Letters to the Editor

A FUNDAMENTAL METHOD FOR MEASURING TIME

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ACCORDING to presently available methods, time is measured by the frequency of any given periodic process. The accuracy of the time measurement is determined here by the stability and the accuracy of the measurement of the frequency. The most accurate types of "frequency" methods for measuring time involve so-called atomic and molecular clocks, which use the frequency of the electromagnetic radiation generated during transition from one energy level to the next. The exceptionally high stability of these clocks is due to the fact that changes in external conditions have relatively little effect on the atomic or molecular energy spectra. However, the accuracy of these clocks is limited in principle and is determined by the characteristic width of the spectrum lines and hence by the lifetimes of the energy levels. The time intervals of the electromagnetic transitions in atoms and molecules which can be recorded as continuous electromagnetic radiation (not as particles, or γ quanta) range from 10^{-10} to 10^{-6} sec. These figures also determine the accuracy limit attained up to now in the measurement of time.

Another method for measuring time, different in principle from the "frequency" methods, is described below. By applying this method it is possible to increase considerably the accuracy of measurement. The principle of this method, which we shall call "nuclear," is very simple and is based on utilizing the number of disintegrations of radioactive nuclei (or unstable particles).

The components of the proposed method for measuring time are essentially as follows: a) a source — radioactive nuclei (or unstable particles) b) a transducer to record the particles or decay products, c) an electronic scaler and d) the display device — a counter calibrated directly in units of time corresponding to a given number of decay particles.

The stability of this "nuclear" clock exceeds the stability of atomic and molecular clocks because changes of external conditions have practically no influence on the decay constant of the nuclear transition.[1] At any rate the changes possible in this case would be far less than the corresponding changes in the energy spectra of the atoms or molecules.

Let us examine the basic limits in the proposed method for measuring time. This method is based on the uniformity of the decay process as a function of time, which in turn enables us to take into account the decay probability per unit of time. However, as has been shown previously, according to the general premises of the quantum theory, the law of decay is in principle not homogeneous in time (the decay law deviates from exponential) and hence the concept of decay probability per unit of time is in general only an approximation.[2] It is precisely this deviation of the decay law as a function of time which sets the basic limitations for the accuracy of the measurement of time in the proposed "nuclear" method. However, as has been shown previously, the condition under which the law of decay will be homogeneous in the time (i.e., with small non-exponential corrections), is

$$(\Gamma t/\hbar)\, e^{-\Gamma t/\hbar} \geqslant (\Gamma/E_0)^2, \qquad (1)$$

where Γ is the width of the decaying energy level and E_0 is its energy. It appears from (1) that the decay law becomes more homogeneous in time as Γ/E_0 decreases, i.e., the smaller the value of Γ and the larger E_0. We therefore conclude that for the purpose of measuring time it is desirable to select a decay state with small Γ, i.e., with a long lifetime. On the other hand, the selection of a long lifetime is justified because no corrections are needed to compensate for the decay of the source.* Let us make some elementary estimates on the basis of (1) in order to ascertain the fundamental limits of the proposed "nuclear" method for time measurement. For instance if the α emitter U^{238} with $T_{1/2} = 4.5 \times 10^9$ years is used as the radioactive nucleus and if the energy level of the α particles is $E_0 \approx 4$ Mev, then the (nonexponential) correction factor for a measured time interval of ~ 1000 years will be of the order of 10^{-60}. Thus, though in principle the "nuclear" method for measuring time also has an upper limit of accuracy, this limit can be moved very far away by a choice of nuclides with long lifetimes (small Γ) and high values of the energy E_0.

If the decay law is considered homogeneous in time, and has been shown to be true with a very

high degree of accuracy (practically "infinite"), then the degree of accuracy of measuring time by the proposed "nuclear" method will be limited only by the statistical accuracy, i.e., the value of $N^{-1/2}$, where N is the number of disintegrations recorded by the counter. Thus a specified high accuracy in measuring time can be attained by selecting a sufficiently large N. This evidently reduces in turn to the choice of a high source power (number of disintegrations) and a low-inertia transducer capable of recording (without being "swamped") all the disintegration events. In order to obtain some practical figures let us consider the following examples: 1 g-atom of Li^8 is needed to measure 0.1 sec with an accuracy of 10^{-11}, ~ 1 g-atom of C^{11} is required to measure 1 min with an accuracy of 10^{-11}, and to measure 1 year with a degree of accuracy of 10^{-11}, either $\sim 10^8$ g-atoms of U^{238} or 10 g-atoms of Ni^{63} are required. To achieve 100% registration of all the disintegration events, one can use either a large number of ordinary (inertial) transducers or low-inertia ones recording the particles through stimulation of very short-lived nuclear energy levels.

It is evident that the accuracy of the proposed "nuclear" clock increases with increasing time interval to be measured, i.e., with increasing clock operating time.

Even though various technical problems may be encountered in the course of developing the proposed "nuclear" method for measuring time (such as the production of thin films of very large amounts of radioactive substance, the need to eliminate "collective effects," etc), it would be natural to attempt it experimentally, because the method enables us in principle to obtain a sharp increase in the accuracy of time measurement, in comparison with even the most highly developed contemporary "frequency" methods.

Finally, let us note that the development of a very accurate method for measuring time will permit a detailed investigation of the decay law of short-lived physical systems (especially the deviation of the decay law from the exponential), particularly of elementary unstable particles, thus yielding valuable information on elementary-particle interactions.[2]

In conclusion, I express my gratitude to Academician I. E. Tamm, Professor V. L. Ginzburg, Professor E. L. Feĭnberg, and to all the participants in the theoretical seminar at the Physics Institute of the Academy of Sciences, and also to Professor G. I. Petrashen, Professor S. É. Khaĭkin, Yu. N. Demkov, and A. M. Khalfin for valuable discussions and comments.

*It must be noted, to be sure, that it is not absolutely necessary to use very long-lived states for the proposed method of measuring time, because corrections for decay can be obtained by determining the lifetime by means of an experiment on resonance scattering of decay products, which is independent of the experiment on the time measurement. Let us also note that the choice of very long-lived states is not convenient for practical purposes, because it will involve a very large amount of radioactive substance.

[1] H. Byers and R. Stump, Phys. Rev. **112**, 77 (1958).

[2] L. A. Khalfin, Doklady Akad. Nauk SSSR **115**, 277 (1957), Soviet Phys.-Doklady **2**, 340 (1958).

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DETERMINATION OF THE CHARGE-EXCHANGE CROSS SECTION FOR PION-PION COLLISION FROM THE ANALYSIS OF THE $\pi^- + p \rightarrow \pi^- + \pi^+ + n$ REACTION AT 290 Mev

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THE importance of studying π-π interactions is evident and has been reiterated earlier.[1,2] However, the experimental determination of π-π scattering data is very difficult because one has to use only indirect methods. All the available information on π-π interaction is given in Table I. It should be pointed out that only order-of-magnitude measurements of the π-π interaction cross section were attempted in references 1, 2, and 3.

In the present paper use was made of photoemulsion data (200 events) obtained from the study of the reaction

$$\pi^- + p \rightarrow \pi^- + \pi^+ + n \qquad (1)$$