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A NEW METHOD TO MEASURE THE GRAVITATIONAL ACCELERATION OF THE ANTIPROTON AT VERY LOW ENERGIES

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A New Method to measure the Gravitational Acceleration of the Antiproton at Very Low Energies.

Abstract: a new possible method to measure in lab the gravitational acceleration "g" of the antiproton is presented assuming that very low energy particles can be used. A shematic lay-out is described and preliminary results on "g" obtained by a simple simulation are given. The features of the method and its possible experimental problems are discussed.

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1. Introduction

Since some years ago a proposal of an experiment to measure the gravitational acceleration "g" of the antiproton was presented at the CERN P.S.C.C. Committee [1],the knowledge on some relevant experimental problem of the proposed method has been improved, but, at present, a definitive solution for the final set-up has not yet be found.

On the other hand, the strong physical motivation to perform such an experiment [2,3] leads people of the collaboration to search also for experimental methods different from the proposed one [1].

Referring to the original idea, the possibility to work with particles cooled at very low temperature ($T \leq 10$ °K) is still foundamental here, but a completely different method to measure "g" for antiprotons is presented.

The method suggested in the CERN original proposal [1] is based on the technique to measure the distribution of the time of flight (T.O.F.) of particle vertically moving in vacuo guided by a vertical axial magnetic field ($B \approx 1$ T).

In addition to systematic errors due to effects of stray electric fields or magnetic field gradients, this method is affected by intrinsec problems deriving from the fact that the T.O.F. distribution strongly depends on fluctuation of the average temperature of the particles leaving the launching trap as well as on the type of the initial velocity distribution assumed for the stored particles.

The average temperature and the kinetic energy distribution of the trapped particles are relevant parameters very difficult to be measured and, since large statistics are needed, i.e. several launches of bunches of particles, fluctuations of those quantities must be controlled with very high accuracy, a not trivial task.

Moreover, De Angelis et al. have evaluated [4] that, when bunches of charged particles are launched in a drfit tube, the couloumbian repulsion randomly affects the T.O.F. distribution and, therefore, the possibility to measure "g" is lost.

In section 2. are presented a schematic set-up and a method to measure "g" for antiprotons independently, in principle, from the initial particle temperature and velocity distributions.

In section 3. are presented preliminary results on "g" of a Montecarlo simulation and in section 4. some final remarks are summarized.

2. Schematic lay-out and method.

In figure 1 is shown a possible lay-out to measure "g" for antiprotons. Particles at a given average temperature T are stored in a launching trap having its longitudinal axis in the x-y horizontal plane; the particles of axial kinetic energy greater than the potential well generated by the electrodes of the trap drift to a vacuum chamber through a collimator.

In the vacuum chamber the particles are deflected by a constant and uniform magnetic field **B** parallel to the gravitational acceleration vector **g** and directed parallel to the z-axis of figure 1.

The particle orbits in the vacuum chamber are given by the composition of a cyclotron motion in the x-y plane and a free fall motion in the z-direction; after a half round of cyclotron motion, the antiprotons are detected by their annihilation in an array-detector; its surface and the exit hole of the collimator lie on the same x-z plane.

In an ideal condition where the initial particle speed has null component in the x-direction and any electromagnetic perturbation to the particle motion is neglected, the vertical impact-coordinate on the array detector is given by

$$\begin{aligned} z(\tau) &= z_o + v_{oz}\tau - 1/2\, g\, \tau^2 = \\ &= z_o + v_{oz}/(2f_c) - 1/2\, g\, (2f_c)^{-2} = \\ &= z_o + v_{oz}(\pi m/qB) - 1/2\, g\, (\pi m/qB)^2 \qquad (1) \end{aligned}$$

where z_o and v_{oz} are the initial parameters of the particle motion, $f_c = 2/\tau = 2\pi m/qB$ is the cyclotron frequency, τ is the drift time in the vacuum chamber, m and q are the rest mass and the charge of the antiproton.

Since a very low pressure ($p<10^{-12}$ torr) must be kept, the dimensions of the vacuum chamber can not be too large; in the case in which the axial average temperature of the particles in the trap is $<T_y>\approx 10$ °K, i.e. $<|v_{oy}|>\approx 3\ 10^2\ ms^{-1}$, and the cyclotron radius is $R \leq 1$ m, an uniform magnetic field $B \approx 0.1$ Gauss is required in the vacuum chamber.

The collimator is needed to reduce the initial speed components orthogonal to v_{oy}; however, if one assume that $|v_{oz}|$ can be reduced to some percent of $<|v_{oy}|>$ at $T \leq 10$°K, the term proportional to "g" in equation (1) is still a sizable factor smaller than the term proportional to v_{oz}; for this reason, if symmetric distributions of z_o and $v_{o,i}$ (i=x,y,z) are assumed, as usually, for the analysed sample of trapped particles,an average over a large number N of particles is necessary to improve the sensitivity of the measurement on the gravitational fall; in this case the average vertical coordinate of the impact point on the array-detector is given by

$$<z(\tau)> \quad = 1/N\ (\Sigma_n\ z_{o,n} + v_{oz,n}\tau - 1/2\ g\ \tau^2) =$$
$$= <z_{oz}> + <v_{oz}>\tau - 1/2\ g\ \tau^2 \qquad (2)$$

with

$$\lim_{N\to\infty} \Sigma_n\ z_{o,n} = \lim_{N\to\infty} \Sigma_n\ v_{oz,n} = 0 \qquad (3)$$

Moreover, by adding the condition $|<v_{ox}>| << <|v_{oy}|>$, the term proportional to "g" of equation (2) is independent, in fist approximation, from the initial average particle axial temperature; in the physical case with $v_{ox} \neq 0$, equation (2) must be corrected as

$$<z(\tau)> \approx <z_{oz}> + <v_{oz}>\tau - 1/2\ g[1 + (<\alpha>/2\pi)^2]\ \tau^2 =$$
$$= <z_{oz}> + <v_{oz}>\tau - 1/2\ g\ \tau^2 + O(<\alpha>^2) \approx$$
$$\approx <z_{oz}> + <v_{oz}>\tau - 1/2\ g\ \tau^2 \qquad (4)$$

with

$$<\alpha> = 1/N\ \Sigma_n\ tg^{-1}(|v_{ox}/v_{oy}|_n) \approx 1/N\ \Sigma_n\ (|v_{ox}/v_{oy}|_n) \qquad (5)$$

and

$$\lim_{N\to\infty} \Sigma_n\ v_{ox,n} = 0, \qquad (6)$$

i.e. equation (4) is independent from the particle initial temperature at the first order in $<\alpha>$.

Since the first and second term of equation (4) could still be not negligible with respect to the third-one proportional to "g" even for N very large, the accuracy in measuring "g" can be improved by performing several measurements with high statistics at different values $B = 1/\tau$ of the vertical magnetic field, and by fitting the corresponding results $<z(\tau)>$ to equation (4), being $<z_{oz}>$, $<v_{oz}>$, and 1/2 g the coefficients of the quadratic curve to be determined by the fit.

3. Preliminary results of a Montecarlo simulation.

In order to evaluate the sensitivity on "g" of this method versus the required number of antiprotons, a preliminary numerical analysis has been performed; the quantities <z(t)> were calculated using equation (4) at 10 different values B of the magnetic field by generating the initial spatial and velocity coordinates of each particle from given Gaussian distributions and by selecting the particles entering the vacuum chamber with different choises of the geometrical collimator. Moreover only particles with cyclotron radius $R \leq 1$ m and impact point on the detector with $|z| \leq 10$ cm have been included in the average.

The values B of the magnetic field used for the fit range between 0.05 Gauss and 0.25 Gauss; the spread of the axial initial velocity of the particle in the trap was $\sigma(v_{oy}) \leq 200\ ms^{-1}$ and the collimator select s particles with speed components so that $|v_{oz,max.}| = |v_{ox,max.}| \leq 10^{-1}\ \sigma(v_{oy})$. Results on "g" and its statistic error "Δg" were obtained with a number N of particles generated at fixed B ranging between 10^5 and 10^7; finally, a vertical spatial resolution Δs = 1 mm is required to the array-detector, a standard performance, for instance, for silicon strips detectors which have the advantage, in this experiment, to operate without high bias-voltages and, therefore, without generating sizeble stray electric fields.

In figures 2 and 3 the value of "g" and its relative error "$\Delta g/g$" obtained by the fit are plotted versus the total number N of particles leaving the collimator and used in the full simulation; in figure 4 the relative error "$\Delta g/g$" is plotted versus the particle average temperature in the trap being $N = 10^8$ the total number of analysed particles.

The number N is related to the required total number N' of particles to be extracted from the trap by an efficiency factor ε

$$N = \varepsilon N'. \tag{7}$$

The quantity ε is very difficult to be evaluated since it strongly depends on the particle velocity distribution in the trap, on the collimator characteristics, and on the way in which the trap is open. For instance, if a Penning trap [5] is used and the potential well is very slowly reduced after each trap filling, also the particles in the tail of the initial velocity distribution leave the trap at very low axial kinetic energy and can be deflected on thè the detector by the low vertical magnetic field B.

Referring to figs. 2-4, the value $N = 10^8$ can be taken as a reference value of the number of particles escaping the collimator required to measure "g" at some percent of accuracy. To evalute the required initial number N" of antiprotons from the source, the value N must be devided by the factor ε defined above and by an other factor ε' describing the full efficiency of capture and cooling at very low temperatures. Assuming the reasonable values $\varepsilon = 10^{-1}$ and $\varepsilon' = 10^{-3}$ [6], one gets

$$N'' = N/(\varepsilon\,\varepsilon') = 10^{12} \tag{8}$$

The improved LEAR facility at CERN can be considered the antiproton source; operating at 2 Mev/c, LEAR can store 10^9 antiprotons with a repetition cicle of 2 hours; in these condition about 100 days of data acquisition are requested to measure "g" at some percent of accuracy level.

4. Conclusions

In this section, the advantages and some experimental problem of this method are discussed and a few final remarks on the feasibility of the measurement are presented.

Among the possible advantages of this method with respect to the one presented in the CERN proposal [1], the following seem more relevant:
- in first approximation, the measurement is independent from the initial velocity distribution;
- once filled the launching trap, there is the possibility to work in continuos mode at a fixed value of the magnetic field in the vacuum chamber; when the potential well in the trap is slowly reduced, all particles escaping the trap and the collimator at low kinetic energy can be used in the measurement;
- no time of flight measurement is required;
- charge-space effect are strongly depressed since no bunch is used in the drift motion;
- no high temperature stability inside the trap is required; temperature fluctuation should affect only the acquisition-time, but not the accuracy on the results;
- the average temperature inside the trap can be evaluated from the average cyclotron radius by measuring the coordinate in the y-direction of the impact point on the array-detector.

As far as regard the lay-out, in addition to the problems of vacuum and systematic errors due to the effects of stray electromagnetic fields already discussed in ref. [1], two main problems are related to the magnetic field in this case:

a) the magnetic field B must be constant, uniform and exactly parallel to gravity everywhere in the vacuum chamber and for relatively low values ($B \leq 0.25$ Gauss);

b) a large magnetic field gradient is present in the region of the collimator (a few cubic centimetres); inside the trap a magnetic field $B_o \approx 1$ T is required to axailly confine a large number of particles in a small volume (a few cubic centimetres).

Finally a major problem is that this is an absolute measurement since it can not be performed relatively to the H^- ion because, at present, there is no possibility to detect matter-particles at the required low energies.

Nevertheless, face to the strong physical motivation to measure "g" for antimatter and to the difficulties in searching alternative ways like the proposed-one to use neutral antimatter [6], if an efficient method to cool and to store charged particles at very low temperatures will be really found, it's a worth job to develop studies of improvements and criticims of the method here presented.

References

[1] N. Beverini et al., CERN Proposal PSCC/86-2/P-94.

[2] T. Goldman et al., Phys. Lett., 171B (1986) 217.

[3] N. Beverini et al., Phys. Lett., 206B (1988) 533.

[4] A. De Angelis et al., I.N.F.N. internal report, INFN/TC-87/14,17-12-1987.

[5] G.H. Demhelt, Ad. At. and Mol. Phys., 3 (1967) 53.

[6] N. Beverini et al., 'Possible Measurement of the gravitational Acceleration with Neutral Antimatter', to be published on Hyperfine Interactions.

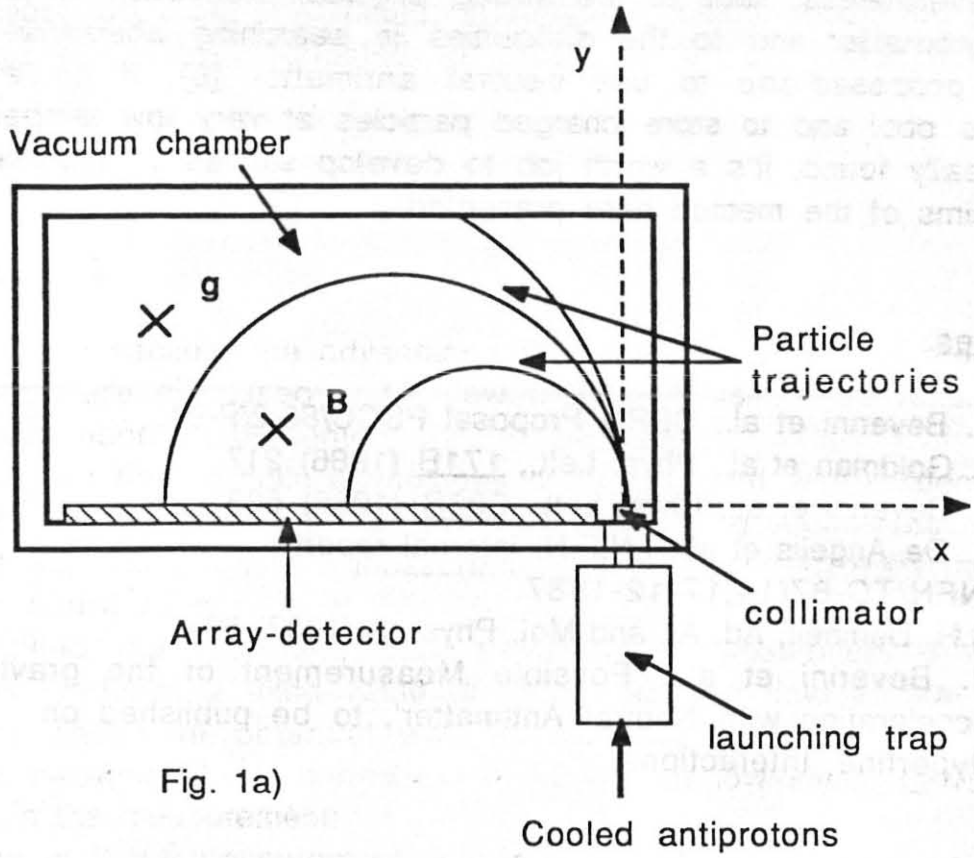
Figure captions.

Fig. 1: a) Schematic lay-out; b) Schematic array-detector.

Fig. 2: Values of "g" from the fit of the results obtained by the simulation of the particle drift in the vacuum-chamber at 10 different values of the magnetic field B versus the total number N_{tot} of generated particles; $\sigma(v_{oy})$ = 200 ms^{-1} $|v_{ox,max.}| = |v_{oz,max.}| = 10^{-2}\,\sigma(v_{oy})$

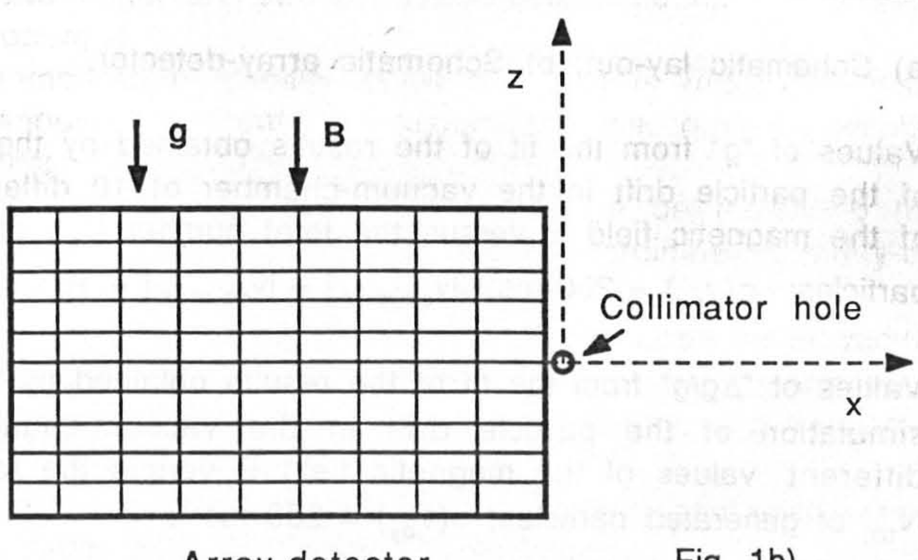
Fig. 3: Values of "$\Delta g/g$" from the fit of the results obtained by the simulation of the particle drift in the vacuum-chamber at 10 different values of the magnetic field B versus the total number N_{tot} of generated particles; $\sigma(v_{oy})$ = 200 ms^{-1};
solid line: $|v_{ox,max.}| = |v_{oz,max.}| = 10^{-2}\,\sigma(v_{oy})$;
dashed line: $|v_{ox,max.}| = |v_{oz,max.}| = 10^{-1}\,\sigma(v_{oy})$.

Fig. 4: "$\Delta g/g$" versus the particle average temperature inside the trap; $N=10^8$, $|v_{ox,max.}| = |v_{oz,max.}| = 10^{-2}\,\sigma(v_{oy})$



y
Vacuum chamber
g
B
Particle trajectories
x
collimator
Array-detector
launching trap
Cooled antiprotons

Fig. 1a)



z
g
B
Collimator hole
x
Array-detector

Fig. 1b)

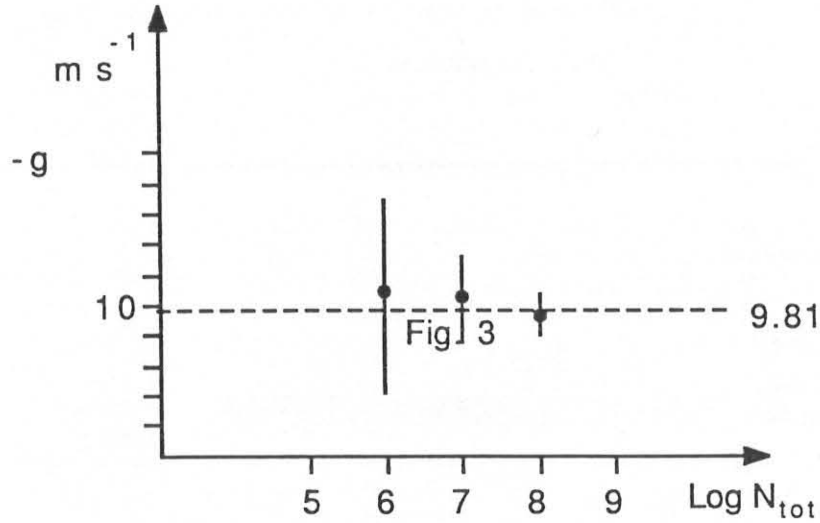


Fig. 2

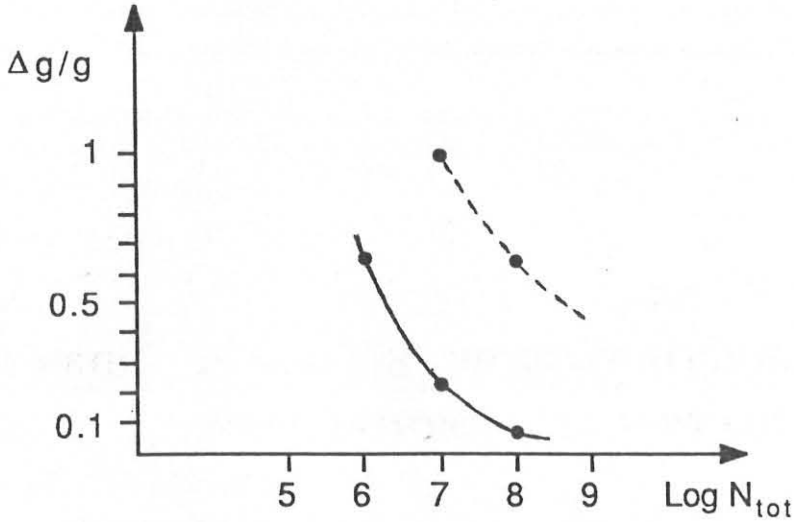


Fig. 3

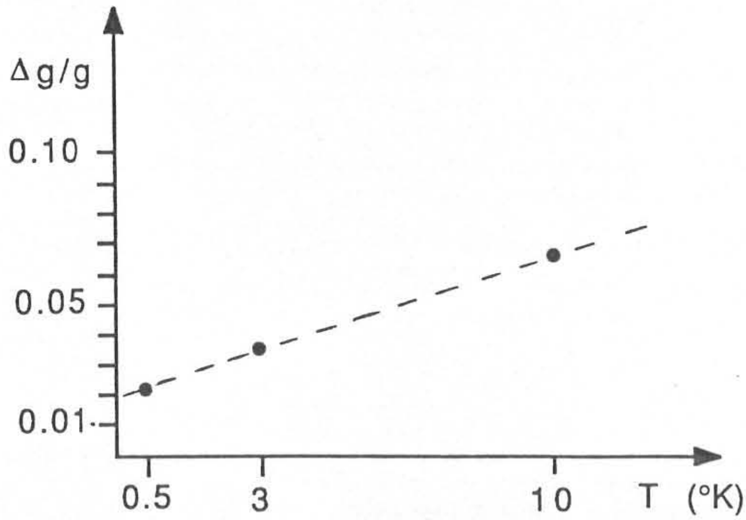


Fig. 4