EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/82-56
24 May 1982

ANTIPROTON MASS MEASUREMENT USING STORED BEAMS COOLED BY ELECTRONS

H. Poth^{*)}

Kernforschungszentrum Karlsruhe, Institut für Kernphysik, Karlsruhe

ABSTRACT

A method is proposed for measuring the antiproton-proton mass difference with high precision. Antiprotons and H^- ions (protons) are kept in a storage ring at low energy and cooled by an electron beam to equal velocities. By measuring the revolution frequencies of the coasting beams the $\bar{p}p$ mass difference can be determined.

(Submitted to Nuclear Instruments and Methods)

^{*)} Visitor at CERN, Geneva, Switzerland.

1. INTRODUCTION

The precise knowledge of the antiproton-proton mass difference is of basic interest for a test of the validity of fundamental invariance principles. With the availability of cooled low-energy $\bar{p}$ beams from LEAR [1] high-precision measurements can be anticipated. An absolute determination of the $\bar{p}$ mass $m_{\bar{p}}$, as obtained from the X-ray spectra of antiprotonic atoms, could ultimately lead to the accuracy to which the p mass m_p is known (± 2.7 keV). However, the mass difference, which is the relevant quantity, can be determined with a much higher precision, when measured directly, as pointed out previously [2]. This can be accomplished with stored counter-rotating p and $\bar{p}$ beams using the storage device as a high-resolution spectrometer. Either a common frequency is imposed on both beams and the radial separation is measured [3], or their velocity is matched and the revolution frequency of the two coasting beams is compared. While the first method is limited by the accuracy to which the beam positions can be measured, in the second case virtually a much higher sensitivity could be obtained. However, it remains the problem to match the beam velocities exactly. In principle, this can be achieved by cooling the beams with a bidirectional electron beam. Technically it is much easier, however, to measure the revolution frequency of the $\bar{p}$ beam relative to that of a co-rotating H^- beam cooled by the same electrons. This will be feasible when LEAR is operating in the $\bar{p}H^-$ storage mode, which was originally proposed for the formation of the $\bar{p}p$ atoms in flight [4].

Recently the precise measurement of $m_{\bar{p}}$ relative to the H^- mass with a radio-frequency mass spectrometer has been proposed [5]. This experiment aims at a very high precision and requires ultracold $\bar{p}$ of very low energy.

In the following we discuss in more detail the above-mentioned method, which could improve the present limit for the $\bar{p}p$ mass difference by more than two orders of magnitude without involving special effort.

2. METHOD

The revolution-frequency spectrum of a coasting beam is given by

$$\frac{f - f_0}{f_0} = \eta \frac{p - p_0}{p_0}$$

where

$$\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2} \text{ off-momentum function}$$

$m\gamma_t c^2$ = transition energy of the storage ring

m = particle mass

$$\gamma = (1 - \beta^2)^{-\frac{1}{2}}$$

βc = particle velocity .

Particles with a momentum of $p_0 = m\beta_0\gamma c^2$ circulate on the nominal orbit (with a circumference $2\pi R$) with a revolution frequency of $f_0 = c\beta_0/2\pi R$. A beam-momentum distribution characterized by its r.m.s. width Δp leads to a distribution of the same shape in the frequency domain with a width Δf . At low energies the momentum spread $\Delta p/p_0$ is essentially due to the velocity spread of the particles in the beam:

$$\frac{\Delta p}{p_0} = \frac{\Delta \beta}{\beta_0} .$$

For coasting $\bar{p}$ and H^- beams of equal velocities the momenta differ by the relative mass difference $\mu = \delta m/m \approx 10^{-3}$ ($\delta m = m_{H^-} - m_{\bar{p}}$, $m = m_{H^-}/2 + m_{\bar{p}}/2$).

In general, however, the measurement of the revolution-frequency spectrum of the two beams will result in the observation of two separated peaks with a spectral width proportional to the velocity spread of each beam. The centres of the peaks will be separated by

$$\frac{\delta f}{f_0} = \eta \left(\mu + \frac{\delta \beta}{\beta_0} \right) .$$

Here $\delta \beta = \beta_{H^-} - \beta_{\bar{p}}$ is the difference between the respective mean velocities of $\bar{p}$ and H^- ions.

In order to determine the $\bar{p}H^-$ mass difference with high precision it is necessary that $\delta \beta/\beta_0 \ll \mu$. This can be achieved by cooling both beams with a monochromatic electron beam. Antiprotons and H^- ions are cooled to the same velocity if provision is made for the electron velocity not to depend on the radial

position or if both beams intersect the electron beam at the same position. A constant radial electron velocity can be obtained by space-charge neutralization of the electron beam. On the other hand, the radial separation of $\bar{p}$ and H^- beams can be made very small by having the momentum compaction α_p close to zero in the cooling section. Since for this measurement only a small electron-current density is needed, already for an uncompensated electron beam the radial velocity dispersion can be made very small.

The frequency spectrum can be measured with a resonant Schottky pick-up system tuned to a high harmonic of the revolution frequency. Frequency analysis of both beams can be made simultaneously since their revolution frequencies are well separated from each other. The peak positions should be measurable to a precision better than 1% of their FWHM. The latter is determined by the equilibrium momentum spread reached with electron cooling. In previous cooling experiments, values of $\Delta p/p \leq 10^{-5}$ and a beam emittance of $E \leq 1\pi \text{ mm}\cdot\text{mrad}$ had been achieved [6].

It should also be possible to measure directly the beat frequency μf_0 between the two revolution frequencies.

3. ESTIMATE FOR LEAR

In the following we estimate the accuracy which could be obtained with LEAR and the foreseen electron cooling system without special effort whenever H^- ions are available. We take the following design values for $\bar{p}H^-$ operation [7] in the centre of the cooling section:

$$\gamma_t^2 = -6.3, \quad \alpha_p = 2.7 \text{ m}, \quad \beta_H = 1.3 \text{ m}, \quad \beta_v = 5 \text{ m} \quad (2\pi R = 78.54 \text{ m}),$$

and for the electron beam [8]

$$\text{diameter: } \phi = 5 \text{ cm}, \quad \text{perveance: } P = 10^{-7} \text{ AV}^{-3/2}, \quad I = PV^{3/2},$$

where I is the electron current and V the electron-gun voltage.

Let us consider stored $\bar{p}$ and H^- beams at 300 MeV/c ($\beta = 0.35$, $1/\gamma^2 = 0.91$). Then $\eta = -1.066$ and the n^{th} harmonic of the revolution frequency is

$$f_{\bar{p}}^n = n \times 1.16 \text{ MHz}, \quad |f_{\bar{p}}^n - f_{H^-}^n| = n \times 1.24 \text{ kHz}.$$

The beams would be separated radially in the cooling section by

$$\delta x = \alpha_p \cdot \mu = 2.7 \text{ mm} .$$

In an uncompensated electron beam the electron velocity varies with the distance d from its beam axis as

$$\frac{\Delta \beta_e}{\beta_e} = 3 \times 10^4 \times P \left(\frac{d}{\phi} \right)^2 .$$

A radial adjustment of the circulating-beam axis symmetrically to either side of the electron-beam axis allows one to obtain equal mean velocities for $\bar{p}$ and H^- owing to the parabolic shape of the electron velocity distribution.

With cooled beam emittances $E \leq 1 \pi \text{ mm} \cdot \text{mrad}$ and the beta function given above, the horizontal beam width Δx would be $\Delta x = \pm 1 \text{ mm}$. The width of the velocity distribution introduced by the horizontal beam width would be less than 2×10^{-6} . It should thus be possible to keep the average velocity difference between both beams below a tenth of this value, i.e.

$$\frac{\delta \beta}{\beta_0} \leq 2 \times 10^{-7} .$$

This limits the precision to which μ can be determined to $\Delta \mu = \delta \beta / \beta_0$ or $\Delta \mu / \mu = \pm 2 \times 10^{-4}$. The frequencies can be measured much better than this. For instance, with a beam-momentum spread below 10^{-5} the revolution-frequency spread is $\Delta f \leq n \times 10 \text{ Hz}$. The peak position should be measurable to a hundredth of this value yielding an accuracy of

$$\Delta \left(\frac{\delta f}{f} \right) / \frac{\delta f}{f} \leq \frac{10^{-2} \times n \times 10 \text{ Hz}}{n \times 1.24 \text{ kHz}} = \pm 8 \times 10^{-5} .$$

4. CONCLUSIONS

The calculations outlined show that the relation $\bar{p}H^-$ mass difference $\mu = 2(m_{H^-} - m_{\bar{p}}) / (m_{H^-} + m_{\bar{p}})$ could be measured without special effort to a precision of $\Delta \mu = \pm 2 \times 10^{-7}$ with LEAR and its electron cooling system, using accelerator techniques. The method outlined is non-destructive and virtually does not consume $\bar{p}$. Such a precision lowers the limit for an eventual $\bar{p}p$ mass difference to

200 eV. This is 250 times more precise than the measured $\bar{p}$ mass and more than one order of magnitude better than m_p . With some effort it should be possible to lower this limit further.

Since this method does not require high beam intensities it can be applied also to determine the mass difference between other stable charged particles and antiparticles, and isotopes with high precision.

REFERENCES

- [1] P. Lefèvre, D. Möhl and G. Plass, The low energy antiproton ring (LEAR) project, Proc. 11th Int. Conf. on High Energy Accelerators, Geneva, 1980 (Birkhäuser, Basle, 1980), p. 819.
- [2] H. Poth, Phys. Lett. 77B, 321 (1978).
- [3] S. van der Meer, CERN/PS/AA 78-18 (1978).
- [4] G. Audi, A. Coc, M. Ephère, R. Ferreau, P. Guimbal, M. de Saint Simon, C. Thibault, F. Touchard, E. Haebel, H. Herr, R. Klapisch, G. Lebée, G. Petrucci, G. Stefanini, High precision mass measurements with a radio-frequency mass spectrometer, CERN/PSCC/81-84 (1981).
C. Thibault, High precision $\bar{p}p$ mass comparison, to be published in Proc. of Workshop on Physics at LEAR with Low Energy cooled Antiprotons, Erice 1982.
- [5] U. Gastaldi, $\bar{p}p$ experiments at very low energy using cooled antiprotons, Proc. 4th European Antiproton Symposium, Barr, France, 1978 (CNRS, Paris, France, 1979) (Ed. A. Fridman), p. 607.
- [6] G.I. Budker, N.S. Dikansky, V.I. Kudelainen, I.N. Meshkov, V.V. Parchomchuk, D.V. Pestrikov, A.N. Skrinsky and B.N. Sukhina, Part. Accel. 7, 197 (1976).
M. Bell, J. Chaney, H. Herr, F. Krienen, P. Möller-Petersen and G. Petrucci, Nucl. Instrum. Methods 190, 237 (1981).
- [7] G. Plass (ed.), Design study of a facility for experiments with low-energy antiprotons, CERN/PS/DL 80-7 (1980).
- [8] H. Haseroth, Ch. Hill, H. Poth and P. Möller-Petersen, On the use of the ICE gun for electron cooling in LEAR, CERN/PS/LR/Note 80-7 (1980).