ing to be able to go much further in determining the effective interaction in these regions.

We would like to acknowledge valuable discussions with Professor R. Sorensen, concerning his (unpublished) studies of the quasiparticle random-phase approximation in odd-mass nuclei, and helpful discussions with Professor A. Goswami and Professor W. W. True. We would also like to acknowledge the assistance of Mrs. M. Ratner in the numerical calculations and the Case Computing Center for the use of their computing facilities.

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RELATIVISTIC CORRECTIONS FOR TERRESTRIAL CLOCK SYNCHRONIZATION*

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The development of atomic maser clocks has made possible extraordinarily accurate synchronization of time standards over the earth's surface, and it is therefore of interest to consider the relativistic effects for which one must eventually compensate.

In this note we examine the case in which the clocks concerned are rotating with the earth, and our aim will be to derive a formula for the relative drifts of clocks at widely separated localities. These drifts arise from differences in the local gravitational potentials and in the special-relativity time dilation from the earth's rotational velocity. Both of these effects are minute, and we show that they give rise to drifts of one part in 10^{12}, or about 30 μsec/yr. However, it is now possible to synchronize clocks at widely separated localities to within 1 μsec by using artificial satellites, Loran-C techniques, and even portable clocks,[1] and time standards stable to within 5×10^{-13} are now in use.[2]

Using an approximate treatment based on the principle of equivalence, we first show that clocks fixed on the geodetic "geoid" surface do not drift relative to each other. The geoid[3] is defined as that surface which is everywhere perpendicular to a local plumb line and which at the sea shore coincides with mean sea level.

All geodetic elevations are conventionally given as height above the geoid measured along a local plumb line.

The fact that the sum of the gravitational and centrifugal forces is by definition perpendicular to the geoid implies that the inertio-gravitational potential[4,5] $\Phi \equiv \varphi - \frac{1}{2}\omega^2\rho^2$ is constant on the geoid, where φ is the Newtonian gravitational potential, $\omega \simeq 7.3\times10^{-5}$/sec is the earth's angular velocity, and $\vec{\rho}$ is the radius vector to the field point taken from, and perpendicular to, the axis of rotation. One easily sees that the total "acceleration of gravity"[6] is $-\mathrm{grad}\,\Phi = -\mathrm{grad}\,\varphi + \omega^2\vec{\rho} = \vec{g} - \vec{a}_c$, where $\vec{a}_c = \vec{\omega}\times(\vec{\omega}\times\vec{\rho})$ is the centripetal acceleration and $\vec{g}$ is the real gravitational acceleration.

Now, in a nonrotating system a surface of constant φ would be a surface of zero time drift, as is well known from the equivalence principle.[4,7] But in a frame rotating with the earth the potential Φ retains the local properties that φ had in the nonrotating frame; that is, $-\mathrm{grad}\,\Phi$ gives the resultant force on a unit mass fixed in the rotating frame. Therefore, the principle of equivalence implies that, in the rotating frame, clocks at constant Φ (for example, on the geoid) will not drift relative to each other.

It further implies that the total drift Δ of clocks at different Φ, relative to the rate of running of a clock fixed at infinity in an inertial frame at rest with respect to the earth's center of mass, is, analogously to the nonrotating case,

$$\frac{dt_2}{dt_\infty} - \frac{dt_1}{dt_\infty} \equiv \Delta_{12} \simeq (\Phi_2 - \Phi_1)/c^2$$
$$= (\varphi_2 - \varphi_1)/c^2 + \tfrac{1}{2}\omega^2({\rho_1}^2 - {\rho_2}^2)/c^2. \quad (1)$$

The second term on the right in Eq. (1) is the approximate difference $(1-{v_2}^2/c^2)^{1/2} - (1-{v_1}^2/c^2)^{1/2} \simeq \frac{1}{2}({v_1}^2 - {v_2}^2)/c^2$ between the special-relativity time dilatation factors induced by the earth's rotational velocity.

Note that if the ocean were at rest with respect to the rotating frame, its whole surface would constitute part of the geoid.[3] This fact may be rigorously proved by using the hydrodynamic equations of motion. However, the existence of ocean currents of velocity $v \lesssim 100$ cm/sec causes permanent distortions of the oceanic surface away from the geoid. These are due mostly to Coriolis forces and are of dimension $h \sim v\omega R_e/g$, where R_e is one earth radius, and give rise to drifts $\Delta \sim gh/c^2 \sim 5\times10^{-15}$, which is far from detectable. Deviations due to tidal effects are of smaller magnitude. Drifts caused by the change in the solar and lunar gravitational potentials across the earth's diameter are about 10^{-12} or 10^{-1} μsec/d, but average out to zero over periods longer than a day.

Thus for clocks at mean sea level, the relativistic drifts cancel each other to very great accuracy, no matter how far apart on the earth they are located. Each of the two terms in Eq. (1) separately from equator to pole, with $\rho_2 = 0$, $\rho_1 = 6.4\times10^8$ cm, gives $\Delta \simeq 1.2\times10^{-12} = 38$ μsec/yr.

We now compute the drift of a clock at an elevation Δh above the geoid, relative to a clock on the geoid. Since elevations are conventionally given as distance above the geoid measured along a local plumb line,[3] we may integrate $\mathrm{grad}\,\Phi$ from the geoid along a plumb line, neglecting changes in g over the path of integration and getting

$$\Delta \simeq \Delta\Phi/c^2 = c^{-2}\int_0^{\Delta h} \mathrm{grad}\,\Phi\cdot d\vec{h}$$
$$= c^{-2}\int_0^{\Delta h} |\vec{a}_c - \vec{g}|\,dh \simeq g_0\Delta h/c^2,$$

where $g_0 = |\vec{a}_c - \vec{g}|$ is the local value of the "acceleration of gravity."

One may find the relative rates of running of clocks at different elevations Δh_1 and Δh_2 by subtracting their respective Δ's. Strictly speaking, one should allow for the differences in g_0 over the earth's surface, but this would amount to corrections in Δ of less than 5×10^{-15}. We thus obtain

$$\Delta_{12} \simeq g_0(\Delta h_2 - \Delta h_1)/c^2. \quad (2)$$

For $\Delta h_1 = 0$ and $\Delta h_2 = 9000$ m (Mt. Everest), $\Delta_{12} \simeq +9.8\times10^{-13} = +31$ μsec/yr.

We have remarked that clocks stable to within 5×10^{-13} are being currently used and that long-distance time synchronization to within one μsec is now attainable. One might expect the development of clocks stable to within 10^{-14} in a few years, and thus the relativistic effects manifested in Eq. (2) could easily be seen.

Indeed, the null result from equator to pole at sea level might be checked even today with the use of several clocks at each locality for the sake of better statistics. This would eventually allow a check on the principle of equivalence to better accuracy than the Mössbauer effect experiments of Pound and Rebka.

There is no plethora of verifications of the equivalence principle, and thus we await with interest the development of more refined techniques in chronometry.

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ANNIHILATION OF NUCLEON-ANTINUCLEON AS THE SOURCE OF ENERGY FOR CERTAIN RADIOASTRONOMICAL OBJECTS*

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In the model of the metagalaxy considered by Alfvén and Klein,[1] a basic assumption is that matter and antimatter should enter in a symmetric way. A plasma consisting of both types of matter is called an "ambiplasma" by Alfvén.[2] He showed that such a plasma might be a strong emitter of radio waves. In the following, results of detailed calculations are presented regarding the shapes of the expected radio-frequency spectra.

The nuclear processes in the ambiplasma are annihilations of nucleons and antinucleons leading to mesons, mostly pions, which through their well-known decays quickly give rise to γ rays, neutrinos and electrons. Starting from the experimentally measured number and energy distribution of the pions produced in the average $p\bar{p}$ annihilation,[3] one finds that 1.6 electrons and an equal number of positrons, each with a mean energy of 100 MeV, are produced together with 3.4 γ rays with 180 MeV energy and 9.6 neutrinos with about 95 MeV energy. The energy available is $2m_pc^2 = 1876$ MeV of which 17% or 320 MeV goes to the electronic component, 33% or 620 MeV to the γ-ray component, and 50% to the neutrino component. If the conditions within the ambiplasma are favorable, a large part of the energy in the electron component will be emitted in the form of synchrotron radiation. Instead of assuming an arbitrary source of electrons, one has here a source which during its lifetime supplies new electrons with a calculable energy distribution. Detailed calculations through the decay chain $\pi \to \mu + \nu_2$ and $\mu \to e + \nu_1 + \nu_2$ have been performed with the result shown in Fig. 1. The energy distribution of the electrons is characterized by a peak at about 30 MeV. Below this energy only few electrons are produced. The mean electron energy is close to 100 MeV and the spectrum extends up to a few hundred MeV. Similar calculations have been made independently elsewhere[4] with some approximations but on the whole the same result.

If a magnetic field is present in the region of the ambiplasma, the electrons will lose energy due to synchrotron radiation. The spectrum with-