New Experimental Limits to the Time Variations of $g_p(m_e/m_p)$ and α

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A new experimental limit to the possible time variation of the proton gyromagnetic ratio times the electron-to-proton mass ratio has been obtained from the frequency comparison data between Cs and Mg atomic beam standards. The measurements, made over a period of one year, lead to an upper limit for the rate of change of $g_p(m_e/m_p)$ of 5.4×10^{-13}/yr. This result, based only on the validity of the quantum mechanical theory of the atomic spectra, together with astrophysical data regarding analogous products of atomic fundamental constants, leads also to a new limit for the time stability of the fine structure constant $\alpha(2.7\times10^{-13}/\text{yr})$.

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The time stability of atomic fundamental constants is an important subject not only for theoretical physics [1-4], but also for dimensional metrology and, among them, the fine structure constant α plays a relevant role in the definition of the International System (SI) of units [5]. The possible time variation over cosmic time scales of fundamental constants or of products of them has been investigated by several authors using mainly astrophysical data [6,7]. Furthermore an experiment has been reported [8] regarding the frequency comparison between atomic beam Cs standards and superconducting cavity stabilized oscillators (SCSO), which provides a limit to the "instantaneous" rate of change of the product of atomic constants $\alpha^3 g_I(m_e/m_p)$, where g_I is the Cs nucleus gyromagnetic ratio and m_e/m_p is the electron-to-proton mass ratio.

The test described in this paper involves a comparison between two quantum frequency standards: the Cs atomic clock [9] and the Mg frequency standard recently developed [10]. The frequency of the Cs atomic clock ($\nu\approx9.2$ GHz), corresponding to the $F=3,m_F=0\rightarrow F=4,m_F=0$ hyperfine transition in the ^{133}Cs ground state $6^2S_{1/2}$ and adopted for the definition of the SI second, may be expressed, through the Fermi-Segrè relation as

$$\nu_{\rm hfs}=\frac{32cR_\infty\alpha^2Z_s^3}{3n^3}g_I\frac{m_e}{m_p}[1+\text{higher orders}]\,, \qquad (1)$$

where n is the principal quantum number, c is the speed of light, R_∞ is the Rydberg constant, and Z_s is the effective nuclear charge. The higher order terms take into account finite nuclear mass and relativistic and quantum electrodynamic corrections [11]. The frequency of the $^3P_1\rightarrow{}^3P_0\Delta m_j=0$ fine structure transition in the metastable triplet of ^{24}Mg ($\nu\approx601$ GHz), used as clock transition in the Mg standard, may be written as [11]

$$\nu_{\rm fs}=\frac{cR_\infty\alpha^2Z_s^4}{6n^3}[1+\text{higher orders}]\,. \qquad (2)$$

Omitting higher order terms in Eqs. (1) and (2), whose contribution is less than 10^{-2} of the final value, it is possible to write the following expression:

$$\frac{d}{dt}\ln\left(\frac{\nu_{\rm hfs}}{\nu_{\rm fs}}\right)=\frac{d}{dt}\ln\left(g_I\frac{m_e}{m_p}\right), \qquad (3)$$

which relates the time derivative of the ratio between the two atomic standard frequencies to that of $g_I(m_e/m_p)$.

The Cs clock used in our experiment is a commercial apparatus with a long term fractional stability [1 yr of 1×10^{-13}, daily controlled with respect to the laboratory primary Cs standard of Physikalisch-Technische Bundesanstalt, Germany (PTB)] via satellite time comparison. The Mg atomic clock is a prototype developed in our laboratories, whose absolute frequency is known with a relative uncertainty of $\pm1\times10^{-12}$ and whose stability reaches the value 2×10^{-13} for measurement times $\tau=3000$ s; a detailed description of this frequency standard is reported elsewhere [10]. The measures of the Mg frequency with respect to the Cs reference are reported in Fig. 1 and have been obtained in two steps. First, the mean value and the standard deviation of the frequency measures performed in a day versus the local Cs reference are evaluated. All the central values are then corrected for the second order Zeeman and Doppler shifts, taking into account the effective operating parameters which affect the Mg output frequency error budget [10]. As a second step, the frequency measures are referred to the PTB laboratory primary Cs standard (whose relative frequency accuracy is about 2×10^{-14}) by evaluating the frequency deviation of the local reference. The quality of such a long-distance comparison, effectuated via satellite synchronizations, strongly depends on the number of observed satellites and on the measurement equipment at both sides, and can be different from day to day.

By combining the uncertainties of the local measurements and of the long-distance comparisons the error bars reported in Fig. 1 have been obtained ranging from 0.19 to 0.56 Hz (3-9×10^{-13} in relative values). Introducing

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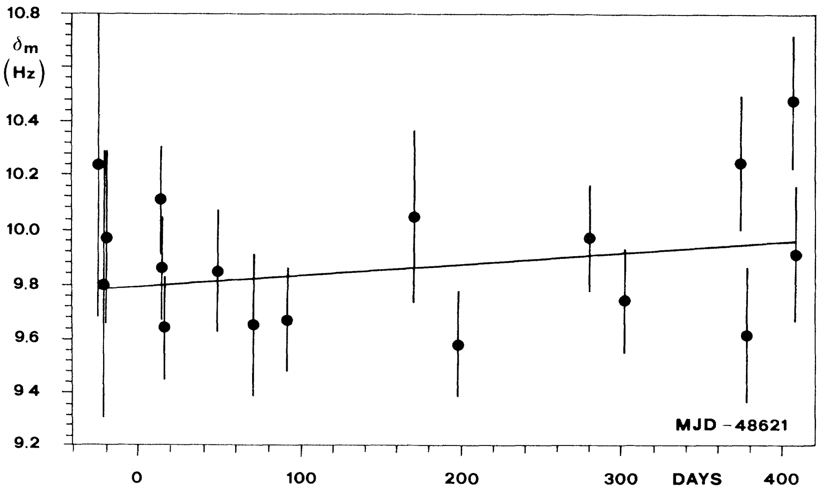

FIG. 1. Mg offset frequencies (δ_m) with respect to Cs standard versus the modified Julian date (MJD). ($\delta_m=0$ corresponds to $\nu=601\,277\,157\,859.2\pm0.6$ Hz.)

in (3) the slope of the above measures, obtained through a weighted least square linear fit and normalized to ν_{fs}, we get

$$\frac{d}{dt}\ln\left[g_l\frac{m_e}{m_p}\right]=(-2.5\pm2.3)\times10^{-13}\,\mathrm{yr}^{-1}\,. \tag{4}$$

Recent frequency comparisons between H masers and Cs primary standards have been reported [12], from which the following inequality can be inferred:

$$\left|\frac{d}{dt}\ln\left[\frac{g_p}{g_l}\right]\right|\le5.5\times10^{-14}\,\mathrm{yr}^{-1}\,, \tag{5}$$

which allows us to write the relation (4) in terms of the proton gyromagnetic ratio

$$\left|\frac{d}{dt}\ln\left[g_p\frac{m_e}{m_p}\right]\right|\le5.4\times10^{-13}\,\mathrm{yr}^{-1}\,, \tag{6}$$

where limits are to be intended as |central value| + 1σ. The above result is also reported in the last row of Table I together with analogous results reported in the literature and regarding the atomic fundamental constants considered here; in the second column we have also indicated the physical origin of the data. We point out that the astrophysical method, based mainly on the spectroscopic observation of redshifted atomic emissions from extragalactic radio sources, is based both on the quantum mechanical model of the atomic spectra and on a cosmological model of the universe. The comparison between SCSO and Cs standards is based on the quantum theory of the atomic spectra and on a model for the dependence of the size of a superconducting cavity on the fundamental constants, while the comparison of two atomic clocks, Mg and Cs, reported in this work, is based only on the quantum model of the atomic spectra. Furthermore, it is worth noting that the astrophysical data give information over a time interval ($\sim2\times10^9$ yr) corresponding to a significant fraction of the age of the universe, under the hypothesis of a constant rate of change for the fundamental constants, and that the laboratory measurements can set limits on the almost instantaneous rate of change of the above quantities [13].

Taking in account the above discussions, anyway, as far as the fine structure constant α is concerned, the measurements reported here and the upper bounds on the rate

TABLE I. Upper limits to time variations of the logarithm of some dimensionless products of fundamental constants. In the last two rows g_p has been substituted for g_l in accordance with (5).

Product of constants	Method	Limit (yr^{-1})	Reference
α	Astrophysical	1.5×10^{-12}	Bahcall *et al.* [6] 1967
$\alpha^2 g_p\frac{m_e}{m_p}$	Astrophysical	2×10^{-14}	Wolfe *et al.* [7] 1976
$\alpha^3 g_p\frac{m_e}{m_p}$	SCSO-Cs	1.4×10^{-11}	Turneaure *et al.* [8] 1976
$g_p\frac{m_e}{m_p}$	Mg-Cs	5.4×10^{-13}	This work 1992

of change of $\alpha^2 g_p(m_e/m_p)$, as deduced by Wolfe, Brown, and Roberts [7], lead to the following limit:

$$\left|\frac{d}{dt}\ln\alpha\right| \leq 2.7\times 10^{-13}\,\mathrm{yr}^{-1}\,, \tag{7}$$

which represents an improvement of nearly an order of magnitude with respect to previously reported values [6,7].

As a result of the development under way of frequency measurement techniques up to the visible region and of frequency standards based on vibrational molecular transitions (CH_4,OsO_4,...) [14,15] or on electronic transitions (I_2,Ca,...) [15,16], new data are expected to be available in the near future which would allow a reevaluation of the inequality (7) only in the frame of the quantum mechanical theory.

Geophysical data based on the relative isotopic abundances (^{149}Sm/^{147}Sm) in laboratory and geological samples have also been proposed [17,18] to test the time stability over cosmic time scales of products of fundamental constants involving α; they also appear to be a powerful tool for this aim; in fact Shlyakhter derives an upper limit for the rate of variation of α of 10^{-17} yr^{-1} from beta-decay measurements. This limit, tighter than ours by approximately 4 orders of magnitude, is probably not weakened when reconsidered in the frame of the standard model of electroweak interactions, but requires at least a reexamination of the hypothesis that the possible variations of other fundamental constants involved in the theory are unimportant [5].

As a conclusion, from the recently performed frequency comparisons between the Cs primary standard (based on a hyperfine structure transition) and the Mg standard (based on a fine structure transition) we have obtained for the first time a limit to the possible rate of change of the quantity $g_p(m_e/m_p)$; moreover our result, combined with data of astrophysical origin, leads to a new experimental limit for the time variation of the fine structure constant.

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