Application of He^4 superfluid state for the Dark matter particle detection

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Observational data denote existence of about 90% of galaxies mass, which has being detected only by gravitational effect and is named as dark matter. Particles of nonbarionic cold dark matter may be the presumable particles of elementary particle physics. For the purpose of conducting of energy, momentum measurements a large number of experimental facilities was created by the various scientific groups within the last years. The liquid helium is the subject often used in experiments with elementary particles. We submit for consideration schemes which apply the liquid helium for WIMP registration.

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On dark matter we will understand the matter which may be detected only due to its gravitational interaction on environment bodies and particles. The main evidences of dark matter existence are the plotting of rotational curves for galaxies (fig. 1)

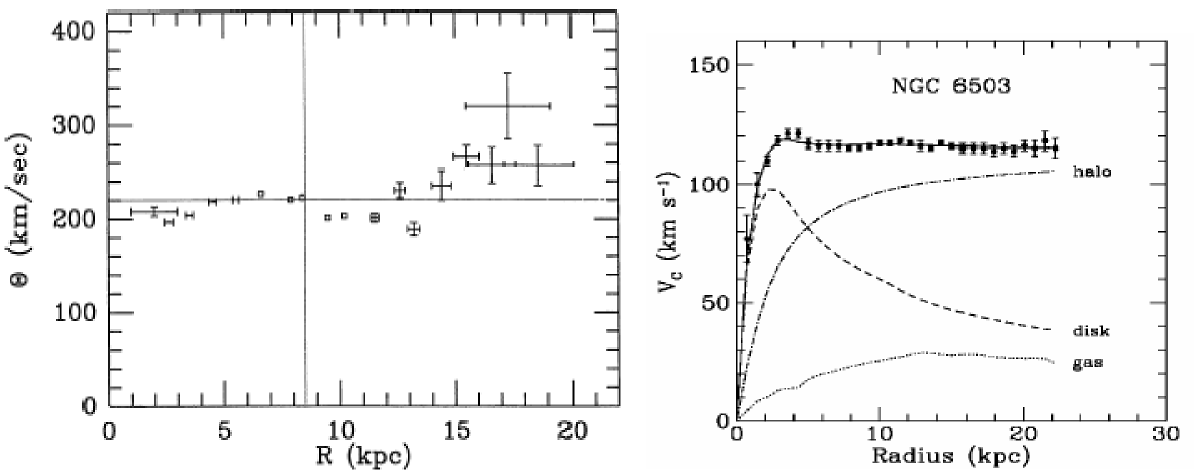

Fig. 1. The rotational curves for the galaxies "Milky Way" and NGC 6503

and microlensing of the electromagnetic galactic radiation. An alternative to the dark matter existence is the supposition that the gravitational forces are getting stronger with distance. However more than successive explanation of observed anomalies is based on availability of dark matter in galaxies. At the same time let us mention that the assessed density of Universe (about 1 hydrogen atom in 1 m^3) is too small, therefore "the dark energy" for the dynamics description of Universe is still introduced [1].

Observational data denote existence of about 90% of a galaxies mass, which is being detected only by gravitational effects. It is common practice to discriminate three types of dark matter:

- Baryonic dark matter
- Cold dark matter
- Hot dark matter.

The last two species are of nonbarionic nature. It is necessary to use the cold dark matter for the explanation of star beginning and/or stars restraining in galaxies. Particles of nonbarionic cold dark matter may be the presumable particles of elementary particle physics. For example there are axions, WIMPs, SIMPs, stranglets, technibaryons, ChaMPs. Therefore the registration of dark matter particles is actual both for astrophysics and for elementary-particle physics.

Let us consider the parameters of cosmic WIMPs (table 1).

Table 1

MASS	M_W	**10 – 5000 GeV/c^2 (~ 10 –5000 m_P)**
VELOCITY	V_W	**10^5 --10^6 m/s**
DENSITY	ρ_W	**0.3 (GeV/c^2)/cm^3**
CROSSECTION	σ_W	**<10^{-10} pbarn (~10^{-44} cm^2)**
FLUX	Φ_W	**$\sim 5 * 10^4$ 1/(cm^2 s)**

For comparison we will cite the masses of other particles (table 2).

Table 2

MASSES OF OTHER PARTICLES	
NEUTRINO	**<30eV/c^2**
AXION	**10 eV/c^2**
NEUTRALINO	**>20 GeV/c^2**
MAJORANA FERMION	**>20 GeV/c^2**
FAST NEUTRONS	**>1 MeV/c^2**

The nonbarionic nature of WIMPs and the absence of an electric charge permit the registration of these strange particles only by mass presence in case of the frontal particle collision with a nuclei of ordinary matter.

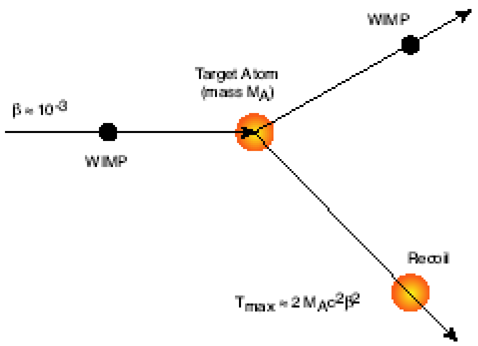

Fig.2. Model of interaction between WIMP – atom

As the result of a collision the recoiled atom receives energy. It can be registered by various methods:
A) in gases, recoiled atoms produce ionization that may be detected and measured by electronic devices. In some gases there may be the scintillation (the emergence of bursts of radiation) in case of the deceleration of an ionized atom motion;
B) in a condensed media (some fluids and crystals) the scintillation also there may be. The radiation intensity depends on the energy of recoil atoms;
C) if a recoil energy is large, then in a condensed media the excitation of acoustic waves produced along the path of a registered particle is possible (the shock waves and the splits in media along a track)[2];
D) in crystals a recoil energy can be transformed in lattice oscillations (phonons). These oscillations are to be recorded at cryogenic temperatures by the bolometric technique;

E) in semiconductors (for example in silicon or germanium) the electric charge freed by a recoiled atom can be registered as in the case A);
F) it is possible to measure the change of an atomic magnetic moment of conventional substance, due to its collision with WIMP.

For the purpose of conducting of such measurements within the last years by the various scientific groups a large number of experimental facilities were created. The main groups are realizing the direct and indirect search. Whereas in direct experiment we hope to detect exactly WIMP, in the indirect searching the registration occurs after excluding of possible challengers. Such experiments have main goals: to investigate

- Nature of lightest supersymmetric particle,
- Existence of weakly interacting massive particles (WIMPS),
- Possible relevance to models of extra dimensions, string theories and quintessence,
- Insight into unification of gravity and strong interaction.

In Pamela, IceCube, GLAST, BAIKAL, BESS the indirect searching is in progress. The classification of experimental facilities for the direct searching can be realized in a number of ways. Let us lead to one of them (table 3) [1].

Table 3. Direct Dark Matter Search

Experiment	Type	Target	Quenching factor	Mass [kg]	kg·days
Heidelberg/Moscow	I	Ge	0.25	2.88	>165
HDMS	I	Ge		0.20	
GENIUS	I	Ge		1000	
TANDAR/USC/	I	Ge	-	1033	831
PNL/Zaragoza	S	Nal		32	
USC PNL Zaragoza COSME/TWIN	I	Ge			
Neuchatel Caltech PSI	I	Ge			
	S	NaI (Tl)	Na (0.3)	6	>1500
UKDMC	S	Xe	I(0.08)	6	
	S/I	Xe	Xe (0.2)	20	
	S	NaI (Tl)	Ca (0.08)	115	30000
DAMA	S	CaF_2	F (0.12)	0.37	10
	S	Xe	Xe (0.65)	6.5	823
ELEGANT-V	S	NaI (Tl)		662	241630
ELEGANT-VI	S	CaF_2		8	
Saclay	S	Nal			
Amherst UCB	O	Mica	-	-	1 Gyr
SIMPLE (CERN Lisbon Paris)	O	Freon		1	0.190
Montreal Chalk River	O	F, Cl		1	
Tokyo Dark Matter Search	P	LiF	1	0.168	
Milano	P	TeO_2		1	

ROSEBUD	P	Sapphire	0.100
CRREST	P	Sapphire	0.262
CMDS	P/I	Ge	0.262
EDELWEISS	P/I	Ge	0.900
Orpheus	O	Sn	0.032
Salopard	O	Sn	0.100

Where I – ionization method; S – scintillation method; P – registration of `phonons' (vibrations of a crystal lattice); O – other methods.

The results received at facilities CDMS (USA) and DAMA (Italy) (figs.3,4) are considered as the most significant. Let us mention that apart from experiments, in which it is possible to register WIMP directly, in a number of other experiments it is able to obtain oblique evidences of the existence of dark matter particles. In its turn, one can break the direct experiments on two classes. In the first class(CDMS, Edelweiss, Zeplin - 1) the total energy of nuclear recoil of a detector working medium is registered, and the signal is extracted from background, created by the nuclei collisions with the other particles. In the second (DAMA) the modulation of a count rate is registered. The modulation of a flow of dark matter particles can be conditioned by Earth motion around the Sun, and consequently the detector movement through a halo of dark matter of our galaxy. In standard experiments the modulation is low (< 2%).

Other possibility of an emergence of modulation of flow is the orientation change of a detector concerning vector of the solar velocity relative to the centre of our galaxy.

Underneath the results of two experimental groups are given.

The Sierra Grande curve is plotted from a long exposure germanium experiment in which a search for both daily and annual modulation has been performed, and the results from the daily modulation search are shown. No significant signals are seen.

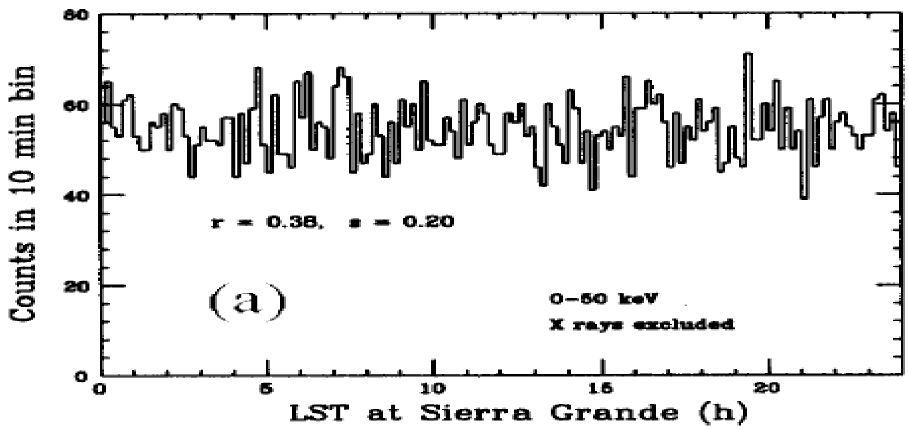

Fig. 3 Background rate from 428.1 days of data binned in 10-minute intervals and folded to look for daily modulation

An example of an annual modulation search in the DAMA program is shown below.

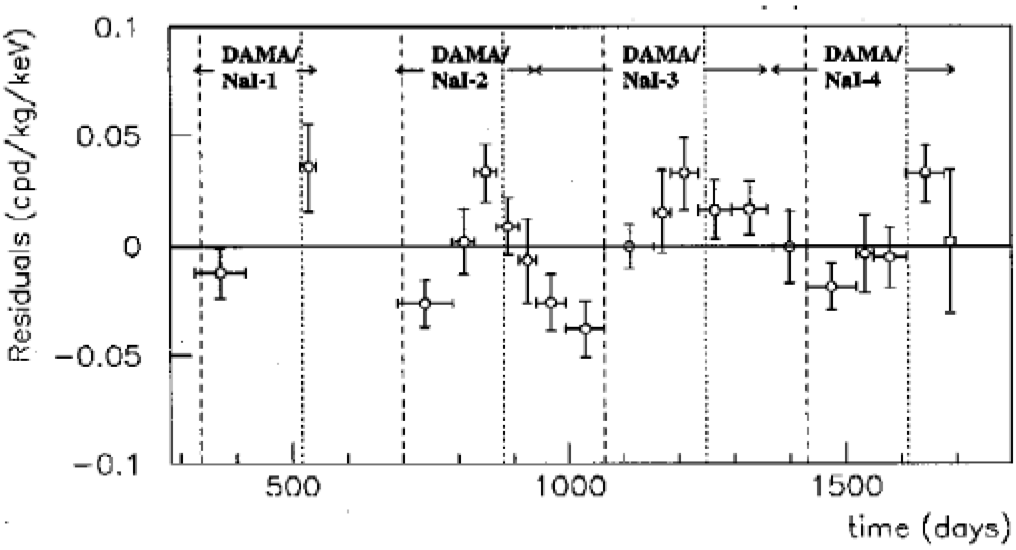

Fig.4 Results of an annual modulation search using ~ 4 years of data from the DAMA experiment

Although the investigation paths are already known we would like to discuss the possible ways of registration again. Some of our registration methods exploring the unique behavior of liquid helium in the previous PIRT session were offered [3]. We shall consider another scheme here.

How can we detect a high energy but weakly interacting particle? Let us examine the case with an elastic medium. It seems that the highest energetic sensitivity is achieved now in the gravitational waves detection. For Weber bars with length L the longitudinal dilatations are about $\frac{\delta L}{L} = 10^{-22}\, Hz^{-1/2}$ in the 1 Hz frequency band [detector AURIGA, see ref. 4]. At the same time the typical value of the energetic sensitivity in such frequency band is

$$\langle E_{kin}\rangle + \langle E_{pot}\rangle = 2\langle E_{pot}\rangle = 2\left(\frac{\mathrm{E}\,(\delta L/L)^2}{2}V\right) \approx 2\frac{10^{10}\,Pa\,\left(10^{-20}\right)^2}{2}1m^3 \approx 10^{-30}\,J \approx 60\times 10^{-12}\,eV\,.$$

One can get this expression from Hook law and its estimation from physical handbooks.

The scale of the elementary particles energy 1eV÷1TeV is huge relative to 6 peV value even on its low-energy "edge". This estimate gives hope to detect WIMP by Weber bar. More over the flux of cosmic particles is really indicated on the operating resonant gravitational waves antennae. Such events regard as a noise during the operation [5]. At that time only negligible portion of a particle energy to Weber bar at frequencies near to the eigenfrequency of oscillation $f=c_s/L$ (where c_s is the sound velocity in a bar) is transferred. This takes place because of a small time interaction between the particle and the bar medium, which is estimated as the relation of the scattering length to the particle velocity $\tau \approx a_d/v_p$, and as a result only a small factor before a proper component in Fourier array is.

Such estimation leaves for τ a wide range of possible values. However the real time of an interaction is limited on top by values which are not greater than few nanoseconds. At that if we assume the condition of a complete linearity of a system, then the energy of a hypersonic response (frequencies about $10^9 \div 10^{12}$Hz) generated by the local deformation after a point nanosecond shock is not transferred into acoustic frequencies (approximately 100Hz-10kHz), on which the registration puts practically. The energy transformation of a hypersonic pulse into conventional sound waves is possible only in cases of the special fractional power nonlinearity of a system or when the certain conditions of a parametric interaction of oscillations are fulfilled. In both cases here arise not only multiple ($F_n = n\times 1/\tau$), but also fractional ($F_{1/n} = 1/n\times 1/\tau$) harmonics, that, in principle, provides the energy pumping from hypersonic modes into sound ones. However even at a "good" solid body (which has high Q oscillating system Q >> 10^6) a similar nonlinearity and parametrical effects have to be extremely small, that limits the efficiency of an energy transfer into the low-frequency modes. Therefore the TeV particle leaves afterwards the peV level response in the Weber bar working medium. So it is hardly to use the common Weber bar for elementary particle detection in the TeV energy range.

In order to increase the efficiency of a power transfer for a transiting particle it should be searched a "more direct" way of an energy conversion into sound oscillations. Formally for this purpose τ should be dragged onto a millisecond range. It is possible to increase substantially the effective value τ_{eff}, if one makes a preference to some more slow processes in the interaction of a particle with a substance that results in generation of the sound response in kHz frequency band. Such processes must be sufficiently long for an effective energy swapping from a particle to a sound respond. In other words, the typical size must be compared with the response wave length $L=c_s/f\approx(10^2\div10^3 m/s)/1kHz=0.1\div1m$.

For example, a pulsed non-equilibrium evaporation of a fluid when the passing particle energy has the value at the level of $E\approx1eV$, is not evidently intended as a "good" technique for a sonic wave's generation. Indeed, the estimate for a size of a gas bubble $L_{bub}\approx\sqrt{\frac{RT_bE}{\sigma q_{mole}}}$ gives us the value $L_{bub}\approx3\div30$ nm if "conventional" for fluid values of its boiling temperature T_b, surface tension coefficient σ, and molar heat of vaporization of q_{mole} are taken into account. That in no way does not comply with $c_s/L_{bub}\approx(10^2\div10^3 m/s)/(3\div30nm)=3\div300Ghz>>100kHz$ in a low acoustic frequencies band.

More suited to the process of this kind the transformation of a shock wave into an acoustic one appears to be. The shock wave is formed when an individual helium atom moves in a liquid superfluid He^4 with a supersonic velocity. The atom gained that velocity as a result of a frontal collision with the incoming elementary particle. E. g., having received the energy of 1eV the atom He^4 will run with a speed of 10km/s at the first moment when similar collision occurs, however in any case such energy packet was not enough for its ionization. Emission observation of neutral atoms of He^4, emitted from the bath, which is filled by the superfluid He, in the direction of a pulse, transmitted to these atoms by elementary particles, was suggested [6,7] to use in researches on neutrino physics. We suggest to register the acoustic signal, accompanying the supersonic motion of an atom instead of detection of neutral atoms emission. The comparatively high efficiency of a sound generation is expected due to the "great length" of the considered process. Indeed, a neutral atom piercing with a supersonic velocity the bath with He^4, may leaves it off, but hence "the length" of the process appears to be of the same order of magnitude as the dimension of the bath and so of the order of its fundamental sound overtone wavelength.

At the supersonic motion the object leaves behind itself the shock wave front forming cone [8], both scrolling in space together, the object being in the cone point all along. When the front reaches the surface of a solid body, the line of an intersection of Mach cone with the surface will move also "as the object shadow" along the surface. The abrupt change of a pressure, corresponding to this line, is moving on the solid body surface, causing the generation of acoustic waves on it.

Consequently, the line of intersection of Mach cone with the surface forms the chain of secondary sound sources, whereby these secondary sources, moving on along the solid body surface, synchronously excites acoustic waves in it in each elapsed point.

Such process will particularly be effective, if the phase velocity vector of the resultant sonic wave along surface coincides with the velocity vector of line motion which is an intersection of Mach cone with the body surface. In its turn the velocity magnitude of this line appears to be equal to the velocity of the "pulled out from the whole" atom He^4, if this individual atom shall be moving parallel to a surface. The accurate calculation of efficiency of transformation of kinetic atom energy in sound requires taking into consideration a large number of input parameters. Therefore the significant quantitative efficiency evaluations of such complicated multistage process (the elementary particle $\xrightarrow{\delta E_P}$ the individual atom He^4 $\xrightarrow{\delta E_{He4}}$ the shock wave in liquid He^4 $\xrightarrow{\delta E_{He4}}$ the sonic wave in solid body) may be really obtained if they are based either on the computational experiment, or in experiment artificially simulating the similar process.

As a whole, this long chain combining several different mechanisms of an energy conversion is needed for registration of elementary particles. Therefore, the role of a solid body "inside of chain" is necessary to play role of an acoustic sensor, namely a supersensible microphone. The last shall be able to catch the amplitude of tensile elongations at the level $\frac{\delta L}{L} = 10^{-20}\, Hz^{-1/2}$ on acoustic frequencies. The above estimation shows that this tensile elongation will conform to the acoustic wave energies in an acoustic sensor at the level 60 peV (the volume of a solid working medium about $1m^3$). The transfer of energy 0.01eV ($v_{He4} \approx 1$km/s > c_s) to an atom He^4 in comparison with 60 peV leaves the reserve of registration possibility, expressed in the eight orders of. This reserve covers any conceivable loss at all stages of energy conversion in the chain from elementary particle up to sonic wave in working solid body of an acoustic sensor. One should note that the energy resolution at the level of 0.01eV in proportional mode would apparently allow to determine the neutrino mass according to spectrums of β-decay.

In the equilibrium conditions the superfluid He^4 is not a boiling liquid (due to its inherent superthermoconductivity [9]). Consequently, there are no "background" and "noise" bladders (which are caused by environment). In cooling as a result of Bose-Einstein condensation the population of a ground state by phonons appears to be the diverged function of the temperature. This is resulting in exponential reduction of the thermal phonons number and reducing the height of the acoustic noise in the system down to the values restricted by the quantum fluctuations because of Heisenberg uncertainty relation. Therefore the energetic detector sensitivity determined here is mainly the sensitivity of a used microphone. If as the latter one can use considered in the paper [10] the system SQUID/magnetostrictor which sensitivity is of about $\frac{\delta L}{L} = 10^{-20}\, Hz^{-1/2}$ then the desired sensitivity of the registration scheme would be provided.

Indeed, let us estimate the elongation ΔL/L of a rod made from magnetostriction material with the cross-section S, which causes a change of magnetic flux ΔΦ at the input of SQUID'a. The alteration corresponds to the magnetostrictor resolution δΦ. For evaluating of the specific value δΦ let us take the typical value resolution of modern commercial DC-SQUID

$$\delta\Phi \approx 10^{-5}\Phi_0 \big/ \sqrt{Hz} = 2{,}07 \times 10^{-20} Wb \big/ \sqrt{Hz}\,.$$

The change of the input flow ΔΦ appears to be proportional to the rod deformation ΔL/L as a consequence of the reverse magnetostrictive effect (that is ΔL/L → ΔΦ), which is contrast to the direct effect: the field alteration causes the deformation (that is ΔΦ → ΔL/L). In this case both the direct and the reverse effects are observed, only if the magnetostrictive sample is placed in the external field of sufficient value $H_0 \neq 0$. The magnetostrictive sensitivity "constant" $\Lambda = \Lambda(H_0)$ is the simplest performance of the reverse magnetostrictive effect, which when H_0=const connects the variation of magnetic induction ΔB with an elastic stress σ causing the variation $\Delta B = \Lambda \cdot \sigma = \Lambda \cdot (E\Delta L/L)$. For conventional magnetic materials Λ is of the order of 10^{-8} Tl/Pa and above. Then, putting to use the typical value of Young modulus for solid bodies, E=100GPa and supposing the sectional area of $S=10^{-2}\, m^2$ one can derive from condition ΔΦ=δΦ the minimal detectable elongation $\frac{\Delta L}{L} = \frac{\delta\Phi}{S\Lambda E} \approx 2 \times 10^{-21} \big/ \sqrt{Hz}$ of the rod. Thus it is necessary to actuate the system SQUID/ magnetostrictor, which is playing the role of supersensitive microphone, in contact with superfluid He so that proposed detector begins to function, i.e. practically to sink the magnetostrictive converter into the bath with He^4. The temperature of the He^4 inside the bath is due to be below λ-point ($T < T_\lambda$ = 2.17K). At the same time the magnetostrictive converter and the bath of He^4 must have comparable dimensions.

It would appear that so high sensitivity may be additionally increased through a decrease of a working medium volume: indeed $\langle E_{kin} \rangle + \langle E_{pot} \rangle = 2\langle E_{pot} \rangle = 2\left(\frac{E \cdot (\delta L/L)^2}{2} V \right) \sim V$.

However the advantage of such system is apparently the potentiality of realization of a very high energy resolution even if there is the requirement of the detector useful capacity buildup, i.e. the volume of liquid He^4. Such necessity generally arises in neutrino experiments and in WIMP searching, when the interaction cross-section of detected particles is remarkably small.

In conclusion let us note two main factors providing in case of "other equal terms" the higher process efficiency of an energy conversion, occurred on the basis of scheme: elementary particle $\rightarrow$ liquid helium $\rightarrow$ Weber bar, placed into the bath with liquid He^4 as a microphone, in contrast with the scheme "without intermediary": elementary particle $\rightarrow$ sound oscillations of a Weber bar body.

In the first, the radiation efficiency of a sonic wave is proportional to the square of an emitter dimension (the case of dipole oscillations). In the first scheme this size is compared with the path length $\boldsymbol{\lambda}$ of a He^4 individual atom, moving with a supersonic velocity in a bath filled with liquid helium. So it appears to be about the dimension of the bath. In the second one the effective emitter scale is equal to the interatomic distance in a crystal lattice of a Weber bar body $\mathbf{a_c}$. Relation $\boldsymbol{\eta}$ of efficiency for kinetic energy conversion of an elementary particle into sound in the first and the second schemes is $\boldsymbol{\eta} = \boldsymbol{\lambda}/\mathbf{a_c} = (1m/1nm)^2 \sim 10^{18}$.

In the second place, the favorable ratio of masses adds some more. For the first scheme there is the ratio of an elementary particle mass (M_P) to the atom H^4 (M_{He4}), experiencing the frontal collision with the particle. M_p is assumed mach less than M_{He4}. For the second one there is an analogous ratio but with the atom mass of antenna material (M_{SSt}) as a denominator. When an elastic impact occurs the portion of particle kinetic energy transmitted to a He^4 atom or to an atom of antenna material will be proportional to either (M_P/M_{He4}) or (M_P/M_{SSt}). Consequently, the relation of these efficiency factors for the first and the second detection schemes appears to be at the level of (M_{SSt}/M_{He4}) $\approx 10 \div 10^2$.

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