quantity of passive material, good spatial resolution and decrease in detector cost.

Conclusions

We propose the scintillating crystal detector for the Dark Matter searches. Some advantages of the proposed detector are summarized below.

1. For CsI the lower energy limit of the recoil nuclei detection will be $\sim 2 \ keV$ due to the use of the almost 4π–geometry, the liquid nitrogen working temperature, the single photoelectron

regime of the photomultipliers. This allows effective neutralino interactions search in the mass range 20–100 GeV/c^2.

2. The proposed method of the detector testing allows to carry out the careful studies of the background conditions and to estimate an upper limit of the $WIMP's$ interaction cross-section.

3. The modular detector structure allows to increase scintillator mass in the future.

4. The interaction point of the recoil nucleis (or of the background electrons) in the scintillator and the dependence of light emission time on particle type will be taken into account during the data processing.

5. The electronics of the proposed detector is much simpler and cheaper when compared with all existing or planned devices with analogous aims.

6. For large scintillating crystals PMTs could be replaced by GEMs. This allows to improve background conditions and reduce detector cost without loss of efficiency.

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Препринт отпечатан с оригинала-макета, подготовленного авторами.

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Детектор на сцинтилляционных кристаллах для поисков темной материи. (Предложение).

Оригинал-макет подготовлен с помощью системы L^AT_EX.