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First results of the EDELWEISS-II WIMP search using Ge cryogenic detectors with interleaved electrodes

EDELWEISS Collaboration

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ABSTRACT

The EDELWEISS-II Collaboration has performed a direct search for WIMP dark matter with an array of ten 400 g heat-and-ionization cryogenic detectors equipped with interleaved electrodes for the rejection of near-surface events. Six months of continuous operation at the Laboratoire Souterrain de Modane have been achieved. The observation of one nuclear recoil candidate above 20 keV in an effective exposure of 144 kg d is interpreted in terms of limits on the cross-section of spin-independent interactions of WIMPs and nucleons. A cross-section of 1.0×10^{-7} pb is excluded at 90% CL for a WIMP mass of 80 GeV/c^2. This result demonstrates for the first time the very high background rejection capabilities of these simple and robust detectors in an actual WIMP search experiment.

The existence of Weakly Interacting Massive Particles (WIMPs) is a likely explanation for the various observations of a dark matter component from the largest scales of the Universe to galactic scales [1]. WIMPs are predicted by several extensions of the Standard Model of particle physics. WIMPs distributed in the Milky Way halo may be detected through coherent, elastic scattering on nuclei constituting a terrestrial detector [2]. The expected nuclear recoils have a quasi-exponential energy distribution with typical

s [3–5] set upper $\sim 10^{-2}$ event per kg and per day (evt/kg/d). Minimal extensions of the Standard Model with Supersymmetry where the WIMP is the lightest neutralino predict a particularly interesting range of parameters where their spin-independent scattering cross-section on nucleons lies between 10^{-8} and 10^{-10} pb, corresponding to rates of 10^{-3} to 10^{-5} evt/kg/d. As a consequence, experiments dedicated to the direct detection of WIMPs require large masses of detectors and long exposure times. The radioactive background is the main obstacle to measure such extremely low rates. Provision of passive rejection, such as the use of shieldings and radiopure materials in a deep underground site, must be complemented by a detector technology that enables a clear identification of single nuclear recoils with respect to other types of interactions.

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Cryogenic Germanium detectors [3,6] constitute a leading technology in direct detection of dark matter. Event discrimination is provided by the comparison of the ionization signals to the bolometric measurement of the deposited energy. A long-standing issue with these detectors is the reduction of the charge collection efficiency for interactions occurring close to their surface, which can impair significantly the discrimination between nuclear and electron recoils. The CDMS Collaboration addresses it by adding a discrimination based on the time structure of their athermal phonon signals [3], obtaining with this the best published sensitivity for WIMPs of masses above $\sim$40 GeV/c^2. Recently, the EDELWEISS Collaboration deployed an alternative solution based on a new detector design with interleaved electrodes [7], named ID in the following. In Ref. [8], we demonstrated a rejection factor greater than 10^4 for low-energy surface events induced by electrons emitted from ^{210}Pb source. Combined with a comparable factor for the rejection of bulk electronic recoils, this technology, and the low-background environment achieved in the EDELWEISS-II setup [9], should enable to reach the required sensitivity to probe WIMP-nucleon cross-sections well below 10^{-8} pb. This new technology is also considered for application in more ambitious searches in the 10^{-10} pb range such as in the EURECA project [10].

The work presented in this Letter confirms these results in the conditions of an actual WIMP search, and in particular demonstrates the detector reliability and efficiency over long periods of time. We report on the results of a WIMP search carried out over a period of six months with an array of ten 400 g cryogenic germanium ID detectors. These data are combined with a smaller set recorded during the validation run of the first two ID 400 g detectors and interpreted in terms of limits on the spin-independent WIMP-nucleon cross-section. The reliability and efficiency of the ID technology will be assessed, together with its prospect for a significant improvement of the sensitivity for WIMP detection. These results will be compared to those of other leading WIMP searches.

2. Experimental setup

The experimental setup is described in detail in Ref. [9]. It is located in the Laboratoire Souterrain de Modane (LSM). The rock overburden of 4800 mwe reduces the cosmic muon flux to 4 μ/m^2/day. The flux of neutrons above 1 MeV is 10^{-6} n/cm^2/s [11]. The cryostat housing the detectors is protected from the ambient γ-rays by a 20 cm lead shield. This is surrounded by a 50 cm thick polyethylene shield, covered by a muon veto system with 98% geometric efficiency for thoroughgoing muons. The remaining rate of single nuclear recoils from energetic neutrons induced by muons is less than 10^{-3} evts/kg/day according to GEANT4 simulations of the experiment with its shields and the active rejection of muon-tagged events [12].

The detectors are made from ten hyperpure germanium crystals (less than 10^{10} impurities per cm^3) of cylindrical shapes with a diameter of 70 mm and a height of 20 mm. Five of these detectors have their edges bevelled at an angle of 45° and have a mass of 360 g. The mass of the other five detectors is 410 g. The detectors are in individual copper casings, stacked in towers of two to three ID detectors. During the entire data-taking periods, a dilution refrigerator maintains the detectors at a stabilized temperature of 18 mK.

For each interaction in a detector, two types of signals are recorded: an elevation of temperature and a charge signal. The temperature increase for each event is measured using neutron transmutation doped (NTD)-Ge thermometric sensors glued on each detector, as was the case in the previous EDELWEISS detectors [6]. The charge is collected by electrodes, the design of which and polarization scheme are described in details in Ref. [8]. Basically, the flat surfaces are covered with concentric aluminium ring electrodes of 2 mm pitch, and biased at alternating potentials. Each side has thus two sets of electrodes, each connected to its next but one neighbor through ultra-sonically bonded wires. The biases are chosen as to produce an axial field in the bulk of the detector, while the field close to the surface links two adjacent ring electrodes and is therefore approximately parallel to the surface.

Bulk events are thus identified by the collection of electrons and holes on the set of electrodes with the largest difference of potential across the detector, called *fiducial electrodes* in the following. The two other electrodes act as a veto for surface events. Typical biases for the fiducial and veto electrodes are ± 4 V and ∓ 1.5 V respectively. Two additional plain guard electrodes, typically biased at ± 1 V, cover the outer edges of the crystal. The fiducial volume of the detector is defined as the region for which the charge is collected entirely by the two fiducial electrodes.

The heat and the six charge signals of each detector are digitized continuously at a rate of 100 kHz, using a common clock for all channels. After online filtering, a threshold trigger is applied to each of the heat channels. The value of that threshold is updated continuously within the data acquisition on the basis of the noise level, aiming to keep the trigger rate below a fraction of a Hz. For each event, the raw heat and ionization data of all detectors in the corresponding tower are stored to disk. Triggers detected on more than one detector on the same tower are tagged online as coincidences. The data from detectors that did not participate to the trigger are used to monitor systematically the baseline resolutions as a function of time.

The muon veto has an independent read-out system. Each of the 42 plastic scintillation modules is equipped with 8 photomultipliers, 4 added at each end. A signal is recorded as a veto hit once a coincidence of the 2 ends of a module occurs within a 100 ns wide coincidence window. With a low trigger threshold deliberately chosen as to optimize the muon veto efficiency, the muon veto rate of $\sim$0.2 events/sec is dominated by environmental background. Each muon veto event is tagged with the corresponding time on the common clock used for the cryogenic detector readout. The coincidences between muon veto events and those in the detector towers are identified offline by comparing the respective time tags.

3. Detector performance and fiducial acceptance

After an initial cool-down of the cryostat in March 2009, the bulk of the data presented here was recorded over the following period of six months from April to September. An additional data set was recorded with two detectors during an initial run performed between July and November 2008.

In the six-month running period, the data acquisition was running 80% of the time. Half of the losses are accounted for by regular maintenance operations and the other half by unscheduled stops. The fraction of running time devoted to detector calibration with γ and neutron sources is 6%. Among the 70 read-out channels, only five were defective or too noisy for use: four guards and one veto. Extensive calibrations performed in 2008 have shown that a signal on one of the guards is almost invariably accompanied by another one on either the other guard or a veto electrode, or by an imbalance in the charge collected on the fiducial electrodes. Relying on this redundancy is sufficient to attain high rejection factors even in the absence of a guard channel. Three detectors with one deficient guard signal are thus kept for the WIMP search. One detector had one deficient guard and one deficient veto electrode. In the absence of evidence that this particular combination of two missing channels can be efficiently compensated by the existing redundancies, it was decided a priori not to use this detector for WIMP searches.

The data were analyzed offline by two independent analysis chains. For each event, the amplitudes of the signals from the NTD-Ge thermistors and the six electrode signals were determined taking advantage of the synchronous digitization of all channels, and using optimal filters adapted to their time-dependent individual noise spectra.

The energy calibration of the ionization signal was performed with ^{133}Ba γ-ray sources. No gain variations were observed over the entire period, for a given polarization setting. The gain of the heat signal depends on the cryogenic conditions. It is measured as a function of time by monitoring the ratio of the heat and ionization signal for bulk γ-ray events. The non-linearity of the heat gain as a function of energy is measured using γ-ray calibrations. The baseline resolution on the different heat channels varies between 0.6 and 2 keV FWHM, with an average of 1.2 keV. The ionization baseline resolution for fiducial events varies between 0.8 and 1.2 keV FWHM, with an average of 0.9 keV.

The response of the ID detectors to nuclear recoils induced by neutron scattering was checked using an AmBe source. For these events, the ionization yield Q, defined as the ratio of the charge signal to the recoil energy E_R normalized to the response for γ-ray interactions, follows a behavior consistent with the parametrization used in previous EDELWEISS reports [6]. The nuclear recoil events are centered at $Q = 0.16E_R^{0.18}$, where E_R is in keV, with a dispersion in agreement with the measured resolutions of the ionization and heat channels [13]. These calibrations were also used to verify that the acceptance to low-energy nuclear recoil events is as predicted by the known online trigger threshold and baseline resolutions of the different signals.

The identification of an event as fiducial requires that each of the signals on veto and guard electrodes, as well as the charge imbalance between the two fiducial electrodes, be consistent with zero at 99% CL, according to the resolution on these parameters. The rejection performance of these cuts are discussed in Ref. [8]. The efficiency of those cuts, as well as the fraction of the fiducial volume that they represent, was measured using the low-energy peaks associated with the cosmogenic activation of germanium, producing a uniform contamination by the isotopes ^{65}Zn and ^{68}Ge. The electron capture decays of these long-lived (∼250 days) isotopes result in energy deposition of 8.98 and 10.34 keV, respectively, as shown in Fig. 1(a). Their yield throughout the detector volume can be measured with a uniform efficiency by using recoil energy spectra. Fig. 1(b) and (c) show these distributions for, respectively, events rejected and accepted by the fiducial cut, for all detectors. The fraction of events in the peak that survive the fiducial cuts is the fiducial efficiency. This number fully takes into account the size of the electrostatic fiducial volume, the effects of charge sharing between electrodes due to their expansion and diffusion [14], and the finite resolution on the electrode signals. The study of the cosmogenic peaks is performed individually for each detector. The measured effective fiducial mass, averaged by the relative exposure of each detector, is 166 ± 6 g. This result is consistent with a fiducial volume corresponding approximately to the cylinder defined by the last fiducial electrodes, limited in height to ∼1 mm under the flat surfaces, a value that is similar for detectors with and without bevelled edges. A conservative value of 160 g will be used in the calculation of the total exposure.

The average rate of events from cosmogenically activated isotopes in these recently installed detectors is approximately 4 per day. To reject the several thousands that are expected in a six month exposure, events are accepted in the WIMP search if their ionization yield is 3.72 σ below $Q = 1$, corresponding to a γ-ray rejection factor of 99.99%. Given the measured detector resolutions,

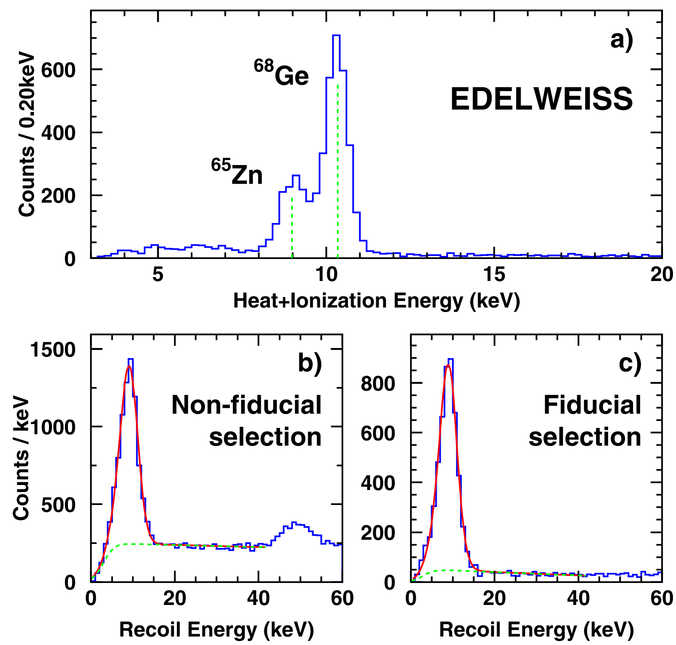

Fig. 1. Top: Energy spectrum of fiducial events recorded by the nine detectors used in the WIMP search, using events with an online heat threshold below 3.5 keV. The γ-ray energy is calculated from the sum of the heat and ionization signals weighted by their resolutions. The two peaks at 8.98 and 10.34 keV are associated with the electron capture decay of the cosmogenically activated isotopes ^{65}Zn and ^{68}Ge. Bottom: Corresponding recoil energy spectra outside (b) and inside (c) the fiducial selection. The 46 keV peak associated with ^{210}Pb decays near the surface of the detectors is clearly visible on (b) and strongly suppressed on (c). Gaussian fits are drawn to guide the eyes. The dashed lines represent the acceptance function resulting from 3.5 keV threshold cuts applied on ionization and heat signals.

this requirement starts to affect the efficiency in the 90% nuclear recoil band below 20 keV. The AmBe neutron calibration data show that another factor reducing the efficiency for nuclear recoils below 20 keV is the restriction of the search to events with a fiducial ionization signal of at least 3 keV. As a consequence, the following WIMP search is restricted *a priori* to recoil energies above 20 keV. This value is well suited to test the rejection performance of the detectors: in EDELWEISS-I, the event rate above this threshold in the nuclear recoil band was as high as 0.4 evt/kg/d [6]. Lowering this threshold requires more studies to determine the acceptance in this region which depends on the detailed understanding of the noise on fiducial and non-fiducial ionization channels. The neutron calibration data show that the 20 keV threshold for nuclear recoil imposes that the online heat threshold must be less than 7 keV for WIMP searches. This requirement was strictly imposed in one of the two analyses, resulting in a flat efficiency above 20 keV, falling rapidly to zero below this energy. The heat cut was moved from 7 to 3.5 keV for the study of the cosmogenic lines at 10 keV outside the fiducial volume. This change had no effect on the fiducial efficiency for these gamma rays, as the heat and ionization signals are not affected by quenching effects. The second analysis did not impose a 7 keV heat threshold but instead computed its efficiency as a function of energy depending on the actual threshold as a function of time. This results in an increased efficiency for nuclear recoils below 20 keV, but in no significant change of exposure in the WIMP search region above this threshold.

4. Results and discussion

In the six-month run, the total exposure for WIMP search of the nine detectors is 1262 detector-days. A time period selection is applied on the baseline resolutions and online heat threshold on an

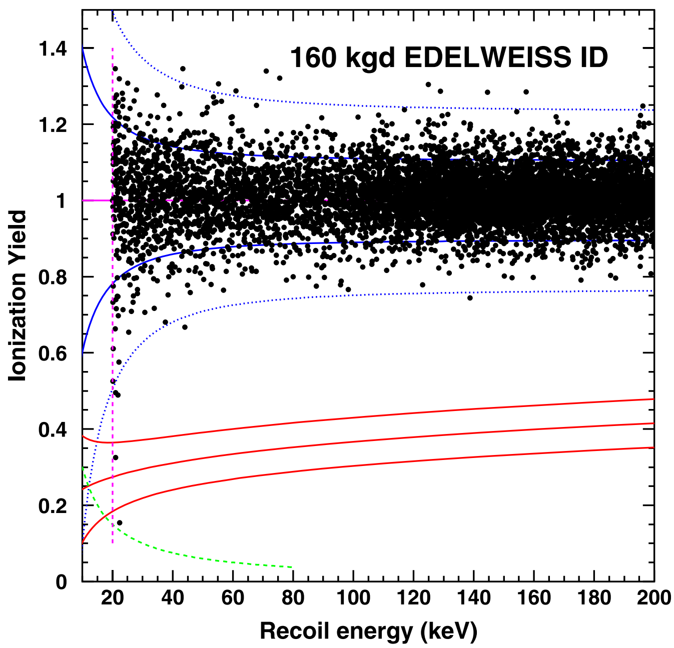

Fig. 2. Ionization yield vs recoil energy of fiducial events recorded by EDELWEISS-II in an exposure of 160 kg d. The WIMP search region is defined by recoil energies greater than 20 keV (vertical dashed line). The 90% acceptance nuclear and electron recoil bands (full blue and red lines, respectively) are calculated using the average detector resolutions. Also shown as dashed lines are the 99.98% acceptance band for the γ (blue) and the 3 keV ionization threshold (green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

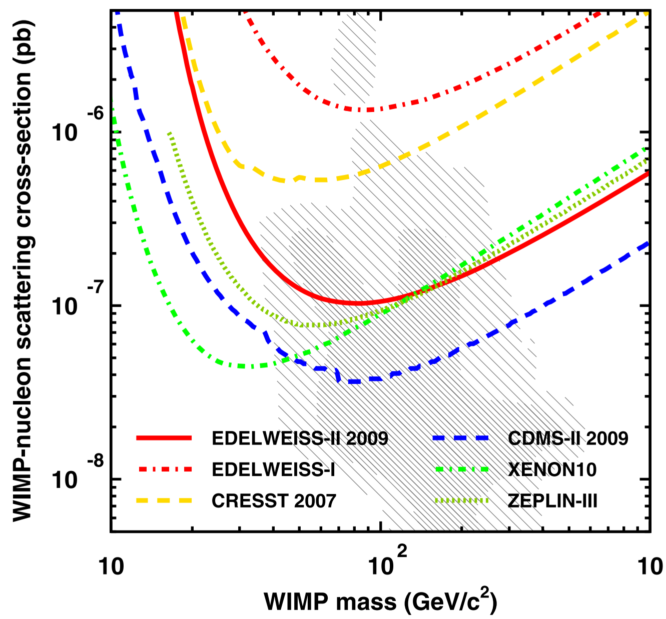

Fig. 3. Limits on the cross-section for spin-independent scattering of WIMPs on nucleons as a function of WIMP mass, derived from the data presented in this Letter, together with limits from other direct WIMP searches. The limits for CDMS, ZEPLIN, EDELWEISS-I and CRESST are from Refs. [3,5,6,20], respectively. The limits for XENON [4] do not include the modification implied by the light yield measurements of Ref. [21]. The hashed (double-hashed) shaded area correspond to the 68% (95%) probability regions of the theoretical cMSSM scan of Ref. [22], with $\mu > 0$.

hour-by-hour basis, in order to ensure that in each selected hour they are compatible with a nearly full efficiency for nuclear recoils above 20 keV. This requirement reduces the exposure by ~20%. In addition, a cut is applied on the reduced χ^2 of the pulse fit for heat and fiducial electrodes of each event. This is done in order to remove short periods of high-noise levels, pile-up events and some populations of ionization-less events associated, for example, with radioactive decays in the NTD-Ge sensor. The χ^2 cut efficiency is controlled using the γ-ray background: its typical value is 97%. The deadtime associated with the online trigger algorithm is ~1% and an additional 3% was lost due to DAQ problems. Less than 1% of exposure is lost due to the deadtime resulting from the anti-coincidence requirement with the other bolometers and with the muon veto within a 50 ms time window.

In the six-month run, after all cuts, the nine ID detectors have a total exposure of 876.7 detector-days. The 2008 data with two of these nine ID detectors provides an additional exposure of 122.3 detector-days. With the average fiducial mass of 160 g, this corresponds to a total of 160 kg d. Finally, taking into account the 90% CL region for nuclear recoils, this data set is equivalent to 144 kg d with an acceptance of 92% at 20 keV and 100% at 23 keV.

Fig. 2 shows the distribution of Q as a function of recoil energy for the entire exposure. The anti-coincidence requirement with the muon veto and with the other detectors removes two events in the nuclear recoil band at 27 and 43 keV. The average rate outside the nuclear recoil band in the 20–100 keV range is 0.16 event/keV/kg/d.

The potential sources of background in the WIMP search region have been investigated. None are expected by itself to result in more than 0.1 event in the present exposure. Given the gamma-ray yield in the fiducial volume and the resolutions of the detectors (tested with a sample of 10^5 gamma-ray events in Ref. [8]), less than 0.01 should fluctuate down inside the region of interest. The predicted number of unrejected surface events is estimated by multiplying the number of observed low-ionization yield events before the rejection of surface events (1800) by the rejection rate measured in Ref. [8] (3×10^4), resulting in 0.06 events. The number of neutrons from interactions of untagged muons is estimated from the number of observed coincidences between the bolometers and the muon veto, multiplied by the muon veto efficiency. Adding the two muon veto coincidences from this work to the three observed above 20 keV in the 280 kg d data sample studied in Ref. [15], the number of coincidences in 160 kg d is 2 ± 1. This number is larger than, but consistent with, the estimate of 0.6 based on the Monte Carlo simulations of Ref. [12]. Taking into account a muon veto efficiency of 98% for the present run, the predicted number of un-vetoed muon-induced neutron event is 0.04. The contribution of neutrons from radioactive decays has been simulated using GEANT3 in Ref. [16] and studied in Ref. [17]. The flux of neutrons from the LSM rock going through the polyethylene shield and from U/Th traces in the lead shield should result less than 0.13 events. The uncertainty on this number is dominated by the upper bound on the presence of U/Th traces in the lead shield. It could decrease as the result of ongoing efforts to improve the different measurements and simulations entering the background estimation. Summing all estimates and upper limits, we arrive at an estimated background of 0.23 events in 144 kg d. Considering the major contributions are upper limits, this corresponds to an upper limit of 21% on the probability of observing one event.

In both analyses, one event is observed in the nuclear recoil band at 21.1 keV. This represents a factor ~50 reduction relative to the event rate above 20 keV measured in EDELWEISS-I. The upper limits on the WIMP-nucleon spin-independent cross-section are calculated using the prescriptions of Ref. [18], and the optimal interval method [19] (Fig. 3). A cross-section of 1.0×10^{-7} pb is excluded at 90% CL for a WIMP mass of 80 GeV/c^2. The sensitivity above 125 GeV/c^2 is better than those reported by the experiments XENON [4] and ZEPLIN [5]. It is a factor 2.5 away from the cumulative limit reported by CDMS [3]. The present work represents more than one order of magnitude improvement in sensitivity compared with the previous EDELWEISS results [6] based on detectors without surface event identification. The sensitivity can be further improved by an increase of exposure, and, as of end 2009, the present run is being pursued until a significant number of additional detectors are ready to be installed in the EDELWEISS-II cryostat.

As a further indication of the robustness of the ID technology, it should be noted that no events were observed in the nuclear recoil band in the exposure of 18 kg d of the detector not included in the present search because of its missing guard and veto channels.

5. Conclusion

The EDELWEISS II Collaboration has performed a direct search for WIMP dark matter using nine 400 g heat-and-ionization cryogenic detectors equipped with interleaved electrodes for the rejection of near-surface events. A total effective exposure of 144 kg d has been obtained after six months of operation in 2009 at the Laboratoire Souterrain de Modane and additional data from earlier runs with two detectors in 2008.

The observation of one nuclear recoil candidate above 20 keV is interpreted in terms of limits on the cross-section of spin-independent interactions of WIMPs and nucleons. Cross-sections of 1.0×10^{-7} pb are excluded at 90% CL for WIMP masses of 80 GeV/c^2. Further analysis are going on in order to reduce the effective threshold of the detectors to better address the case of lower-mass WIMPs. This result demonstrates for the first time the very high rejection capabilities of these simple and robust detectors in an actual WIMP search experiment. It also establishes the ability of the EDELWEISS-II experiment for long and stable low-radioactivity data taking and for the rejection of neutron-induced nuclear recoils.

The EDELWEISS Collaboration aims to increase the cumulated mass of the detectors in operation at the LSM, in order to soon probe the physically significant 10^{-8} pb range of spin-independent WIMP-nucleon cross-sections.

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