How to detect the dark matter of the galaxy if it is made up of weakly interacting neutral particles with masses 1–10 GeV/c^2

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An emission detector with a liquid saturated hydrocarbon might be used as the working medium for detecting the particles of the cold, dark matter of the galaxy with masses $\gtrsim 0.7$ GeV/c.

According to the present understanding, the mass of the gravitating matter of the local galaxy is an order of magnitude greater than the mass of observable matter.[1] There are reasons to believe that the "dark matter" which is so far unobservable is of a nonbaryon nature[2] and is made up of massive neutral particles which interact with baryons with cross sections on the order of weak-interaction cross sections.[3] These particles are called "WIMPs" ("weakly interacting massive particles"). Being discussed as candidates for the particles of the dark matter are new types of neutrinos, axions, supersymmetric particles, Goldstone bosons, mirror particles, etc.[3,4]

Among the methods which have been proposed for detecting WIMPs, the most attractive is the possibility of directly detecting particles with masses of $1-10^3$ GeV/c^2 from the recoil nuclei, which could be detected regardless of the mechanism by which the particles interact with the working medium of the detector. This principle has been implemented in an experimental search for WIMPs using a low-background germanium semiconductor detector. A limit has been found on the mass of Dirac neutrinos in the role of WIMPs[5]: $m_{\nu_D} < 12$ GeV/c^2. This limit is dictated primarily by the detection threshold of the detector, which was ~3 keV in this case. Plans call for the use of silicon detectors with a detection threshold ~0.8 keV; this modification will make it possible to improve the sensivity of the apparatus with respect to the mass m_{ν_D} to 4 GeV/c^2.

We would like to call attention to two circumstances. First, it is clear from kinematic considerations that the best target particles with a mass of 1–10 GeV/c would be light nuclei such as ^{1}H and ^{12}C (Fig. 1). The ^{1}H nucleus furthermore has a large nuclear spin, so it would be suitable for detecting axially interacting particles. Among the most abundant natural isotopes of germanium and silicon, the only ones which have a comparable nuclear spin are $^{73}_{32}$Ge and $^{29}_{14}$Si, whose abundances are low: 7.8% and 4.7%, respectively. For this reason, detectors using a natural isotopic mixture of germanium or silicon would be relatively insensitive to axially interacting WIMPs.

Second, the WIMP detection threshold could be lowered substantially by using a gas-discharge detection approach sensitive to individual electrons. The emission detector which we are proposing for use in searching for WIMPs combines a high density of the working medium (for efficient detection of weakly interacting particles) with a sensitivity with respect to ionization of the gas-discharge method.

The working medium of the detector might be 2,2,4-trimethylpentane (isooctane) or 2,2,4,4-tetramethylpentane, which are liquids at room temperature, from which electrons can be emitted, and in whose vapor electron breeding can occur.[6,7] Of these two media, isooctane would be preferred because of the comparatively low emission threshold (70 V/cm versus $\gtrsim 10^3$ V/cm for tetramethylpentane).

The operating principle of the detector is illustrated by Fig. 2. A WIMP is scat-

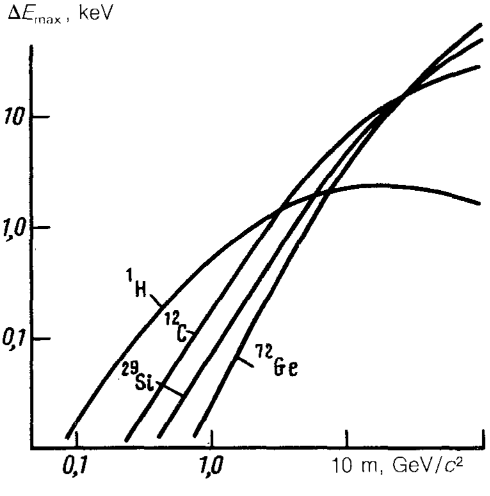

FIG. 1. Maximum energy release $\Delta E_{\max}$ in the elastic scattering of particles of mass m by various nuclei.

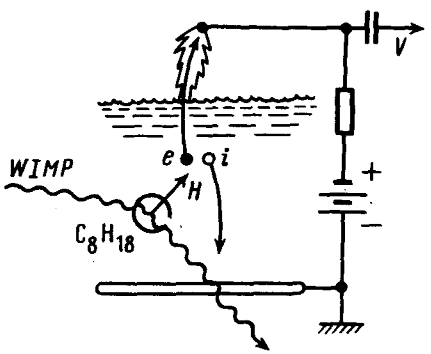

FIG. 2. Detection of a WIMP (the wavy line) in an emission detector with a liquid hydrocarbon (isooctane, C_8H_{18}) as working medium.

tered elastically by a hydrogen nucleus (in the case of an axial interaction) or by a carbon nucleus (if the scattering is coherent) which is part of the isooctane molecule (C_8H_{18}). If the energy transferred to the nucleus is greater than the binding energy of the corresponding atom in the molecule (~ 2 eV), the recoil ion or atom will leave the molecule; if this recoil particle has a sufficiently high kinetic energy, it will ionize the isooctane. The ionization yield of free charges per 100 eV of absorbed energy in liquid isooctane is[8] $G_{fi} = 0.33$. It follows that the probability for a yield from a track of a single electron is ~ 1 if the ionizing particle has an energy $(\sim 100 \text{ eV})/G_{fi} = 300$ eV. This energy could be adopted as the detection threshold of an isooctane detector.

The electrons formed upon the ionization of the isooctane by a recoil ion or atom will drift in the external electric field toward the interface. If the field has a strength $\gtrsim 100$ V/cm, there is a probability ~ 1 that these electrons will leave the liquid and go into the equilibrium gas phase, where they can be detected in a proportional-counter approach at a wire anode.

This proposed detector will thus detect, at a probability ~ 1, events in which the recoil nucleus has acquired an energy $\gtrsim 300$ eV. It would thus be possible to detect particles of the cold, dark matter of the galaxy if they have a mass $\gtrsim 0.7$ GeV/c^2.

If the working medium consists of 100 liters of isooctane, the count rate of the WIMPs interacting with the Majorana neutrino would be ~ 50 day^{-1} if their mass is 1 GeV/c^2 or ~ 20 day^{-1} if their mass is 10 GeV/c^2. The count rate for WIMPs which interact as standard Dirac neutrinos would be ~ 200 day^{-1} or ~ 500 day^{-1} at a mass of 1 or 10 GeV/c^2, respectively (Fig. 3). Estimates in Ref. 9 show that if such a detector were put in an underground laboratory such as that of Baksan Neutrino Observatory and surrounded with a liquid scintillator, to serve as active anticoincidence shielding, and if there were also passive shielding consisting of a layer (~ 1 m thick) of distilled water, low-background concrete (~ 0.5 m), and crushed dunite (~ 1 m), then the background in the energy range of interest would not exceed 35 events per day. The sensitivity of the apparatus to the cold, dark matter would thus be limited primarily by the detection threshold; i.e., the apparatus would be capable of detecting WIMPs with masses as low as ~ 0.7 GeV/c^2. An indication of an observed effect would be variations at the level of 5–8% in the count rate associated with the oribital motion of the earth.[10] Experiments with different working media would make

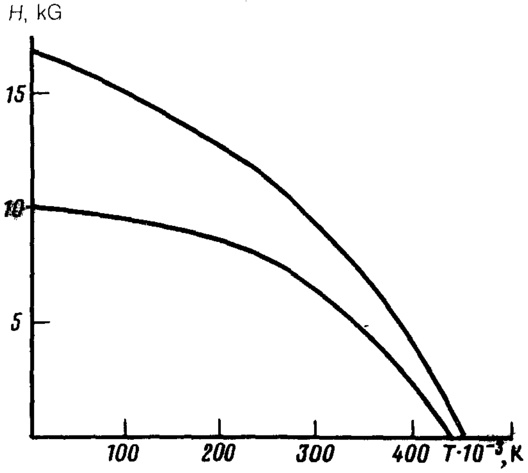

FIG. 1. Count rate of WIMP scattering events in 100 liters of isooctane versus the mass of the WIMPs. a—In the case of coherent scattering with the cross section of a Dirac neutrino; (b)—in the case of incoherent scattering with the cross section of a Majorana neutrino.

it possible to distinguish the effects stemming from the coherent and incoherent scattering of particles.

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