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ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА. ЭКСПЕРИМЕНТ

DIRECT DARK MATTER INVESTIGATION

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Experimental efforts and theoretical developments support that most of the Universe is dark and a large fraction of it should be made of relic particles; many possibilities are open on their nature and interaction types. This motivates experimental efforts to investigate the direct detection of these particles with various techniques. In particular, experiments offering a model-independent signature for the presence of Dark Matter (DM) particles in the Galactic halo are mandatory. In this paper, some general arguments will be summarized and particular care will be given to the results obtained by the DAMA/LIBRA experiment (sensitive mass: ~ 250 kg) at the Gran Sasso National Laboratory of the INFN by exploiting the model-independent DM annual modulation signature with highly radiopure NaI(Tl) target-detectors. Cumulatively with the former DAMA/NaI experiment (sensitive mass: ~ 100 kg) an exposure of 1.17 t $\cdot$ y, collected over 13 annual cycles, has been released so far; a model-independent evidence of the presence of DM particles in the Galactic halo is supported at 8.9σ confidence level (C.L.). In addition, experimental and theoretical uncertainties and their implications in the interpretation and comparison of different kinds of results will be shortly addressed. Some perspectives will be mentioned.

Экспериментальные наблюдения и теоретические исследования указывают на то, что Вселенная, в основном, темна и большая ее часть состоит из реликтовых частиц, природа которых и типы их взаимодействий еще неизвестны. Поэтому усилия многих исследователей направлены на прямое наблюдение этих частиц при помощи различных экспериментальных методик. В частности, необходимы эксперименты, использующие модельно независимые сигнатуры присутствия темной материи в гало нашей Галактики. В этой работе мы сделаем общий обзор экспериментальных подходов, акцентировав внимание на результатах эксперимента DAMA/LIBRA (чувствительная масса ~ 250 кг), проводимого в Национальной лаборатории Гран-Сассо (INFN) и использующего модельно независимую сигнатуру годовой модуляции сигнала от темной материи в мишенном детекторе высокой радиоактивной чистоты. Совместно с предыдущим экспериментом DAMA/NaI (чувствительная масса ~ 100 кг) общая экспозиция эксперимента, полученная в течение 13 лет набора экспериментальных данных, составляет 1,17 т $\cdot$ лет. В результате получено модельно независимое указание на существование темной материи в галактическом гало со статистической значимостью 8,9 стандартных отклонения. В работе также кратко обсуждаются экспериментальные и теоретические неопределенности и их влияние на интерпретацию результатов и сравнение с другими типами данных. Обсуждаются дальнейшие перспективы исследований.

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INTRODUCTION

The problem of the existence of Dark Matter in our Universe dates back to the astrophysical observations at the beginning of the past century, but its presence in our Universe has been definitively accepted by the scientific community only about 40 years later, when two groups performed systematic measurements of the rotational velocities of celestial bodies in spiral galaxies. After the 1970s many other observations have further confirmed the presence of Dark Matter in the Universe and, at present, the measurements are mainly dedicated to the investigation of its quantity, its distribution (from the cosmological scale down to the galactic one) and its nature.

In particular, the measurements of the cosmic microwave background (CMB) temperature anisotropy by WMAP, analyzed in the framework of the Big Bang cosmological scenario, are consistent with a flat geometry of the Universe and, therefore, support a Universe density $\Omega = \rho/\rho_c \simeq 1$ (where ρ is the average density of matter and energy in the Universe, and $\rho_c = 1.88h^2 \cdot 10^{-29}$ g $\cdot$ cm^{-3} is named critical density; $h \simeq 0.7$) further crediting that most of the Universe is dark. In fact, the luminous matter can only account for a density $\simeq 0.007$. However, the detailed composition of Ω in term of matter, Ω_m, and of energy, Ω_Λ, cannot be inferred by the CMB data alone; thus, the results of dedicated observations on supernovae type Ia at high red-shift as standard candles and those on clusters have been included obtaining a «concordance model» which supports that $\simeq 74\%$ of Ω is in form of a dark energy and $\simeq 26\%$ is in form of matter. Other kind of observations and models has allowed one to credit that the latter is made of $\simeq 4\%$ baryonic matter, of $\lesssim 1\%$ neutrinos and of $\simeq 22\%$ Dark Matter particles not described in the Standard Model of particle physics. Thus, large space for Dark Matter particles in the Universe exists.

In particular, as regards our Galaxy, from dynamical observations one can derive that it is wrapped in a dark halo, whose density nearby the Earth has been estimated to be, for example, in [1,2]: $\rho_{\rm halo} = 0.17{-}1.7$ GeV $\cdot$ cm^{-3}. It is evident the relevance to experimentally test the latter by direct model-independent approach.

Many candidates as Dark Matter particles have been proposed having different nature and interaction types as, e.g.: SUSY particles (as neutralino [3] or sneutrino in various scenarios [4]), inelastic Dark Matter in various scenarios [5, 6], electron interacting Dark Matter (including WIMP scenarios) [7], a heavy neutrino of the 4th family, sterile neutrino [8], Kaluza–Klein particles, self-interacting Dark Matter, axion-like (light pseudoscalar and scalar candidate) [9], mirror Dark Matter in various scenarios [10], resonant Dark Matter [11], DM from exotic 4th-generation quarks [12], elementary black holes, Planckian objects, Daemons [13], composite DM [14], light scalar WIMP through Higgs portal [15], complex scalar Dark Matter [16], specific two Higgs doublet models, exothermic DM [17], secluded WIMPs [18], asymmetric DM [19], isospin-violating Dark Matter [20], singlet DM [21], specific GU [22], SuperWIMPs [23], WIMPzilla [24], and also further scenarios and models as, e.g., [25]. Moreover, even a suitable particle not yet foreseen by theories could be the solution or one of the solutions.

Furthermore, it is worth noting that often WIMP is adopted as a synonymous of Dark Matter particle, referring usually to a particle with spin-independent elastic scattering on nuclei. On the contrary, WIMP identifies a class of Dark Matter candidates which can have different phenomenologies and interaction types; this is true also when considering a precise candidate as, for example, the neutralino. In fact, the basic supersymmetric theory has a very large number of parameters which are by the fact unknown and, depending on the assumptions, they can present well different features and preferred interaction types. Often constrained SUGRA models, which allow easier calculations for the predictions, e.g., at accelerators, are presented as SUSY or as the only way to SUSY, which is indeed not the case.

Other open aspects, which have a large impact on model-dependent investigations and comparisons, are, e.g.: i) the right description of the dark halo and related parameters; ii) the right related atomic/nuclear and particle physics aspects (form factors, spin factors, scaling laws, etc.); iii) how many kinds of Dark Matter particles exist in the Universe, considering the richness in particles of the luminous Universe which is just 0.007 of the density of the Universe with respect to $\simeq 0.22$ of the Dark Matter attributed to relic particles.

1. CONSIDERED APPROACHES AND SOME RELATED RESULTS

The large number of open questions on the topic briefly mentioned above would require the realization of experiments using approach and/or target materials with a wide sensitivity to many of the possibe scenarios. This is not generally the case, and instead various activities have a limited possibility. Let me briefly mention a few aspects of the present situation.

As regards experiments at accelerators, they could prove — when a solid model-independent result would be stated — the existence of some possible Dark Matter candidate particle(s) beyond the Standard Model, but they cannot credit by themselves that this particle is in the halo as the solution or the only solution for Dark Matter particle(s). Moreover, DM candidates and scenarios (even for neutralino) exist which cannot be investigated at accelerators.

As regards the so-called indirect DM searches, they are generally performed as by-product of experiments located underground, underwater, underice or in space having different main scientific purposes. They search for the presence of secondary particles produced by some Dark Matter candidates able to annihilate in the celestial bodies if some specific assumptions are fulfilled. Therefore, the results of similar approaches are restricted to some DM candidates and some particular physical scenarios; in addition, they require the modeling of the existing — and largely unknown — competing background for the secondary particles they are looking for. As regards underwater and underice experiments investigating upgoing muons ascribed to muon neutrino interaction in the Earth and assuming they have been produced in the annihilation of some Dark Matter candidate provided that some particular scenario would hold, results are available from Antares [26] and Icecube [27]; both have observed no excess above their estimation of upgoing muons from atmospheric neutrinos. Similar approaches have been considered in underground detectors as well. As regards the space investigations, an excess of the measured positron fraction above an assumed background model was presented by Pamela experiment [28], but analogous background models also exist with different secondary production giving no very significant deviation. It is worth noting that, since no excess has been observed in the antiproton spectrum, a similar candidate should be «leptophilic»; that is, e.g., not observable by those direct-detection experiments which select just recoil-like events from their measured counting rate, as, e.g., CDMS, EDELWEISS, CRESST, XENON, etc.[1], while it can be detected in DAMA experiments which exploit a different methodology

[1] In fact, to produce results on electron recoils, those experiments should, e.g., abandon the many data selections they apply. Thus, since generally their original counting rate is very large, they are by the fact insensitive to signals from electron recoils. Therefore, such (leptophilic) candidates can hardly be detected by those experiments.

(see later). Anyhow, additional aspects arise when trying to explain the Pamela data in a Dark Matter interpretation since, e.g., a very large boost factor would be required. Thus, this excess can be due to an inadequacy of the model used to describe and propagate all the possible sources of positrons. In literature it has also been shown that some kinds of known sources can account for a similar positron fraction; therefore, no constraint on direct detection phenomenology arises from Pamela positron fraction. Anyhow, if such a possible excess might be interpreted — under some assumptions — in terms of Dark Matter, this would be not in conflict with the effect observed by DAMA experiments. Another possible positive hint from space, that can be compatible with the DAMA result as well, was discussed in [29] considering a particular analysis of some data from FERMI; however, e.g., the inclusion of some other astrophysical objects can offer an alternative explication of the data. All that shows the intrinsic uncertainties of the DM indirect searches to unambiguosly assess the presence of a Dark Matter signal, even in the scenario to which they plan to be sensitive.

It is also important to stress that no quantitative comparison can be directly performed between the results obtained in direct and indirect searches because it strongly depends on assumptions and on the considered model framework. In particular, a comparison would always require the calculation and the consideration of all the possible configurations for each given particle model (e.g., for neutralino: in the allowed parameters space), since a biunivocal correspondence between the observables in the two kinds of experiments does not exist: cross sections in direct-detection case and, e.g., flux of muons from neutrinos (or of other secondary particles) in the indirect searches. In fact, the counting rate in direct search is proportional to the direct-detection cross sections, while the flux of secondary particles is connected also to the annihilation cross section. In principle, these cross sections can be correlated, but only when a specific model is adopted and by nondirectly proportional relations.

The direct detection of DM particles is based on various approaches. The DM interaction processes can be of well different nature depending on the DM particle, thus — considering the many available candidate particles and scenarios and the existing uncertainties on the astrophysical (e.g., halo model and related parameters, etc.), nuclear (e.g., form factors, spin factors, scaling laws, etc.) and particle physics (e.g., particle nature and interaction types, etc.) — a widely-sensitive model-independent approach is mandatory as well as a suitable exposure, and full control of the running condition over the whole data taking.

Indeed, most of the activities in the field release marginal exposures even after many years underground, do not offer suitable information, e.g., about operational stability and procedures during the running periods, and base their analysis on a particular «a-priori» assumption on the nature of the DM particle and its interaction, of all the astrophysical, nuclear and particle physics aspects and parameters.

Originally the so-called «traditional» approach was pursued by simply comparing the measured counting rate with an expectation from an assumed scenario (which implies to adopt many assumptions and approximations). This is the only approach which can be pursued by small scale or poor duty cycle experiments. Recently, to try to reduce the experimental counting rate, large data selections and several subtraction procedures are often applied to derive a set of recoil-like candidates assuming a priori — among others — the nature and interaction type of the DM candidate. It is worth noting that not only many uncertainties in the applied procedures and related efficiencies can exist, but well-known side reactions exist able to give similar recoil-like candidates surviving the applied subtractions. In particular, e.g., the applied subtraction procedures are statistical and the tails of the subtracted populations can give rise to events undistinguishable from recoils as well (recoil-like candidates). Considering that the stability of the running conditions and of the many applied «subtraction windows» is never suitably proved at the needed level of precision, the surviving candidates can never be stated for sure as recoils (induced by neutrons, Dark Matter or whatever else) and any estimation of surviving background events cannot be achieved at the claimed levels of precision.

Although often the limits achieved by this approach are claimed as robust reference points, it can be easily understood that similar results are quite uncertain not only because of possible underestimated or unknown systematics in the large data selections/subtractions (generally claiming a reduction of orders of magnitude) and in some experimental aspects, but also because the results refer only to a certain (generally largely arbitrary) set of assumptions. The accounting of the many existing experimental and theoretical uncertainties can significantly vary the given model-dependent results; moreover, background processes giving rise to recoil-like events exist.

The approach to try to reduce the experimental counting rate by large data selections and subtractions procedures in order to derive a set of recoil-like candidates (assuming a priori the interaction type and the nature of the DM candidate), is pursued by experiments as XENON, CDMS, EDELWEISS, CRESST, etc. Only few of them are mentioned in the following as examples.

In the double read-out bolometric technique, the heat signal and the ionization signal are used in order to try to discriminate between electromagnetic events and the recoil-like ones. This technique is used by CDMS and EDELWEISS Collaborations. In particular, the CDMS-II detector consists of 19 Ge bolometers of about 230 g each one and of 11 Si bolometers of about 100 g each one. The experiment released data for an exposure of about 190 $\mathrm{kg} \cdot \mathrm{day}$ [33] using only 10 Ge detectors in the analysis (discarding all the data collected with the other ones) and considering selected time periods for each detector. EDELWEISS employs a target fiducial mass of about 2 kg of Ge and has released data for an exposure of 384 $\mathrm{kg} \cdot \mathrm{day}$ collected in two different periods (July – November 2008 and April 2009 – May 2010) [34] with a 17%-reduction of exposure due to run selection. These two experiments claim to have an «event-by-event» discrimination between noise + electromagnetic background and recoil + recoil-like (neutrons, end-range alphas, fission fragments, ...) events by comparing the bolometer and the ionizing signals for each event, but their results are, actually, largely based on «a priori» huge data selections and on the application of other preliminary rejection procedures which are generally poorly described and often not completely quantified. An example is the time-cut analysis used to remove the so-called surface electrons that are distributed in the electromagnetic band and in the recoiling one, spanning from low to high energy. No detailed discussion about the stability and the robustness of the reconstruction procedure is given; a look-up table to identify such an event is used but systematical errors on the stability in time of such a table are not discussed. In these experiments few recoil-like events survive the many selections/subtractions cuts applied in the data analysis; these events are generally interpreted in terms of background. It is worth noting that most efficiencies and physical quantities entering in the interpretation of the claimed selected events have never been suitably accounted. In addition, further uncertainties are present when, as done in some cases, a neutron background modeling is pursued. As regards, in particular, their application to the search for time dependence of the data (such as the annual modulation signature), it would require — among others — to face the objective difficulty to control all the operating conditions — at the needed level ($< 1\%$) — despite of the required periodical procedures, e.g., for cooling and for radiation source introduction for calibration as well as of the limitation arising from the reachable duty cycle. For example, the attempt by CDMS-II to search for annual modulation in Ge target has been performed by using only 8 detectors over 30 and using — among others — data that are not continuous over the whole annual periods considered in the analysis [35]; the use of non-overlapping time periods collected with detectors having background rate within the signal box that differ orders of magnitude does not allow one to get any reliable result in the investigation of an effect at the order of some % (see, e.g., arguments in [36]).

The XENON project uses instead dual phase liquid/gas detectors. Experiments exploiting such a technique (like also WARP, ZEPLIN, Dark Side) perform statistical discrimination between nuclear recoil-like candidates and electromagnetic component of the measured counting rate through the ratio of the prompt scintillation signal ($S1$) and the delayed signal ($S2$) due to drifted electrons in the gaseous phase. The XENON100 experiment has released data for an exposure of 224.6 days, using a fiducial volume of 34 kg of XENON target mass [30]. The experiment is affected by a relevant counting rate and, in order to try to lower it, it needs to apply many data selections, subtractions and handling. Each selection step can introduce systematic errors which can also be variable along the data-taking period, and the efficiencies of the adopted procedures are not explained in the needed details. After the selections procedures, an analysis based on some statistical discrimination between the electromagnetic radiation and the recoil-like candidates is applied. Concerns are discussed in literature about the real response of such devices, in particular, to low-energy recoils [31, 32]. The technical performance of the apparatus, confirmed also by similar experiments, has shown that: i) the detectors are affected by strong non-uniformity; some kind of corrections may be estimated and applied, but significant systematics has to be accounted for; ii) the response of these detectors is not linear, i.e., the number of photoelectrons/keV depends on the energy scale and depends also on the applied electric field; iii) the physical energy threshold is not proved by suitable source calibrations in the energy interval of interest; the calibrations are done with external sources (due to the use of electric fields) and the lowest energy calibration point is 122 keV of ^{57}Co; no calibration is possible at the claimed energy threshold; Monte Carlo reconstruction of the spectrum is also required; this limits the sensitivity of the method and the reliability of the results; iv) the use of energy calibration lines from Xe activated by neutrons cannot be applied as routine and the studies on a possible calibration with internal sources in the same running conditions have not been realized so far; v) despite of the small light response (2.28 photoelectron/keVee), an energy threshold at 1.3 keVee is claimed; vi) the energy resolution is poor; vii) in the scale-up of the detectors the performances deteriorate; viii) the behaviour of the light yield for recoils at low energy is uncertain in every case.

The CRESST experiment exploits the double read-out bolometric technique, using the heat signal due to an interacting particle in the $CaWO_4$ crystals and the scintillation light produced. A statistical discrimination of nuclear recoil-like events from electromagnetic radiation is performed. The last data released by the experiment have been collected with 8 detectors of 300 g each one, for an exposure of about 730 kg · day [37]. As regards the cuts and selection procedures applied, most of the above discussion also holds. After selections, 67 recoil-like events have been observed in the Oxygen band. The evaluated background contribution cannot account for all the observed events. The unexplained excess of events and their energy distribution can be interpreted in terms of a WIMP candidate with spin-independent interaction and a mass in the range of 10–30 GeV. This is compatible with interpretations of the annual modulation result previously reported by DAMA in terms of a similar scenario and with the hint reported by CoGeNT (see later). CRESST plans to improve the radiopurity of the set-up in order to reduce the known source of background. Future results are foreseen.

Other positive hints of a possible light Dark Matter signal have been reported by the CoGeNT experiment [38]. The set-up is composed by 440 g, p-type point contact (PPC) Ge diode, with a very low energy threshold at 0.4 keVee. In the data analysis no discrimination between electromagnetic radiation and nuclear recoils is applied; only noise events are rejected. The experiment observes an excess of events with respect to an estimated background in the energy range of 0.4–3.2 keVee. The energy spectrum of the excess is compatible with a signal produced by the interaction of a DM particle with a mass around 10 GeV. In addition, in an exposure of 146 kg · days the CoGeNT experiment also reports an evidence at about 2.8σ C.L. of an annual modulation of the counting rate (see later) in 0.5–0.9 keV with phase and period compatible with a Dark Matter signal. This observed modulation effect with Ge target is similar to the one previously observed with much higher statistical significance by the DAMA Collaboration with NaI(Tl) target.

It is worth noting that — in every case — in experiments using discrimination procedures the result will not be the identification of the presence of DM particle elastic scatterings because of the known existing recoil-like indistinguishable background which can hardly be estimated at the needed level of precision. Finally, the electromagnetic component of the counting rate, statistically «rejected» in this approach, can contain the signal or part of it and will be lost.

To search for DM particles elastically scattering on target nuclei, the approach based on the so-called directionality signature can also be considered. It is based on the correlation between the distribution of the recoiling events with the galactic motion of the Earth. In practice, this approach has some technical difficulties because it is arduous to detect the short-recoil track. Different techniques are under consideration but, up to now, they are at R&D stage and have not produced yet competitive results in the field (see, e.g., the DRIFT project or the DM-TPC experiment). To overcome such a difficulty, it has been suggested the use of anisotropic scintillator detectors [39]; in particular, low-background $ZnWO_4$ crystal scintillators have been recently proposed since their features and performances are very promising [40]. We also recall the new idea of using DNA for nanometer tracking [41].

In conclusion, suitable experiments offering a model-independent signature for the presence of Dark Matter particles in the Galactic halo are mandatory. In particular, the use of the highly radiopure DAMA/LIBRA (and, previously, DAMA/NaI) NaI(Tl) scintillators as target-detectors offers many specific advantages thanks to, e.g., the intrinsic radiopurity, the large sensitivity to many of the DM candidates, the interactions of astrophysical, nuclear and particle physics scenarios, the granularity of the set-up, the data taking up to the MeV scale (even though the optimization is made for the lowest energy region), the full control of the running conditions, etc.

2. THE ANNUAL MODULATION SIGNATURE AND THE DAMA PROJECT

The DAMA project is an observatory for rare processes located deep underground at the Gran Sasso National Laboratory of the INFN. It is based on the development and use of low-background scintillators. Profiting of the low-background features of the realized set-ups, many rare processes are studied [7–9, 42, 44–60].

The main apparatus, DAMA/LIBRA, is investigating the presence of DM particles in the Galactic halo by exploiting the model-independent DM annual modulation signature.

In fact, as a consequence of its annual revolution around the Sun, which is moving in the Galaxy traveling with respect to the Local Standard of Rest towards the star Vega near the constellation of Hercules, the Earth should be crossed by a larger flux of Dark Matter particles around $\sim$ June 2nd (when the Earth orbital velocity is summed to the one of the solar system with respect to the Galaxy) and by a smaller one around $\sim$ December 2nd (when the two velocities are subtracted). Thus, this signature has a different origin and peculiarities than the seasons on the Earth and than effects correlated with seasons (consider the expected value of the phase as well as the other requirements listed below). This DM annual modulation signature is very distinctive since the effect induced by DM particles must simultaneously satisfy all the following requirements: i) the rate must contain a component modulated according to a cosine function; ii) with one-year period; iii) with a phase that peaks roughly around $\sim$ June 2nd; iv) this modulation must be present only in a well-defined low-energy range, where DM particles can induce signals; v) it must be present only in those events where just a single detector, among all the available ones in the used set-up, actually «fires» (*single-hit* events), since the probability that DM particles experience multiple interactions is negligible; vi) the modulation amplitude in the region of maximal sensitivity has to be $\lesssim 7\%$ in case of usually adopted halo distributions, but it may be significantly larger in case of some particular scenarios such as, e.g., those in [61, 62]. At present status of technology it is the only model-independent signature available in direct Dark Matter investigation that can be effectively exploited.

The exploitation of the DM annual modulation signature with highly radiopure widely sensitive NaI(Tl) as target material can permit one to answer — by direct detection and in a way largely independent of the nature of the candidate and of the astrophysical, nuclear and particle physics assumptions — the main question: «Are there Dark Matter (DM) particles in the Galactic halo?» The corollary question: «Which are exactly the nature of the DM particle(s) detected by the annual modulation signature and the related astrophysical, nuclear and particle physics scenarios?» requires subsequent model-dependent corollary analyses as those available in literature. One should stress that no approach exists able to investigate the nature of the candidate either in the direct or indirect DM searches which can offer these latter information independently of the assumed astrophysical, nuclear and particle physics scenarios.

The DAMA/LIBRA data released so far correspond to six annual cycles for an exposure of 0.87 $t \cdot y$ [56, 57]. Considering these data together with those previously collected by DAMA/NaI over seven annual cycles (0.29 $t \cdot y$), the total exposure collected over 13 annual cycles is 1.17 $t \cdot y$; this is orders of magnitude larger than the exposures typically collected in the field.

The DAMA/NaI set-up and its performances are described in [44, 46–48], while the DAMA/LIBRA set-up and its performances are described in [55, 57]. The sensitive part of the DAMA/LIBRA set-up is made of 25 highly radiopure NaI(Tl) crystal scintillators placed in a 5-rows by 5-columns matrix; each crystal is coupled to two low-background photomultipliers working in coincidence at single photoelectron level. The detectors are placed inside a sealed copper box flushed with HP nitrogen and surrounded by a low background and massive shield made of Cu/Pb/Cd-foils/polyethylene/paraffin; moreover, about 1 m concrete (made from the Gran Sasso rock material) almost fully surrounds (mostly outside the barrack) this passive shield, acting as a further neutron moderator. The installation has a 3-fold levels sealing system which excludes the detectors from environmental air. The whole installation is air-conditioned and the temperature is continuously monitored and recorded. The detectors' responses range from 5.5 to 7.5 photoelectrons/keV. Energy calibrations with X-rays/γ sources are regularly carried out down to a few keV in the same conditions as the production runs. A software energy threshold of 2 keV is considered. The experiment takes data up to the MeV scale and thus it is also sensitive to high-energy signals. For all the details see [55].

2.1. Short Summary of the Results. Several analyses on the model-independent DM annual modulation signature have been performed (see [56, 57] and references therein). Here, Fig. 1 shows the time behaviour of the experimental residual rates of the *single-hit* events collected by DAMA/NaI and by DAMA/LIBRA in the 2–6 keV energy interval [56, 57]. The superimposed curve is the cosinusoidal function: $A\cos\omega(t-t_0)$ with a period $T = 2\pi/\omega = 1$ y, with a phase $t_0 = 152.5$ day (June 2nd), and modulation amplitude, A, obtained by the best fit over 13 annual cycles. The hypothesis of absence of modulation in the data can be discarded [56, 57] and, when the period and the phase are released in the fit, values well compatible with those expected for a DM particle induced effect are obtained [57]; for example, in the cumulative 2–6 keV energy interval: $A = (0.0116 \pm 0.0013)$ cpd/kg/keV, $T = (0.999 \pm 0.002)$ y and $t_0 = (146 \pm 7)$ day. Summarizing, the analysis of the *single-hit* residual rate favours the presence of a modulated cosine-like behaviour with proper features at 8.9σ C.L. [57].

The same data of Fig. 1 have also been investigated by a Fourier analysis — including the treatment of the experimental errors and of the time binning — obtaining a clear peak corresponding to a period of 1 y [57]; this analysis in other energy regions shows instead only

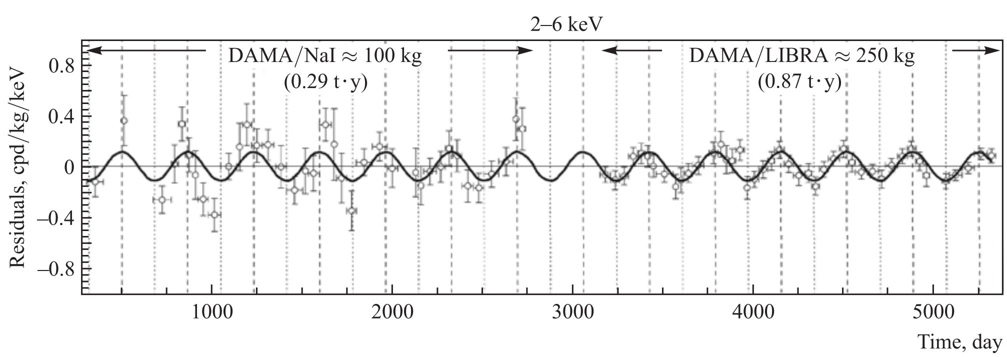

Fig. 1. Experimental model-independent residual rate of the *single-hit* scintillation events, measured by DAMA/NaI over seven and by DAMA/LIBRA over six annual cycles in the 2–6 keV energy interval as a function of time [47, 48, 56, 57]. The zero of the time scale is January 1st of the first year of data taking. The experimental points present the errors as vertical bars and the associated time bin width as horizontal bars. The superimposed curve is $A\cos\omega(t-t_0)$ with period $T = 2\pi/\omega = 1$ y, phase $t_0 = 152.5$ day (June 2nd) and modulation amplitude, A, equal to the central value obtained by the best fit over the whole data: cumulative exposure is 1.17 t·y. The dashed vertical lines correspond to the maximum expected for the DM signal (June 2nd), while the dotted ones correspond to the minimum. See [56, 57] and the text

aliasing peaks. Moreover, in order to verify absence of annual modulation in other energy regions and, thus, to verify also the absence of any significant background modulation, the time distribution in energy regions not of interest for DM detection has also been investigated: this allowed the exclusion of background modulation in the whole energy spectrum at a level much lower than the effect found in the lowest energy region for the *single-hit* events [57]. A further relevant investigation has been done by applying the same hardware and software procedures, used to acquire and to analyze the *single-hit* residual rate, to the *multiple-hits* events in which more than one detector «fires». In fact, since the probability that a DM particle interacts in more than one detector is negligible, a DM signal can be present just in the *single-hit* residual rate. Thus, this allows the study of the background behaviour in the same energy interval of the observed positive effect. The result of the analysis is reported in Fig. 2 where it is shown the residual rate of the *single-hit* events measured over the six DAMA/LIBRA annual cycles, as collected in a single annual cycle, together with the residual rates of the *multiple-hits* events, in the same considered energy interval. A clear modulation is present in the *single-hit* events, while the fitted modulation amplitudes for the *multiple-hits* residual rate are well compatible with zero [57]. Similar results were previously obtained also for the DAMA/NaI case [48]. Thus, again evidence of annual modulation with proper features, as required by the DM annual modulation signature, is present in the *single-hit* residuals (events class to which the DM particle induced events belong), while it is absent in the *multiple-hits* residual rate (event class to which only background events belong). Since the same identical hardware and the same identical software procedures have been used to analyze the two classes of events, the obtained result offers an additional strong support for the presence of a DM particle component in the Galactic halo further excluding any side effect either from hardware or from software procedures or from background.

The annual modulation present at low energy has also been analyzed by depicting the differential modulation amplitudes, S_m, as a function of energy; S_m is the modulation amplitude

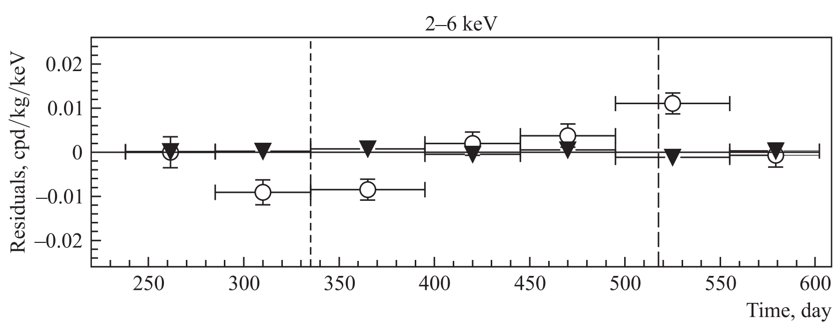

Fig. 2. Experimental residual rates over six DAMA/LIBRA annual cycles for *single-hit* events (open circles) (class of events to which DM events belong) and for *multiple-hits* events (filled triangles) (class of events to which DM events do not belong). They have been obtained by considering for each class of events the data as collected in a single annual cycle and by using in both cases the same identical hardware and the same identical software procedures. The initial time of the figure is taken on August 7th. The experimental points present the errors as vertical bars and the associated time bin width as horizontal bars. The errors of the *multiple-hits* residual rates are slightly smaller than the filled triangles symbol. See the text and [56, 57]

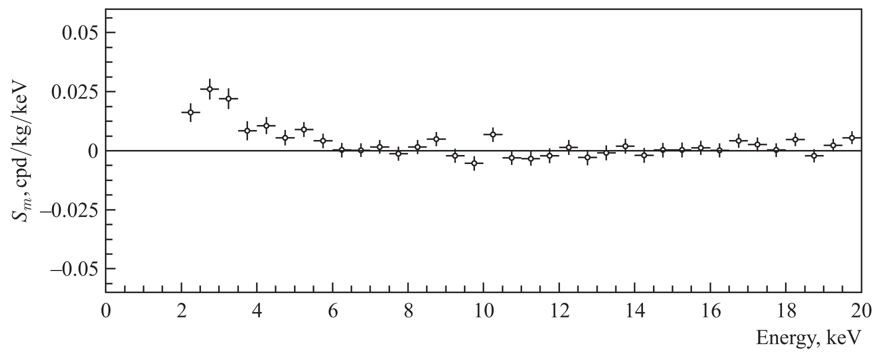

Fig. 3. Energy distribution of the modulation amplitudes S_m for the total cumulative exposure 1.17 t · y obtained by maximum likelihood analysis. The energy bin is 0.5 keV. A clear modulation is present in the lowest energy region, while the S_m values compatible with zero are present just above. In fact, the S_m values in the 6–20 keV energy interval have random fluctuations around zero with χ^2 equal to 27.5 for 28 degrees of freedom. See [56, 57] and the text

of the modulated part of the signal obtained by maximum likelihood method over the data, considering $T = 1$ y and $t_0 = 152.5$ day. The S_m values are reported as a function of energy in Fig. 3. It can be inferred that a positive signal is present in the 2–6 keV energy interval, while the S_m values compatible with zero are present just above; in particular, the S_m values in the 6–20 keV energy interval have random fluctuations around zero with χ^2 equal to 27.5 for 28 degrees of freedom. It has been also verified that the measured modulation amplitudes are statistically well distributed in all the crystals, in all the annual cycles and energy bins; these and other discussions can be found in [57].

In order to release in the maximum likelihood procedure the assumption of the phase fixed at $t_0 = 152.5$ day, the signal has been alternatively written as: $S_{0,k} + S_{m,k}\cos\omega(t - t_0) + Z_{m,k}\sin\omega(t - t_0) = S_{0,k} + Y_{m,k}\cos\omega(t - t^*)$, where $S_{0,k}$ and $S_{m,k}$ are the constant part and the modulation amplitude of the signal in the kth energy interval.

Obviously, for signals induced by DM particles one would expect: i) $Z_{m,k} \sim 0$ (because of the orthogonality between the cosine and the sine functions); ii) $S_{m,k} \simeq Y_{m,k}$; iii) $t^* \simeq t_0 = 152.5$ day. In fact, these conditions hold for most of the dark halo models; however, it is worth noting that slight differences in the phase could be expected in case of possible contributions from nonthermalized DM components, such as, e.g., the SagDEG stream [49] and the caustics [63]. The 2σ contours in the plane (S_m, Z_m) for the 2–6 keV and 6–14 keV energy intervals and those in the plane (Y_m, t^*) are reported in Fig. 4 [57]. The best fit values for the 2–6 keV energy interval are (1σ errors): $S_m = (0.0111 \pm 0.0013)$ cpd/kg/keV; $Z_m = -(0.0004 \pm 0.0014)$ cpd/kg/keV; $Y_m = (0.0111 \pm 0.0013)$ cpd/kg/keV; $t^* = (150.5 \pm 7.0)$ day; while for the 6–14 keV energy interval they are: $S_m = -(0.0001 \pm 0.0008)$ cpd/kg/keV; $Z_m = (0.0002 \pm 0.0005)$ cpd/kg/keV; $Y_m = -(0.0001 \pm 0.0008)$ cpd/kg/keV and t^* is obviously not determined. These results confirm those achieved by other kinds of analyses. In particular, a modulation amplitude is present in the lower energy intervals, and the period and the phase agree with those expected for DM induced signals. For more detailed discussions see [57].

Both the data of DAMA/LIBRA and of DAMA/NaI fulfil all the requirements of the DM annual modulation signature.

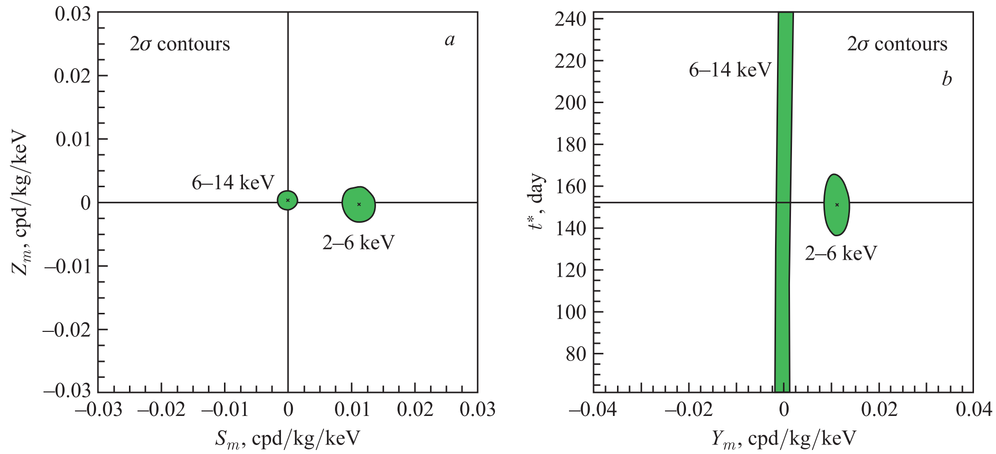

Fig. 4. The 2σ contours in the plane (S_m, Z_m) (*a*) and in the plane (Y_m, t^*) (*b*) for the 2–6 keV and 6–14 keV energy intervals. The contours have been obtained by the maximum likelihood method, considering the cumulative exposure of $1.17\ \mathrm{t \cdot y}$. A modulation amplitude is present in the lower energy intervals and the phase agrees with that expected for DM induced signals. See [56, 57] and the text

Sometimes wrong statements were put forward as the fact that in nature several phenomena may show some kind of periodicity. The point is whether they might mimic the annual modulation signature in DAMA/LIBRA (and former DAMA/NaI), i.e., whether they might be not only quantitatively able to account for the observed modulation amplitude but also able to contemporaneously satisfy all the requirements of the DM annual modulation signature; the same is also true for side reactions.

Careful investigations on absence of any significant systematics or side reaction able to account for the measured modulation amplitude and to simultaneously satisfy all the requirements of the signature have been quantitatively carried out (see, e.g., [47, 48, 55–57, 60, 64], and the references therein). No systematics or side reactions able to mimic the signature (that is, able to account for the measured modulation amplitude and simultaneously satisfy all the requirements of the signature) have been found or suggested by anyone over more than a decade.

2.2. Implications and Comparisons. The model-independent evidence obtained by DAMA is compatible with a wide set of scenarios regarding the nature of the DM candidate and related astrophysical, nuclear and particle physics. For example, some given scenarios and parameters are discussed in [7–9, 42, 45, 47–50] and in Appendix A of [56]. Further large literature is available on the topics [65]; other possibilities are open. Here I just recall the recent papers [66, 67] where the DAMA/NaI and DAMA/LIBRA results, which fulfil all the many peculiarities of the model-independent Dark Matter annual modulation signature, are examined under the particular hypothesis of a light-mass Dark Matter candidate particle interacting with the detector nuclei by coherent elastic process; comparison with some recent possible positive hints [37, 38] is also given. In particular, in [66] allowed regions are given for DM candidates interacting by elastic scattering on nuclei including some of the existing uncertainties; comparison with theoretical expectations for neutralino candidate and with the recent possible positive hint by CoGeNT [38] is also discussed there (see Fig. 5). No other experiment exists,

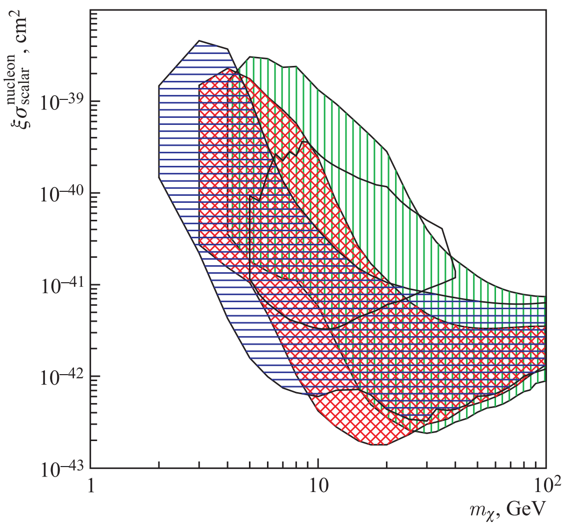

Fig. 5. Regions in the nucleon cross section vs DM particle mass plane allowed by DAMA in three different instances for the Na and I quenching factors: i) without including the channeling effect (green — vertically-hatched region), ii) by including the channeling effect (blue — horizontally-hatched region), and iii) without the channeling effect using the energy-dependent Na and I quenching factors [66] (red — cross-hatched region). The velocity distributions and the same uncertainties as in [47, 48] are considered here. The allowed region obtained for the CoGeNT experiment, including the same astrophysical models as in [47, 48] and assuming for simplicity a fixed value for the Ge quenching factor and a Helm form factor with fixed parameters, is also reported and denoted by a (black) thick solid line. For details see [66]

whose result can be directly compared in a model-independent way with those by DAMA/NaI and DAMA/LIBRA. Some activities (e.g., [30, 33, 34]) claim model-dependent exclusion under many largely arbitrary assumptions (see, for example, discussions in [31, 32, 47, 48, 56]); often some critical points exist in their experimental aspects (e.g., use of marginal exposures, determination of the energy threshold, of the energy resolution and of the energy scale in the few keV energy region of interest, multiple selection procedures, nonuniformity of the detectors response, absence of suitable periodical calibrations in the same running conditions and in the claimed low-energy region, stabilities, tails/overlapping of the populations of the subtracted events and of the considered recoil-like ones, well-known side processes able to mimic recoil-like events, etc.), and the existing experimental and theoretical uncertainties are generally not considered in their presented model-dependent result. Moreover, implications of the DAMA results are generally presented in incorrect/partial/unupdated way.

3. CONCLUSIONS AND PERSPECTIVES

Large efforts are in progress with different approaches and target materials to investigate various kinds of DM candidates and scenarios. Due to the difficulty of measuring at very low energy region several techniques still require further work for results qualifications before instead enlarging their mass, which is only one of the important parameter in such measurements.

As regards possibility to exploit the directionality for some DM candidates, new efforts have to be encouraged towards a first realistic exploitation.

The model-independent annual modulation signature with widely sensitive target materials still remains a major approach, offering a unique possibility for detection; it requires well-known techniques, full proved detector stability, well-known and proved detector response in all the aspects, etc. At present, the DAMA positive model-independent evidence for the presence of DM particles in the Galactic halo is supported at 8.9σ C.L. (on a cumulative exposure of 1.17 $t \cdot y$, i.e., 13 annual cycles of DAMA/NaI and DAMA/LIBRA).

For completeness I also recall: i) the recent possible positive hints presented by CoGeNT and CRESST exploiting different approaches and/or different target materials; ii) the uncertainties in the model-dependent results and comparisons; iii) the relevant argument of the methodological robustness [68].

In particular, the general considerations on comparisons reported in Appendix A of [56] still hold; on the other hand, whatever possible «positive» result has to be interpreted and a large room of compatibility with the DAMA annual modulation result is present.

As regards in particular DAMA/LIBRA, I recall the first upgrade performed in September 2008 when one detector was recovered by replacing a broken PMT and a new optimization of some PMTs and HVs was done, the transient digitizers were replaced with the new ones having better performances and a new DAQ with optical read-out was installed.

A further and more important upgrade has been performed at the end of 2010, when all the PMTs have been replaced with the new ones having higher quantum efficiency (see Fig. 6); details on the reached performances are reported in [69]. The purpose of this last upgrade of the presently running second-generation DAMA/LIBRA set-up is: i) to increase the experimental sensitivity lowering the software energy threshold of the experiment; ii) to improve the investigation on the nature of the Dark Matter particle and related astrophysical, nuclear and particle physics arguments; iii) to investigate other signal features; iv) to improve the sensitivity in the investigation of rare processes other than Dark Matter. DAMA/LIBRA will

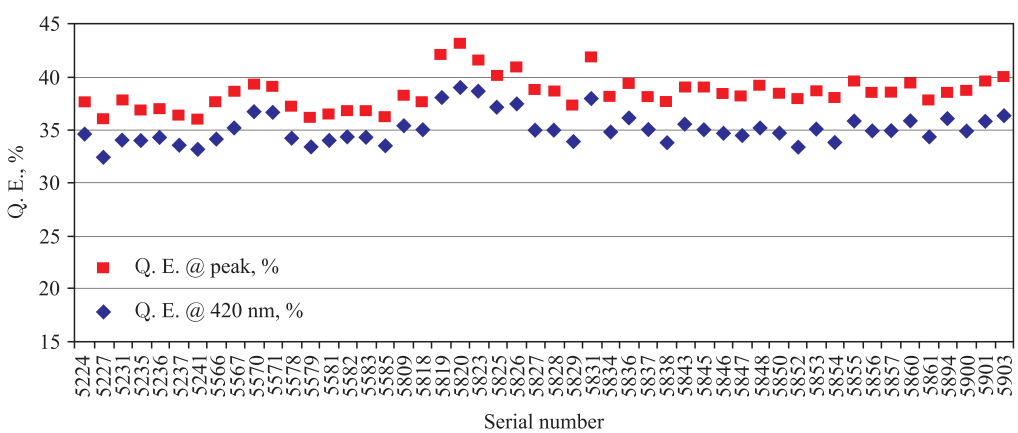

Fig. 6. Quantum efficiency (Q.E.) at peak and at 420 nm of each one of the new 50 high Q.E. HAMAMTSU PMTs, installed in DAMA/LIBRA. The averages (RMS) are 38.5% (1.6%) and 35.1% (1.4%), respectively; the RMS show that the Q.E. spread in the PMTs production is well limited. Details are given in [69]

also study several other rare processes as done by the former DAMA/NaI apparatus in the past [51] and by itself so far [58, 59].

Finally, very useful complementary results can arise from experiment exploiting other target detectors and approaches adopting adequately safe experimental procedures.

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