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Search For Dark Matter with Moderately Superheated Liquids (*).

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Summary. — A «background blind» bubble chamber, which is exclusively sensitive to nuclear recoils and which is operated in a quasi-continuous mode is described for an improved search of dark-matter candidates. The detection principle is based on the metastability of superheated liquids, which can be tuned such that the detector becomes insensitive to ordinary α, β, γ-radiation.

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1. - Introduction.

Results from the first round of dark matter experiments with Ge-detectors together with the implications of Z-width measurements at LEP restrict the types of possible candidate particles, but leave still room for an interpretation of cold dark matter in terms of weakly interacting massive particles with masses larger than 20 GeV [1]. An interesting candidate in this context is the neutralino of the minimal supersymmetric standard models (MSSM). However, a comparison of theory with experiment shows that present experimental sensitivities for direct neutralino searches are not able to arrive at the small rates predicted, even under the most optimistic model assumptions, which maximize the coherent neutralino nucleus interactions [2]. Moreover, with respect to the already favourably biased coherent scattering case, the spin-dependent neutralino interaction rates are still smaller by at least one order of magnitude. Therefore experimentalists are challenged to find new ways, which allow to build in the future much more massive detectors with drastically reduced background rates to improve substantially on the dark matter detection sensitivity.

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The detection of dark matter candidates relies in conventional detectors on the observation of the small ionizing signal of a recoiling nucleus in the energy range from several keV to tens of keV. Taking for example as a target nucleus ^{23}Na, a neutralino mass of 20 GeV (80 GeV) and a threshold on the recoil energy of 10 keV, then a sensitivity of about 10^{-3} (10^{-2}) cts/kg/keV/d above threshold is needed to detect neutralino scattering, as shown in ref. [2] and again assuming the most optimistic coherent cross-section scenario.

Presently scintillation counters (*e.g.* LXe [3], NAl [4]) and solid-state counters (Ge [5, 6]) are used for dark-matter searches. The highest sensitivities have so far been realized for Ge detectors with a background of about 1 ct/kg/keV/d above a recoil threshold of 7.5 keV. In the near future TPCs with lower-energy thresholds ($E_{\text{th}} \sim 1$ keV) and operating at high pressure might be employed successfully [7]. Similarly cryogenic detectors with high sensitivity, very low threshold energies ($E_{\text{th}} < 0.5$ keV) and excellent energy resolution are on the drawing board [8].

Since the detectors of the mentioned types are sensitive to all kind of ionizing radiation, powerful active and passive background rejection techniques are required: the detectors are operated underground, the materials are carefully selected and highly purified in order to avoid radioactive contaminations. Active background suppression is tried by pulse shape discrimination in the case of scintillators and cryogenic detectors; the TPC approach in turn takes advantage of the powerful suppression criteria derived from its good spatial resolution. But still, it is clear that lacking an experimental signature for a dark-matter recoil event, the experimental task is a very difficult one, especially if one aims at sensitivities substantially below 10^{-2} cts/keV/kg/d. In fact, what is needed ideally is a «background blind» detector, exclusively sensitive to dark-matter recoils and of sufficient mass, in order to find unambiguously a signal at the envisaged level.

2. – Detector concept.

In order to meet these requirements a technique for the search of dark matter is discussed, which makes use of some macroscopic metastable state of the detector material itself. If this metastable state can only be quenched by the highly localized energy deposition of a recoiling atom and not by the passage of normal ionizing radiation (fig. 1), a powerful background reduction will become possible.

As is well known from bubble chamber operation, vapor droplet formation in superheated liquids is a process of precisely this kind: In the superheated metastable state potential energy is stored and the microscopic effect of an ionizing particle can trigger a localized macroscopic disturbance, which finally leads to a partial release of stored energy, *i.e.* a bubble is formed. Now by looking closer at the available experimental data it turns out that the superheated state of suitable liquids can be conditioned precisely such that droplet formation occurs only for nuclear recoils. Moreover the energy threshold is adjustable and can be chosen to lie in the interesting range for dark-matter detection. Of course the usual bubble chamber operation is unfavorable for the continuous sensitivity required in dark-matter searches. However in this specific application only moderately superheated liquids are required, which allows for completely different operation conditions.

A similar reasoning led Hahn to suggest radiation-induced cavitation in liquids under tensile stresses for dark-matter searches [9].

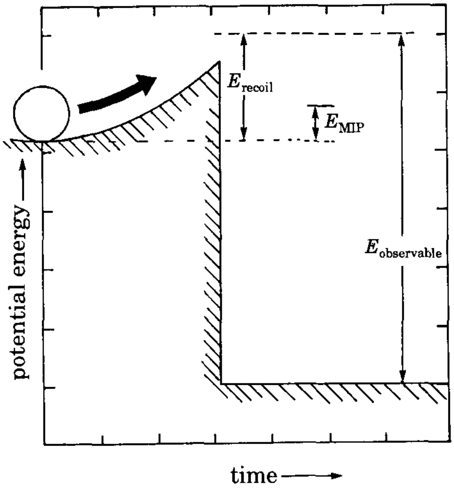

Fig. 1. – The detection principle: the detector material is brought into an excited metastable state, which can only be quenched by the high specific ionization of a recoiling atom with an energy E_{recoil} of several tens of keV, but not by less ionizing particles. The quenching leads locally to the release of a macroscopic quantity of energy $E_{\mathrm{observable}}$.

3. – Theory of operation.

It is generally agreed that the «heat spike» theory of Seitz describes well the process of vapor bubble nucleation [10, 11]. In this model it is assumed that proto-bubbles are created by thermal spikes of released heat on a particle track. The growth of proto-bubbles is damped by adiabatic cooling, heat conduction and viscosity of the liquid. Only if the seed cavity reaches a critical radius R_c, it is large enough to nucleate a macroscopic liquid to vapor phase transition. R_c is defined by $R_c = 2\gamma(T)/\Delta p$, where $\gamma(T)$ is the surface tension of the liquid-vapor interface at the operating temperature T and $\Delta p = p_v(T) - p_0$ is the difference between the vapor pressure in the cavity and the externally applied pressure. Bubble formation is triggered, if an amount of energy larger than a certain critical energy is deposited within a region given by $2R_c$. The critical energy E_c can be calculated within the model and is given by a somewhat complicated expression, which however is roughly proportional to $1/\Delta p^2$. Thus Δp measures the degree of superheat and the larger Δp, the smaller is R_c and also the less heat is required for drop vaporization. Figure 2 shows as an example the vapor pressure curves for Ar, Xe and CCl_2F_2 (freon 12). In order to drive a liquid into the superheated state, the pressure is reduced from above the curve (liquid) to below (vapor) at constant temperature.

The heat deposited along a track is determined by the stopping power of the particle. The evolution of the stopping power as a function of energy is shown for several ions in fig. 3, taken from ref. [12]. Although the stopping power decreases by going towards smaller energies below ~ 1 MeV/a.m.u., it is still quite large in the range of 10 to 100 keV. For example a 100 keV carbon recoil in freon 12 has a stopping power of $\mathrm{d}E/\mathrm{d}x \sim 80$ keV/μm, compared to $\sim$ keV/μm for minimum-ionizing particles. Therefore one can expect that for suitably chosen superheat of the liquid, practically all the energy of the recoiling, short-range nucleus is deposited within $2R_c$ and bubble formation is triggered, whereas a minimum ionizing particle depositing

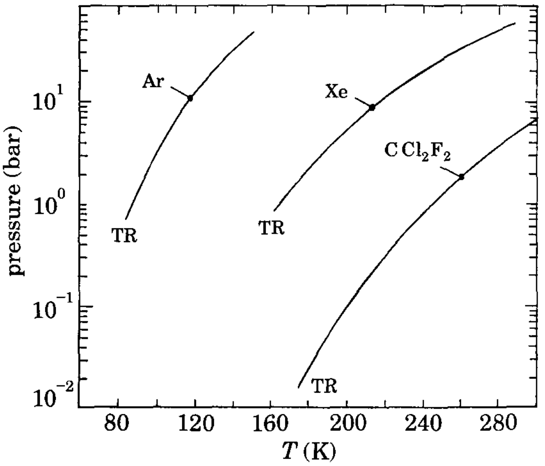

Fig. 2. – Vapor pressure curves for Ar, Xe and CCl_2F_2 (freon 12). The liquid phase is above the curves. A liquid is driven in the superheated state if, *e.g.* at constant temperature, the pressure is reduced to values below the curve. TR denotes the triple point of the liquids.

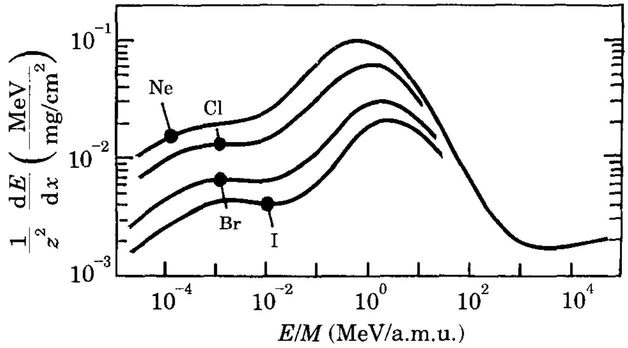

Fig. 3. – Evolution of the stopping power for various ions in Al. Below 0.01 MeV/a.m.u. the nuclear stopping power contributes substantially. The curves are taken from ref. [12].

less than E_c within the critical volume remains unseen. This in fact turns out to be the case.

4. – Detection of nuclear recoils in moderately superheated liquids.

The phenomenon of bubble formation by recoil nuclei has been studied only by few authors. In ref. [13] Riepe and Hahn dispersed an α-emitter in a liquid and the operating conditions were chosen such that, contrary to the recoiling nuclei, the α-particles themselves could not release enough energy inside $2R_c$. By varying Δp the threshold for bubble formation was determined and it was found that the threshold formation energy E_c corresponded precisely to the recoil energy deposited within $2R_c$, namely $E_{rec} = E_c = 110\,\text{keV}$ for a critical radius $R_c = 80\,\text{nm}$. The onset of sensitivity was very sharp and the efficiency for bubble formation, derived from the known source strength, was quoted as 100%. The situation is described in fig. 4 and it is seen that by a small increase in superheat, *i.e.* by going to smaller R_c, the threshold can be adjusted to lie in the range of 10 keV, which is the range interesting for dark matter recoil detection. For high values of superheat, finally sensitivity for electrons is obtained. Electrons however are less efficient in bubble formation: it was found that 2.3 keV electrons, which deposit 1.5 keV within $2R_c$, are only 1% efficient, although according to the authors only 450 eV would be needed in theory to trigger a bubble (a known effect in bubble chamber operation [11]).

Another experimental evidence for the discrimination power of moderately superheated liquids was obtained in a study with neutron recoils in freon 12 [14]. From the data one can infer a threshold energy for recoils in the range of 50 to 80 keV for a superheat corresponding to $\Delta p = 4$ bar at 290 K. Above threshold full recoil detection efficiency was found. The available information on this experiment is summarized in fig. 5, where the dependence of R_c and E_c on the degree of superheat Δp are shown. Under these operating conditions the liquid was exposed also to strong ^{60}Co source and no events were found. Only for γ-energies above 6 MeV, where photonuclear reactions occur, the liquid became sensitive to the produced heavy ions. Sensitivity to minimum-ionizing particles however requires $\Delta p \sim 18$ bar at 340 K!

5. – Detector realizations.

The question of continuous chamber operation has been discussed in ref. [15] in context with a proposed giant (100 t) argon bubble chamber with long sensitive time for nucleon decay experiments. It was estimated that a well-shielded, clean chamber of large size can be kept sensitive for minimum-ionizing particles up to 20 s. Since in the present application only moderately superheated liquids needed, even longer sensitive times can be expected.

There are various schemes, how a liquid can be driven into the moderately superheated state. The superheated state can be produced and maintained using an hydraulic servo system in order to stabilize the operating pressure and refresh periodically, say every 10 to 100 s. The chamber would look like a normal bubble chamber, but with a much smaller stroke volume. Alternatively a standing ultrasonic field can be built up in the liquid: a quartz plate of 70 cm^2 having a fundamental frequency of 300 kHz and pressures of ±5 bar can easily be imposed on the liquid. Thus continuous sensitivity in time can be achieved, however at the expense of volume sensitivity (at the pressure nodes no bubbles are formed).

Another approach proposed and investigated by Hahn [9] is a rotating chamber, where the liquid is sensitized by using negative pressure. The experimental difficulty lies in the large centrifugal forces on the detector structure, which have to be kept well under control.

Since high-resolution tracking information is of no use for recording the short-range nuclear recoils, a very simplified optical read-out system is sufficient. For continuous operation it can be envisaged to take pictures in dark field mode with a CCD camera with 100 to 500 ms integration time. Read-out will introduce a dead time of ~ 1 ms. The frames are stored in a computer memory, compared to the last frame and the changes above a certain threshold are recorded. In addition an acoustical signal can be recorded, whenever a bubble is created.

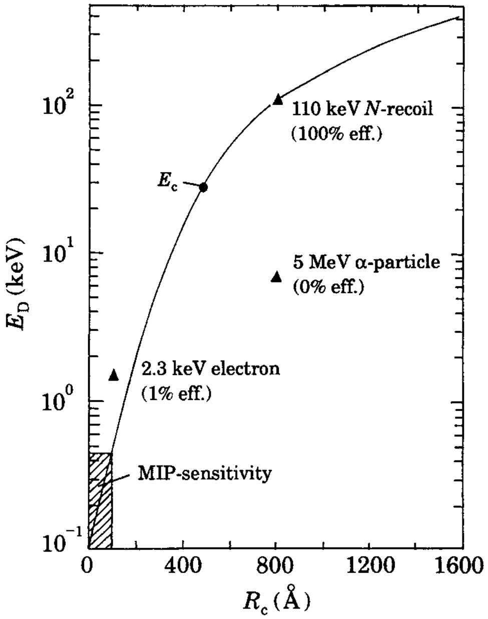

Fig. 4. – The energy E_D deposited within the critical volume is show *vs.* R_c, the critical radius for bubble formation. The curve drawn through the points is an estimate for the critical energy E_c needed for single bubble formation according to the heat spike theory. Triangles refer to the measured points of ref. [13]. At the operating conditions where the 110 keV nuclear recoil is fully efficient, the liquid is insensitive to α-particles.

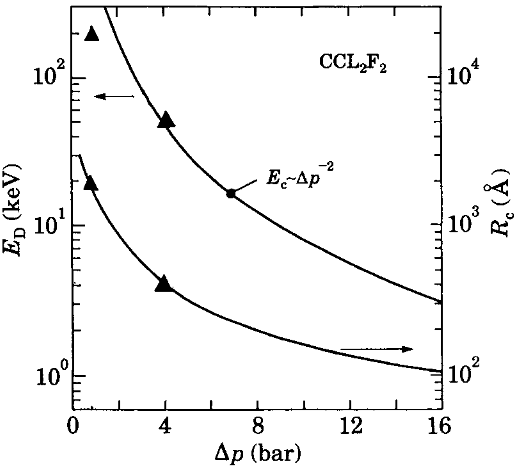

Fig. 5. – Sensitivity of freon 12 inferred from measurements with neutron recoils in [6]. For a superheat corresponding to $\Delta p = 4$ bar the energy threshold for recoils lies around 50 keV. The triangles show deposited energies E_D for which the liquid became fully sensitive and expected critical radii for two values of superheat. The curves show the energy E_c needed to trigger single bubble formation as a function of superheat (left scale), as well as the critical radius R_c as a function of superheat (right scale). For E_c a simple inverse square relation was assumed, which might be a too crude approximation.

6. - Liquids for dark matter searches.

1) *Scintillating liquids*: Certainly an extremely interesting feature would be to use a superheated liquid, which is by itself a scintillator, allowing spectroscopic information and at the same time a powerful background suppression by requiring a coincidence between the scintillator pulse and bubble formation. Possible candidates are liquid argon and xenon. In fact a scintillating liquid argon bubble chamber was successfully operated by Berset *et al.* [16]. In liquid xenon it turned out that bubble formation for minimum ionizing tracks is impeded, as long as scintillation occurs [17]. However as soon as a quenching agent for the scintillation light (*e.g.* 2% wt. ethylene) is added, the liquid becomes sensitive for bubble formation. Thus the energy from ion recombination appears to be dispersed in the form of radiation, instead of being locally released as heat. One can therefore speculate that the situation becomes different for atomic recoils, with their high-density energy deposition. In fact here the luminescence yield is already substantially reduced (by about a factor 3 with respect to minimal ionizing electrons), probably due to quenching collisions between the excited species [18]. Thus it would be extremely interesting to figure out experimentally, whether bubble formation and scintillation coexist for heavy recoils in pure LXe. In case they do, one would expect that a very low recoil threshold is achievable by going to higher Δp.

2) *Non-scintillating liquids*: From its easy operating conditions and its suitable isotopic composition (^{19}F is a spin-$1/2^+$ isotope) CCl_2F_2, *i.e.* freon 12, is an interesting candidate. Even more attractive because of its higher mass is CF_3Br. It has a similar vapor pressure curve as freon 12, and is non-inflammable.

7. - Background considerations.

An important issue is the spontaneous creation of bubbles in the liquid, which are not radiation induced. Since for dark matter searches Δp will be typically a factor four smaller than for usual bubble chamber operation, the effect of germs, which nucleate parasitic bubbles within the volume and especially at the walls should be small; but no quantitative statements can be given at the moment. The only estimate in this direction can be inferred from ref. [14], where freon 12 was sensitized for neutron recoils and exposed under unshielded conditions to the ambient radiation: a count rate was found, which was entirely compatible with the natural background neutron flux at the site of the experiment.

Being not sensitive to α, β and γ-radiation is the big asset of the proposed detector. Still the liquids will be sensitive to nuclear recoils following α-decays. This background (due to U/Th-contamination) can already be largely reduced by purification, since in the discussed cryogenic liquids any spurious dissolved radioimpurities can be frozen out. In non-scintillating chambers the residual α-activity in the detector can be measured directly by lowering the energy threshold. If a coincidence with a scintillation light pulse is possible each individual α-particle can be flagged, since the high energetic α-pulses of several MeVs can in turn be identified reliably by pulse shape discrimination.

Finally, with the detector installed in a deep underground laboratory, consideration has still to be given to the neutron component coming from the rock walls and which will affect type and dimension of the passive detector shielding (*e.g.* fast and slow neutron flux in the Gran Sasso laboratory: $3 \cdot 10^{-6}$ n/cm^2/s [19]).

8. – Conclusion.

From all that is known so far about the response of moderately superheated liquids to nuclear recoils a new dark matter detector seems feasible, which could be built with large mass of up to several 100 kg (or even bigger) and with a sufficiently low-energy threshold in the range of 10 to 50 keV. The main feature of the detector is its insensitivity to α, β, γ-radiation. If other liquids than xenon are used, a detector of this type would even be cheap. The use of scintillating liquids (*e.g.* LAr, LXe) is particularly interesting, since the high background discrimination power of the superheated liquid can then be combined with spectroscopic information. In this context, it remains to be proven whether in liquid xenon, which is by itself an interesting medium for dark-matter search, bubble formation by recoiling nuclei is compatible with scintillation light emission.

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