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Adolescent years of experimental physics

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Contents

Abstract. Examples of outstanding achievements in several fields of experimental physics over the past fifty years are presented. It is argued that a considerable sensitivity margin exists for experiments involving the measurement of small displacements, forces (accelerations), and frequency shifts. Achievements expected in a number of experimental programs over the next twenty years are listed.

1. Introduction

It is well known that at the end of the 19th century, one of the founders of thermodynamics, W Thomson (Lord Kelvin), declared that the advancement of physics was close to its accomplishment, with only two 'cloudlets' remaining: the Michelson experiment, and some unclarity with the photoelectric effect. The first 'cloudlet' gave birth to the special theory of relativity, the second one, together with the measurement of the blackbody radiation spectrum, initiated creation of the quantum theory. The explosive development of physics in the 20th century is convincing proof that W Thomson's prediction was incorrect.

Thus, at present, i.e., more than 100 years after the prediction, the number of such 'cloudlets' seems much larger. At the beginning of the new century, several outstanding physicists published their lists of unsolved basic physical problems. For instance, V L Ginzburg in his paper "What problems of physics and astrophysics seem now to be especially important and interesting (on the verge of the XXI century)?" lists thirty problems of this kind (see book [1]). His very interesting list includes several, indisputably fundamental, problems still 'untouched' by the experimentalists as well as a number of promising research directions that appeared quite recently. Most of the lists have a common feature: the number of unsolved problems is either larger or much larger than the number of major fundamental equations. One can conclude, then, that modern physics is still at the early stage of its development.

These methodical notes have two basic goals:

(1) To give estimates for sensitivities (resolutions) that modern technologies and the quantum theory of measurements allow for certain measuring methods of physics.

(2) To present a forecast of possible achievements in several experimental programs over the next two decades.

The main part of the paper is preceded by a historical review of some achievements in experimental physics in the past 50 years.

2. Some achievements in experimental physics over the past 50 years

The physical experiments where sensitivity (instrumental resolution) played a crucial role were carried out at the end of the 18th century (by H Cavendish and C A Coulomb). In those experiments, forces (accelerations) were measured through the measurement of mechanical displacements (oscillation amplitudes). Later on, in experiments by other researchers, the accuracy of small displacement measurement and, independently, the accuracy of small force (acceleration) measurement increased.

Somewhat later, there appeared a 'culture' of measurements where a physical observable was registered through the variation of a time interval (a frequency difference). In such experiments, as well as in many modern experiments, the ultimate sensitivity is limited by the oscillator frequency stability (narrowness of emission line). High-resolution measurements of small mechanical displacements, small

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accelerations (forces), and small frequency variations (time intervals) led to the discovery of the most important physical laws. One can expect that a further increase in sensitivity in these three kinds of measurements will provide new nontrivial results. Several examples of progress in such measurements during the second half of the 20th century are listed below.

(a) **Measurement of small mechanical displacements (oscillation amplitudes).**

During the 'pre-laser epoch', the best displacement resolution was probably achieved by Jones and Richards [2]. Observing the shift of a diffraction grating image with respect to another grating, they registered a displacement of 10^{-12} cm [2].

Soon after the first lasers appeared, Javan [3] measured the displacement of a Fabry – Perot cavity mirror with respect to the other mirror to an accuracy of 10^{-13} cm. Development of his method led to even more impressive results: in the year 1996, the difference between the oscillation amplitudes of two pairs of cavity mirrors in two Fabry – Perot interferometers was measured using the prototype of a laser-interferometric gravitational-wave antenna with a resolution of $\Delta x_{\mathrm{F-P}} \simeq 2 \times 10^{-16}$ cm [4]. This measurement was performed in the vicinity of the mean frequency 10^2 Hz and with the averaging time $\tau = 10^{-2}$ s. The cavities were almost identical and were excited by a common laser. This undoubted success was due not only to the high stability of the pump laser frequency but mainly to the high quality of the multilayer dielectric coating of the mirrors: the reflection coefficient R differed from unity only by $\simeq 3 \times 10^{-5}$.

(b) **Measurement of small accelerations.**

In the experiment on the verification of the equivalence principle, carried out at Moscow State University in 1970, the resolution achieved in acceleration measurement was 6×10^{-13} cm s^{-2}, with the averaging time 2×10^6 s (see Ref. [5]). In a similar experiment, E Adelberger with colleagues at the University of Washington managed to reduce this limit approximately three-fold (however, their averaging time was slightly larger) [6]. The oscillation amplitude of 2×10^{-16} cm in the vicinity of the above-mentioned frequency 10^2 Hz [4] corresponds to the acceleration amplitude 4×10^{-11} cm s^{-2}. A simple calculation taking into account the values of probe masses in all three experiments, the relaxation time τ^*, and the averaging time τ shows that these three resolutions are close to the limit given by the fluctuation-dissipation theorem (FDT). This limit will be discussed in detail in Section 3.

(c) **Frequency stabilization of oscillators.**

Up to the beginning of the 1950s, the only time (frequency) standard was given by the Earth's rotation period. As the first atomic standards appeared, it became evident that the period of our planet's rotation has a permanent drift and seasonal variations of the order of $\Delta\omega/\omega \simeq 10^{-8}$.

In 1956, a breakthrough happened when N Basov, A Prokhorov, and C Townes developed first ammonium masers, which had a relative frequency instability of $\Delta\omega/\omega \simeq 3 \times 10^{-11}$ during the time interval $\tau \simeq 10^3$ s.

In 1961, N Ramsey invented the hydrogen maser. Further development of this frequency standard, namely, its correction for the effect of a magnetic field on hyperfine atomic transition, for the temperature of the cavity walls, and for the frequency shift caused by the difference between the cavity frequency and the transition frequency, led in the beginning of the 1970s to the frequency instability $\Delta\omega/\omega \simeq 10^{-16}$ (during $\tau \simeq 10^3$ s) and $\Delta\omega/\omega \simeq 10^{-14}$ (during $\tau \geqslant 10^6$ s). This frequency standard played a decisive role in some experiments which, in particular, turned the general relativity (for gravitational potentials much smaller than c^2) into an engineering discipline for high-precision space navigation. Measurement of the red – blue shift of electromagnetic field frequency in the gravitational field of the Earth by Vessot and Levin [7], in which the relative difference between the measured magnitude of the effect and the general relativity prediction did not exceed 0.02%, certainly belongs to this group of experiments. Another experiment of this kind was performed by Reasenberg and Shapiro [8] who registered the delay of an electromagnetic pulse in the gravitational field of the Sun with a relative error of 0.1%.

Atomic frequency standards were successfully used to test the equivalence principle for the gravitational mass defect in the laser probing of the distance between the Earth and the Moon. For the Earth, the relative gravitational mass defect is $\simeq 4 \times 10^{-10}$, for the Moon, it is 2×10^{-11}, and the experiment revealed no difference between the accelerations of the Earth and the Moon with respect to the Sun, the accuracy being at the level of 10% of the possible violation of the equivalence principle caused by the gravitational defect of the Earth's mass [9, 10].

3. Technological and quantum limits of sensitivity

It is reasonable to distinguish between two kinds of sensitivity limits, which are called here the technological and quantum limits. The technological limit is determined by, for instance, the choice of material, the technology of its processing, and the experimental scheme. For such limits, no fundamental restrictions (depending only on fundamental physical constants) have been found so far. The term 'quantum limit' means a sensitivity restriction of purely quantum origin, which can be found from the analysis of a simplified experimental scheme.

3.1 Technological limits for the measurement of small displacements

Let us assume that the mechanical displacement $\Delta X \simeq 2 \times 10^{-16}$ cm during the time $\tau \simeq 10^{-2}$ s, mentioned above, between two absolutely rigid mirrors of an optical Fabry – Perot cavity placed on an absolutely rigid platform should be measured. Then, if the reflection coefficient R of the mirrors is close to unity, an extremely small radiation power is required:

$$\begin{aligned}\Delta X_{\mathrm{F-P}} &\simeq \frac{\lambda_0(1-R)}{2\pi}\sqrt{\frac{\hbar\omega_0}{W\tau}} \simeq 2 \times 10^{-16}\ \mathrm{cm} \\ &\times \frac{\lambda_0}{10^{-4}\ \mathrm{cm}}\,\frac{(1-R)}{10^{-6}}\left(\frac{\omega_0}{2\times10^{15}\ \mathrm{s}^{-1}}\right)^{1/2} \\ &\times \left(\frac{W}{2\ \mathrm{erg\,s^{-1}}}\right)^{-1/2}\left(\frac{\tau}{10^{-2}\ \mathrm{s}}\right)^{-1/2}. \qquad (1)\end{aligned}$$

In Eqn (1), λ_0 is the resonance wavelength, and $\omega_0 = 2\pi c\lambda_0^{-1}$ is the frequency. This estimate is valid if the frequency instability $\Delta\omega_0/\omega_0$ of the pump laser satisfies the condition

$$\frac{\Delta X_{\mathrm{F-P}}}{L} \geqslant \frac{\Delta\omega_0}{\omega_0}\,, \qquad (2)$$

where L is the distance between the mirrors. Besides, formula (1) is derived under the assumption that the fluctuations in the laser radiation are coherent-state fluctuations. As one can see from the numerical example, if the quality of the mirrors corresponds to the recently achieved value of $(1-R)=10^{-6}$ [11], the problem of registering $\Delta X \simeq 2\times10^{-16}$ cm during the time $\tau \simeq 10^{-2}$ s requires a power of only $W \simeq 2$ erg s^{-1}.

Evidently, formula (1) gives an example of a technological limit: the smallness of W and ΔX is first of all determined by the smallness of $(1-R)=10^{-6}$, which is achieved by very accurate coating of the mirror surface with several tens of layers of extremely pure dielectrics of thickness $\lambda_0/4$. For commercial mirrors available now, $1-R$ is approximately ten times larger than 10^{-6}. However, this value is still four (!) orders of magnitude smaller than at the beginning of the laser epoch. Note that no fundamental limit has been found for $(1-R)$ up to now, and there exist preliminary estimates giving the technological limit of $(1-R)\simeq 10^{-8}-10^{-9}$.

If the finite rigidity of the mirrors and their mounting on the platform is taken into account, one should consider one more source of technological noise in this experimental scheme: the Brownian oscillations of the mirrors on the platform. If the mechanical eigenmode frequencies of the set-up are substantially larger than τ^{-1}, an experimenter would deal only with the low-frequency 'tails' of the Brownian vibration modes, each mode having a mean energy of kT. According to the FDT, the larger the mechanical quality factor Q_M of these modes, the smaller their 'tails'. After rather bulky computation, which is omitted here (see, for instance, Refs [12–14]), one finds that for massive mirrors it is possible to register a value of displacement $\Delta X \simeq 10^{-17}-10^{-18}$ cm, when $\tau\simeq10^{-2}$ s and $Q_M \geqslant 10^7$, the latter being quite available at present. It is important to emphasize that in this case, the technological limit for small displacement measurements is 'created' by the FDT and given by the value of Q_M for which no relevant fundamental limit has been found. Note that during the last 20 years, deep purification of fused silica provided the increase of Q_M for mechanical cavities by approximately two orders of magnitude (from 5×10^6 to 2×10^8 [15]).

If the Fabry–Perot cavity mirrors are not rigidly mounted but are free masses, as in ground-based gravitational antennae LIGO (Laser Interferometer Gravitational wave Observatory) and VIRGO, in which the lowest eigenfrequency of the suspension is much smaller than the 'operating' frequencies ω_M at which the signal is expected, then the Brownian displacement of the mirror's center of mass is caused by a small dissipation in the suspension, and the random displacement of the mirror in the vicinity of the frequency $\omega_M \simeq 2\pi\times10^2$ s^{-1} during the time $\tau\simeq10^{-2}$ is given according to the FDT by

$$\sqrt{\overline{\Delta X^2_{\rm FDT}}} \simeq \frac{1}{\omega_M^2}\sqrt{\frac{4kT}{m\tau_M^*\tau}} = 1\times10^{-17}\ \text{cm}$$
$$\times\left(\frac{\omega_M}{2\pi\times10^2\ \text{s}^{-1}}\right)^{-2}\left(\frac{T}{300\ \text{K}}\right)^{1/2}$$
$$\times\left(\frac{m}{10^4\ \text{g}}\right)^{-1/2}\left(\frac{\tau_M^*}{2\times10^8\ \text{s}}\right)^{-1/2}\left(\frac{\tau}{10^{-2}\ \text{s}}\right)^{-1/2}, \tag{3}$$

where m is the mass of the mirror, and τ_M^* is the relaxation time of the mirror on the suspension. In estimate (3), the mirror mass was taken from the project LIGO-I [16] and the value of $\tau_M^* \simeq 2\times10^8$ s $\simeq 5.4$ years was recently obtained by Mitrofanov and Tokmakov [17] for the pendulum mode of a mirror hanging on a thin fibre of high-purity fused silica. As one can see from formula (3), the 'technologicity' of the limit is determined by τ_M^*, for which no fundamental restriction has also been found.

To conclude this discussion of the technological limits for the measurement of small displacements, let us mention two additional types of thermal equilibrium fluctuations, which have been recently predicted by M L Gorodetskiĭ and S P Vyatchanin. These are small 'ripples' on the mirror surface arising, first, from thermodynamic temperature fluctuations (entropy fluctuations) in combination with the nonzero thermal expansion coefficient

$$\alpha_T = \frac{1}{l}\frac{\partial l}{\partial T} \neq 0$$

(thermoelastic noise) and, second, from the temperature dependence of the refractive coefficient n or more precisely

$$\beta_T = \frac{1}{n}\frac{\partial n}{\partial T} \neq 0\,.$$

Fluctuations of this second type are usually called thermorefractive noise. Fluctuations of this second type of is usually called thermorefractive noise. Calculations showed that the contribution from these fluctuations can be made smaller than 1×10^{-17} cm for $\tau\simeq10^{-2}$ s and $\omega_M = 2\pi\times10^2$ s^{-1} if the size of the laser spot on the mirror surface is large enough [18–20].

3.2 Quantum limits for the measurement of small displacements

Limits of purely quantum origin 'appear' in the measurements of coordinate variations (vibration amplitudes) as soon as the finite mass of the probe body and the fluctuation backaction of the measuring instrument on the body are taken into account. In the example with coordinate measurement based on the Fabry–Perot cavity, each photon brings a random momentum

$$\delta P = \frac{\hbar\omega_0}{c}\,\frac{1}{(1-R)} \tag{4}$$

to the mirrors. Evidently, for the increase in sensitivity [by means of increasing W and reducing $(1-R)$] one must 'pay' with increased noise action of photons on the probe body. From this consideration, one can calculate the optimal parameters of the measuring instrument and the typical sensitivity limits, which have been known for more than 30 years [21]. These limits, at the suggestion of K Thorne, are usually called standard quantum limits (SQL). They can also be obtained directly from the Heisenberg uncertainty relations (see, for instance, review [22] and the references cited therein, or book [23]) under the assumptions that the observable to be measured is the coordinate and the measurement takes a finite time interval.

Evidently, there exists a 'family' of SQL for many physical observables (including electric ones) which have a common feature: the quantity is measured by means of the coordinate measurement (for more detail, see Refs [22, 23]). For a point free mass m whose coordinate is measured within the frequency range $\Delta\omega_M \simeq \tau^{-1}$ in the vicinity of frequency ω_M, the SQL is given by

$$(\Delta X_{\mathrm{f.m.}})_{\mathrm{SQL}} \simeq \sqrt{\frac{\hbar}{m\omega_{\mathrm{M}}^2\tau}} \simeq 0.5\times10^{-17}\ \mathrm{cm}\left(\frac{m}{10^4\ \mathrm{g}}\right)^{-1/2} \times\left(\frac{\omega_{\mathrm{M}}}{2\pi\times10^2\ \mathrm{s}^{-1}}\right)^{-1}\left(\frac{\tau}{10^{-2}\ \mathrm{s}^{-1}}\right)^{-1/2}. \quad (5)$$

If the same mass m, together with the rigidity $m\omega_{\mathrm{M}}^2$, forms an oscillator, then, for $\tau > \omega_{\mathrm{M}}^{-1}$, the coordinate SQL is

$$(\Delta X_{\mathrm{osc}})_{\mathrm{SQL}} \simeq \frac{1}{2}\sqrt{\frac{\hbar}{m\omega_{\mathrm{M}}}} \simeq 0.6\times10^{-17}\ \mathrm{cm} \times\left(\frac{m}{10^4\ \mathrm{g}}\right)^{-1/2}\left(\frac{\omega_{\mathrm{M}}}{2\pi\times10^2\ \mathrm{s}^{-1}}\right)^{-1/2}. \quad (6)$$

Examples given in Section 2 (with the record $\Delta X \simeq 2\times10^{-16}$ cm) and the estimate (3) demonstrate that the 'culture' of suppressing technological noise and the sensitivity achieved in measuring the mechanical displacements are so high that the sensitivity in experiments with macroscopic masses is close to the SQL. Indeed, for the mirrors used in the LIGO project, the difference between the actual sensitivity and its SQL is a little larger than one order of magnitude [4]. (For masses in the interval of one gram — tens of milligrams, the achieved value of $\Delta X_{\mathrm{F-P}}$ [see Eqn (1)] is already less than ΔX_{SQL}.)

3.3 Quantum restrictions for the measurement of small accelerations and small forces

The SQL for small accelerations A and small forces F acting on probe masses follow directly from the SQL for the coordinates [see Eqns (4) and (5)]. For a free point mass, one finds

$$A_{\mathrm{SQL}} \simeq \sqrt{\frac{\hbar\omega_{\mathrm{M}}^2}{m\tau}} \simeq 2\times10^{-12}\ \frac{\mathrm{cm}}{\mathrm{s}^2}\left(\frac{m}{10^4\ \mathrm{g}}\right)^{-1/2} \times\left(\frac{\tau}{10^{-2}\ \mathrm{s}}\right)^{-1/2}\left(\frac{\omega_{\mathrm{M}}}{2\pi\times10^2\ \mathrm{s}^{-1}}\right). \quad (7)$$

In this estimate, the values of m, ω_{M} and τ are the same as in the previous example. The estimate obtained for A_{SQL}, similar to the estimate for ΔX_{SQL}, is about one order of magnitude less than the value planned in the first stage of the LIGO project.

Let us evaluate F_{SQL} in another kind of experiment. It is well known that in 1910–1914, R A Millikan measured the electron charge by registering a stepwise electric charge variation for small (with masses $m \simeq 10^{-11} - 10^{-10}$ g) droplets of oil and mercury. In his measurements, the electron charge error for one droplet was $0.1e - 0.03e$ [24]. In 1964–1982, the experiments of Millikan were repeated in a number of laboratories in connection with the hypothesis for the existence of free quarks with electric charges $(1/3)e$ and $(2/3)e$. According to astrophysical predictions, the abundance of such quarks must be rather small, and the probability of registering them in the Millikan experiment must be $\simeq 1\ \% - 0.1\ \%$; hence, much larger probe masses were chosen than in the original experiment. In the last experiment performed at Moscow State University [25], the electric charge was measured for iron balls with masses $m \simeq 10^{-4}$ g, i.e., the probe mass was six orders of magnitude heavier than in Millikan's experiments. The measurement error was approximately $0.1e$. This experiment, as well as experiments performed in other laboratories, gave negative results, and this initiated the development of the gluon model. In fact, it was the force $F = qE$ that was measured in experiments [24, 25], where E is the electric field strength, and q is the charge. Suppose that some hypothesis suggests the existence of particles with an electric charge much less than e, and such particles are supposed to number even fewer than the particles searched for in experiments [25]. Then one can easily estimate the measurable value of q using F_{SQL}:

$$q_{\mathrm{SQL}} = \frac{F_{\mathrm{SQL}}}{E} = \frac{1}{E}\sqrt{\frac{\hbar m\omega_{\mathrm{M}}^2}{\tau}} = 10^{-16}\,\mathrm{CGSE} = 2\times10^{-7}\,e\left(\frac{E}{10\,\mathrm{CGSE}}\right)^{-1}\left(\frac{m}{1\ \mathrm{g}}\right)^{1/2} \times\left(\frac{\tau}{10^3\ \mathrm{s}}\right)^{-1/2}\left(\frac{\omega_{\mathrm{M}}}{1\ \mathrm{s}^{-1}}\right). \quad (8)$$

In the last estimate, the value of τ is the same as in the above-cited experiments [24, 25], $m = 1$ g (i.e., it is 4 orders of magnitude larger than in Ref. [25]), $\omega_{\mathrm{M}} = 1\ \mathrm{s}^{-1}$, and $E = 10$ CGSE (which is close to the field strength used by Millikan). The numerical result indicates that there is a tremendous sensitivity margin in such or similar experiments. However, it should be noted that achieving $q_{\mathrm{SQL}} \simeq 2\times10^{-7}e$ for the chosen mass and measurement times and eliminating the technological limit given by FDT require the relaxation time to be at least $\tau^* \simeq 6\times10^{15}$ s, i.e., 7 orders of magnitude larger than the value obtained so far. Still, this is possible in a vacuum of 10^{-13} Torr, and at temperature $T \simeq 4$ K.

One can see from these two examples that in gravitational-wave experiments, the sensitivity is close to the SQL but, at the same time, in other kinds of experiments the achieved resolution is very far from the SQL.

More than 20 years ago, analysis of sensitivity allowed by the quantum theory in experiments with probe masses showed that the SQL can be overcome. First, basic principles of quantum nondemolition measurements (QNDM) were proposed [26–28]. Recently, Vyatchanin [29] formulated the principle of variation quantum measurements. These two methods have a common feature: in both of them, the coordinate is not registered continuously.

Rather soon after the first works on QNDM had appeared, such measurements were demonstrated successfully in optical experiments with optical modes and wave-packets; however, there was no success in experiments with probe masses (see review [30]). Several years ago, S Haroche and his colleagues successfully demonstrated absorption-free counting of microwave quanta [31]. In my opinion, this is one of the most outstanding experiments conducted during the second half of the 20th century.

At present, several versions of QNDM for gravitational-wave antennae have been developed [32–36]. Naturally, they do not use continuous measurement of the distance between the mirrors (probe masses); instead of the distance, another quantity (for instance, velocity) may be measured. It should be noted, however, that all such versions are not easy to realize. It is probable that a simpler and technologically easier version will be proposed in the future. At the same time, estimations by Khalili [37] show that a 'table' version of QNDM with small probe masses and with the sensitivity exceeding the SQL can be realized in the near future.

3.4 Increasing the frequency stability of self-excited oscillators

The increase of frequency stability of microwave self-excited oscillators, which was extremely rapid during the period 1950–1970 (when stability was improved by more than 6 orders of magnitude), considerably slowed down in the next three decades. Several optimistic programs for improving such oscillators have been published but no substantial progress has been achieved so far. However, during the past three decades, the stability of optical self-excited oscillators (lasers) has noticeably increased.

Relative frequency deviation for a self-excited oscillator based on a Fabry–Perot [1] cavity can be easily obtained from Eqns (1) and (2):

$$\frac{\Delta\omega_0}{\omega_0} = \frac{\Delta X_{\mathrm{F-P}}}{L} = \frac{\lambda_0(1-R)}{2\pi L}\sqrt{\frac{\hbar\omega_0}{W\tau}} = \frac{1}{Q_{\mathrm{e}}}\sqrt{\frac{\hbar\omega_0}{W\tau}}. \tag{9}$$

The second expression for $\Delta\omega_0/\omega_0$ indicates that Eqn (9) is also valid for other types of cavities. Formula (9) is valid for $\tau > Q\omega_0^{-1}$ and under the assumptions that the cavity eigenfrequency is constant and the self-excited oscillator emits coherent radiation (there are no fluctuations except those inherent in the quantum state). This formula, often called the Townes–Shawlow relation, is only valid for small W; it does not take into account the back force action of the emitted photons on the cavity. More than 20 years ago, this effect was taken into consideration [39]: the cavity was assumed to be made of a solid with the Young modulus Y and volume V. If τ substantially exceeds the periods of low-frequency mechanical modes, then the accounting for the back action of photons results in the following SQL for the relative frequency deviation:

$$\begin{aligned}\left(\frac{\Delta\omega_0}{\omega_0}\right)_{\mathrm{SQL}} &\simeq \sqrt{\frac{\hbar}{YV\tau}} \\ &\simeq 5\times10^{-24}\left(\frac{Y}{4\times10^{12}\ \mathrm{erg\ cm^{-3}}}\right)^{-1/2} \\ &\times\left(\frac{V}{10^4\ \mathrm{cm}^3}\right)^{-1/2}\left(\frac{\tau}{10^3\ \mathrm{s}}\right)^{-1/2},\end{aligned} \tag{10}$$

which can be achieved at the optimal power

$$W_{\mathrm{optimal}} \simeq VY\omega_0 \times Q_{\mathrm{e}}^{-2}\,. \tag{11}$$

This estimate, in comparison with $\Delta\omega_0/\omega_0 \simeq 10^{-16}$ being obtained for the hydrogen maser, indicates that there exists an extremely large margin for the frequency stability. It is worth noting that if a solid is ever found (or created) with such a large electromagnetic nonlinearity that could compensate for the ponderomotive nonlinearity of a cavity made from this solid, then a self-excited oscillator with such a cavity will have a relative frequency deviation less than $(\Delta\omega_0/\omega_0)_{\mathrm{SQL}}$ [40].

The example with the achievable frequency stability of self-excited oscillators as well as the above-mentioned perspectives of increasing quality factors of electromagnetic cavities definitely indicate that there exists a very large potential margin of sensitivity in a very broad field of experimental physics — spectroscopy.

[1] It is worth noting that the classical analog of this formula was obtained by I L Bershteĭn as early as 1950 [38].

4. Possible experimental achievements over the next 20 years

Summarizing the previous section, one can say that no limits of achievable sensitivity (resolution) can be given at present for the types of measurements considered above. From the optimistic viewpoint, an increase of sensitivity of at least two orders of magnitude should be expected within the next two decades in this 'field' of experimental physics.

In this section, the author considers only a few examples of experimental programs where basic advances expected were planned and published. In addition, several other possible experiments are briefly commented.

In the above-mentioned LIGO project (for more detail, see the paper [16] and the review [41]), ground-based laser-interferometric gravitational-wave antennae should reach sensitivity in units of the metric perturbation amplitude $h \simeq 10^{-21}$ at the first stage. This value corresponds to the following amplitude of vibrations between the two mirrors:

$$\Delta X \simeq \frac{1}{2}\,hL \simeq \frac{1}{2}\times10^{-21}\times4\times10^5\ \mathrm{cm} \simeq 2\times10^{-16}\ \mathrm{cm}\,. \tag{12}$$

Such a resolution will be achieved in the nearest future. If the coalescence of two neutron stars happens in one galaxy once in 10^5 years, then several bursts with amplitude $h \simeq 10^{-21}$ will be recorded by the LIGO antennae in the course of one year. This will be the first direct demonstration of the existence of gravitational waves.

During the past several years, experimenters have been intensively preparing the upgrade of some key elements of the antennae. The changes will allow a considerable release in the technological sensitivity constraints and reach $\Delta X \simeq 2\times10^{-17}$ cm and, accordingly, $h \simeq 10^{-22}$ (the stage of LIGO-II, 2008–2010). These values are close to the SQL, and the probability of detecting bursts of gravitational radiation from coalescing neutron stars at a distance much exceeding 30 megaparsec or from merging black holes at a cosmological distance is close to 100% for LIGO-II. Let us give a brief list of fundamental data expected from LIGO-II.

(1) The estimate of the population of neutron stars in the metagalaxy and, consequently, the contribution from these stars to dark matter, will be obtained.

(2) The shape of the gravitational burst from neutron stars will indicate which equation of state (from the existing list) would hold for neutron star matter.

(3) Shape analysis of the burst from merging black holes is a very convenient way of testing the general relativity in the ultrarelativistic case, where the relative difference between the gravitational potential and c^2 is much less than unity. As K S Thorne said [42], in this case the experimenters will not observe matter but only the behavior of spacetime. This statement is an example of a reductional approach to the formulation of basic physical laws.

As I have mentioned in the previous section, the experimenters now work on a version of LIGO that could overcome the SQL in the next stage (LIGO-III). Most probably, this will happen much sooner than in the next 20 years. At present, it is difficult to predict qualitatively new results but there is an auxiliary result, mainly of methodical value, which can almost be guaranteed. It is very probable that the measuring technique will be based on registering the variations of relative velocity of the mirrors; hence, their momentum P will also be measured more accurately than allowed by the SQL:

$$\Delta P_{\text{meas}} < \Delta P_{\text{SQL}} = \sqrt{\frac{\hbar m}{2\tau}}\,. \tag{13}$$

Then the kinetic energy of one mirror with respect to the other will also be measured with an error of less than $\hbar/2\tau$:

$$\Delta\mathcal{E}_{\text{meas}} = \frac{\Delta P_{\text{meas}}^2}{m} < \frac{\Delta P_{\text{SQL}}^2}{m} = \frac{\hbar}{2\tau}\,. \tag{14}$$

Such an accuracy will be 'paid for' by the increase in the coordinate uncertainty for the mirror center of mass, since in this case

$$\Delta X > \Delta X_{\text{SQL}} = \sqrt{\frac{\hbar\tau}{2m}}\,.$$

There is another interesting experimental program whose realization will probably bring qualitatively new physical results. This is the LISA (Laser Interferometer Space Antenna) project scheduled for 2010–2012. Basically, it is the same gravitational-wave antenna with free mirrors (masses) combined with a laser interferometer registering small relative oscillations in the mirrors, as in LIGO or VIRGO. The only difference is that LIGO and VIRGO are sensitive to gravitational waves within the frequency range from 30 Hz to approximately 1000 Hz, while LISA is designed for the range 10^{-5} Hz – 10^{-2} Hz. For this reason, the distance between its mirrors is $L \simeq 5 \times 10^{11}$ cm = 5 million km, and the mirrors are placed on three satellites whose center of mass is in the same orbit as the Earth. The expected sensitivity, say, at frequency $\omega_{\text{M}} \simeq 2\pi \times 10^{-4}$ s^{-1} and for the averaging time $\tau \simeq 10^4$ s amounts to $h \simeq 6 \times 10^{-21}$, corresponding to the amplitude of the mirror oscillations $\Delta X \simeq 1.5 \times 10^{-10}$ cm, which, in its turn, means that the acceleration difference of the two mirrors will be $A_{\text{LISA}} \simeq 6 \times 10^{-16}$ cm s^{-2}. The major problem of the LISA project is that A_{LISA} is very small. Although it is 5 orders of magnitude higher than A_{SQL} for the respective ω_{M}, $m = 10^3$ g, and τ, in this case technological limitations play the principal role. The main difficulty is that the trajectories of satellites with moderate mass differ considerably from geodesics (mainly, due to solar radiation pressure and solar wind, which are not constant). This makes the acceleration differ from the Newtonian one by approximately 10^{-6} cm s^{-2}.

In 1972, D DeBra and his colleagues from Stanford University [43] designed a satellite whose acceleration differed from the Newtonian one by only $A \simeq 10^{-8}$ cm s^{-2}. For this purpose, a 'control' mass uninfluenced by solar radiation and solar wind was installed at the gravitational center of the satellite. Contact-free coordinate meters placed around this mass controlled small jet thrusters which returned the satellite to the proper position. Such satellites are now called drag-free. In the LISA program, acceleration compensation is supposed to be 7 (!) orders of magnitude better than in the first DeBra's satellite. In particular, the relaxation time τ_{M}^* required to make the technological limit ΔX_{FDT} less than 1.5×10^{-10} cm should be 4×10^{10} s, i.e., more than a thousand years. Besides, there exist other technological problems but they do not seem to be insolvable at present.

If the LISA program succeeds, one can be confident that relatively low-frequency gravitational radiation from the nearest typical double stars (with a rotation period of several hours) as well as gravitational radiation from stars rotating around black holes will be registered. But the most important discovery expected from the LISA program is the observation of relic gravitational radiation and measurement of its spectral distribution. This discovery will definitely lead to a revolution in cosmology.

5. Conclusions

In conclusion, it is worth mentioning several promising achievements of experimenters in other fields of physics, which were not discussed in these notes.

Recently, H Walther and his colleagues have demonstrated preparation of pure Fock states of the electromagnetic field using a modified technique of a single-atom maser [44]. About the same time, J Kimble and his colleagues demonstrated a microscope where the trajectory of a caesium atom in a small Fabry – Perot cavity was registered using a series of photons, the coordinate measurement error being close to the standard quantum limit [45]. These two examples relate to a rapidly developing field usually referred to as quantum optics. In this field, considerable progress has been achieved in the theory and methods of quantum measurements. As a result, the physical glossary acquired new terms such as squeezed quantum states and entangled states. Preparation and observation of such states has been demonstrated by many quantum optics groups. Recently, Karlsson and Lovesey [46] took advantage of an elegant technique and discovered entangled quantum states in experiments on neutron scattering from samples involving hydrogen isotopes. In this work, entangled states were registered despite their extremely short lifetimes of 10^{-15} – 10^{-16} s.

Examples and arguments discussed in these notes cover only a single branch of experimental physics. Still, in my opinion, they give grounds for using the word 'adolescent' in the title. Intensive development is also expected in many other fields of physical science. For instance, a new method of accelerating elementary particles is being developed in high-energy physics. In this method, particles are accelerated by the strong electromagnetic field of picosecond laser pulses, which is many orders of magnitude higher than typical field strengths in accelerators [47, 48]. This method will probably lead to a revolution in accelerator physics. Another example is from microwave astronomy. One can hope that the idea of N S Kardashev, Yu N Pariĭskiĭ, and N D Umarbaeva will be implemented in the nearest future. According to this idea, satellite-borne receiving microwave antennae should be separated by distances of the order of an astronomical unit. This will provide an angular resolution of about 10^{-13} radian [49]!

It is well known that many fundamental discoveries of the second half of the 20th century were unexpected (unpredicted). Examples include discoveries of X-ray stars, pulsars, bursts of gamma radiation, and the recently discovered spatial distribution of relic radiation (see review [50] and the literature cited therein). All these discoveries became possible due to the development of sufficiently sensitive measuring techniques. Clearly, further advances in physics also rely on the progress of these techniques and the development of new ones.

In my opinion, there are three big problems that most deserve the attention of experimenters, and the 'culture' of probe-mass experiments may be very helpful in solving these problems. They are as follows: (I) possible breaking of symmetries; (II) the number of dimensions in our world where, up to now, only a four-dimensional subspace with three space coordinates and time has been studied, and (III) the Planck mass, length, and time interval.

Experimental studies of the first problem started long ago and continue up to now. In particular, they include tests of the equivalence between inertial and gravitational masses, the search for the dipole moments of electrons and neutrons and testing the equality of the charge modules for electrons and protons. In the research programs STEP (Space Test of Equivalence Principle) and Galileo Galilei, it is supposed to increase resolution by several orders of magnitude. It is possible that the sensitivity of registering the dipole moment of a neutron can be essentially increased by using the methods of weak force measurement [51].

Recently, the hopes aroused for discovering the additional dimensions (problem II) by testing the Newtonian law of universal gravitation at small distances (see review [52]). In this connection, it is worth mentioning the Milgrom hypothesis (see papers [53] and V L Ginzburg's comments [54]) that the Newton's second law of dynamics may not be valid at accelerations less than 10^{-8} cm s^{-2}. In this case, the dark matter hypothesis becomes useless.

The Planck mass, length, and time interval (the third problem) have been a riddle for theorists for already more than a hundred years. It is possible that according to the hypothesis by S Hawking [55] these quantities characterize fluctuating bonds between different worlds (or parts of the same world) and that such bonds cause irreversible events (dissipation) in usual matter (the term 'foam of spacetime' is sometimes used). If this hypothesis holds true, then an experimenter may face some unknown fluctuation influence on the probe masses at a certain level of isolation of the probe masses from the thermostat. If this happens at some stage of LIGO or LISA, it will be very fortunate.

To conclude these notes, it is worth quoting a very appropriate phrase by V Weisskopf: "Until we know why an elementary electric charge is identical in all processes, our interest in fundamental physical problems will continue unabated".

References

1. Ginzburg V L *O Nauke, o Sebe i o Drugikh* (About Science, Myself, and Others) 3rd ed. (Moscow: Fizmatlit, 2002)
2. Jones R V, Richards J C *J. Sci. Instrum.* **36** 90 (1959)
3. Javan A, in *Lasers and Applications* (Ed. W S C Chang) (Columbus, OH: Engineering Experiment Station, Ohio State Univ., 1963)
4. Abramovici A et al. *Phys. Lett. A* **218** 157 (1996)
5. Braginskiĭ V B, Panov V I *Zh. Eksp. Teor. Fiz.* **61** 873 (1971) [*Sov. Phys. JETP* **34** 463 (1972)]
6. Adelberger E G et al. *Phys. Rev. D* **42** 3267 (1990)
7. Vessot R F C, Levine M W, in *Intern. Meeting on Experimental Gravitation, Pavia, 1976* (Atti dei Convegni Lincei, Vol. 34, Ed. B Bertotti) (Roma: Accademia Nazionale dei Lincei, 1977) p. 371
8. Reasenberg R D, Shapiro I I *Acta Austronaut.* **9** 103 (1982)
9. Williams J G et al. *Phys. Rev. Lett.* **36** 551 (1976)
10. Shapiro I I, Counselman III C C, King R W *Phys. Rev. Lett.* **36** 555 (1976)
11. Rempe G et al. *Opt. Lett.* **17** 363 (1992); Kimble H J (private communication)
12. Gillespie A, Raab F *Phys. Rev. D* **52** 577 (1995)
13. Levin Yu *Phys. Rev. D* **57** 659 (1998)
14. Braginsky V B, Levin Yu, Vyatchanin S P *Meas. Sci. Technol.* **10** 598 (1999)
15. Ageev A Yu, Penn S D, Saulson P R (in press)
16. Abramovici A et al. *Science* **256** 325 (1992)
17. Braginskiĭ V B, Mitrofanov V P, Tokmakov K V *Izv. Ross. Akad. Nauk Ser. Fiz.* **64** 1671 (2000) [*Bull. Russ. Acad. Sci. Phys.* **64** 1333 (2000)]
18. Braginsky V B, Gorodetsky M L, Vyatchanin S P *Phys. Lett. A* **264** 1 (1999)
19. Liu Yu T, Thorne K S *Phys. Rev. D* (submitted)
20. Braginsky V B, Gorodetsky M L, Vyatchanin S P *Phys. Lett. A* **271** 303 (2000)
21. Braginskiĭ V B *Zh. Eksp. Teor. Fiz.* **53** 1434 (1967) [*Sov. Phys. JETP* **26** 831 (1968)]
22. Braginsky V B, Khalili F Ya *Rev. Mod. Phys.* **68** 1 (1996)
23. Braginsky V B, Khalili F Ya *Quantum Measurement* (Ed. K S Thorne) (Cambridge: Cambridge Univ. Press, 1992)
24. Millikan R A *Electrons, Protons, Photons, Neutrons, and Cosmic Rays* (Cambridge: The Univ. Press, 1939)
25. Braginsky V B, Kornienko L S, Poloskov S S *Phys. Lett. B* **33** 613 (1970)
26. Braginskiĭ V B, Vorontsov Yu I, Khalili F Ya *Zh. Eksp. Teor. Fiz.* **73** 1340 (1977) [*Sov. Phys. JETP* **46** 705 (1977)]
27. Thorne K S et al. *Phys. Rev. Lett.* **40** 667 (1978)
28. Braginskiĭ V B, Vorontsov Yu I, Khalili F Ya *Pis'ma Zh. Eksp. Teor. Fiz.* **27** 296 (1978) [*JETP Lett.* **27** 277 (1978)]
29. Vyatchanin S P *Phys. Lett. A* **239** 201 (1998)
30. Grangier P, Levenson J A, Poizat J-P *Nature* **396** 537 (1998)
31. Nogues G et al. *Nature* **400** 239 (1999)
32. Braginsky V B, Khalily F Ya *Phys. Lett. A* **218** 167 (1996); Braginsky V B, Gorodetsky M L, Khalili F Ya *Phys. Lett. A* **232** 340 (1997)
33. Braginsky V B et al. *Phys. Rev. D* **61** 044002 (2000)
34. Buonanno A, Chen Y *Phys. Rev. D* **64** 042006 (2001)
35. Khalili F Ya *Phys. Lett. A* **288** 251 (2001)
36. Kimble H J et al. *Phys. Rev. D* **65** 022002 (2002)
37. Braginsky V B, Khalili F Ya, Volikov P S *Phys. Lett. A* **287** 31 (2001)
38. Bershteĭn I L *Izv. Akad. Nauk SSSR. Ser. Fiz.* **14** 145 (1950)
39. Braginskiĭ V B, Vyatchanin S P *Zh. Eksp. Teor. Fiz.* **74** 828 (1978) [*Sov. Phys. JETP* **47** 433 (1978)]
40. Braginskiĭ V B, Vyatchanin S P, Panov V I *Dokl. Akad. Nauk SSSR* **247** 583 (1979) [*Sov. Phys. Dokl.* **24** 562 (1979)]
41. Braginskiĭ V B *Usp. Fiz. Nauk* **170** 743 (2000) [*Phys. Usp.* **43** 691 (2000)]
42. Thorne K S *Vestnik Ross. Akad. Nauk* **71** 587 (2001) [*Herald Russ. Acad. Sci.* **71** 375 (2001)]
43. DeBra D, in *Proc. Int. Conf. on Experimental Tests of Gravitational Theories, Caltech, November 1, 1971*, JPL Technical Memorandum, 33–499 (1971)
44. Varcoe B T H et al. *Nature* **403** 743 (2000)
45. Hood C J et al. *Science* **287** 1447 (2000)
46. Karlsson E B, Lovesey S W *Phys. Rev. A* **61** 062714 (2000)
47. Pukhov A *J. Plasma Phys.* **61** 425 (1999)
48. Gahn C et al. *Phys. Rev. Lett.* **83** 4772 (1999)
49. Kardashev N S, Pariĭskiĭ Yu N, Umarbaeva N D *Izv. Spetsial'noĭ Astrofiz. Observ.* (5) 16 (1973)
50. Novikov I D *Usp. Fiz. Nauk* **171** 859 (2001) [*Phys. Usp.* **44** 817 (2001)]
51. Braginsky V B, in *Quantum Physics, Chaos Theory, and Cosmology* (Eds M Namiki et al.) (Woodbury, NY: American Institute of Physics, 1996) p. 93
52. Rubakov V A *Usp. Fiz. Nauk* **171** 913 (2001) [*Phys. Usp.* **44** 871 (2001)]
53. Milgrom M *Astrophys. J.* **270** 365, 371, 384 (1983); *Ann. Phys.* (New York) **229** 384 (1994)
54. Ginzburg V L *O Fizike i Astrofizike* (About Physics and Astrophysics) (Moscow: Byuro Kvantum, 1995) [Translated into English: *The Physics of a Lifetime. Reflections on the Problems and Personalities of 20th Century Physics* (Berlin: Springer-Verlag, 2001)]
55. Hawking S W *Phys. Rev. D* **37** 904 (1988)