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ENERGY CALIBRATION OF SPEAR BY g-2 PRECESSION

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We have checked the absolute energy calibration of SPEAR near 3.6 GeV to an accuracy of ± 0.02% by measuring the g-2 precession frequency of a stored positron beam at a fixed machine energy. This is considerably more accurate than the ± 0.1% systematic uncertainty assigned to the energy calibration on the basis of field measurements of the SPEAR magnets. Alternatively, these results can be interpreted as a large-γ ($\gamma \sim 7055$) measurement of the positron magnetic anomaly $a_{e^+} = (1.1599 \pm 0.0012) \times 10^{-3}$.

The spin precession frequency ν was inferred by studying the transverse beam polarization as a function of vertical betatron tune ν_y for fixed machine energy E. The method relies on the fact that under certain conditions, the naturally occurring radiative beam polarization will be destroyed by spin resonances. The conditions for spin resonance can be expressed as:

$$\nu \pm i\nu_x \pm j\nu_y \pm k\nu_s = n \tag{1}$$

where i, j, k and n are integers, ν_x is the horizontal betatron tune, and ν_s is the synchrotron frequency. Since ν is related to beam energy by

$$\nu = \gamma a$$
$$a = \frac{g-2}{2} \quad , \quad \gamma = E/m_e \tag{2}$$

(g is the electron g factor and m_e is the electron mass), a measurement of ν provides an absolute determination of E.

Changing machine energy will result in a sweep through a succession of depolarizing resonances whenever condition (1) is satisfied. It is expected theoretically and observed experimentally that only the lower-order resonances (i, j, k, small) are significant. Similarly, it is possible to pass through such resonances by keeping E fixed but varying the characteristic frequencies of particle motion in a storage ring.

The measurements presented here were performed around the resonance described by

$$\nu - \nu_y = 3 \quad . \qquad (3)$$

This resonance was chosen for several reasons.

a. It has been observed to be relatively narrow, thus allowing a precise determination of the central frequency.

b. It is of first-order, and is therefore comparatively strong and reproducible. Furthermore, when sweeping through the resonance only E and ν_y need be controlled carefully.

c. Of resonances satisfying (a) and (b), it appears at the highest available energy (about 3.6 GeV since ν_y is about 5.2). For this measurement, ν_y was varied while E, ν_x and ν_s were held constant. The spin precession frequency associated with this fixed energy is given by

$$\nu = 3 + \bar{\nu}_y \qquad (4)$$

where $\bar{\nu}_y$ is the central betatron tune of the observed resonance. Thus the relative error in ν due to measurement error in $\bar{\nu}_y$ is reduced by choosing the largest practical value of ν. Furthermore, the characteristic build-up time constant for transverse polarization varies inversely with the fifth power of the storage ring energy, and is about 15 minutes at 3.6 GeV. Thus only at fairly high energies is it practical to store a circulating beam long enough for several different asymptotic polarizations to be measured while the resonance region is explored.

The experiment was performed with the SPEAR laser polarimeter.[1] This device measures transverse polarization of the positron beam by Compton scattering of laser photons and detecting an up-down asymmetry in the distribution of backscattered photons. In this analysis, an absolute measurement of polarization is not required. Rather, the ratio r of the measured up-down asymmetry to the maximum asymmetry observed away from depolarizing resonances is sufficient to determine the location of resonances. For a fixed set of machine conditions, radiative beam polarization causes r to vary in time according to:

$$r(t) = r_f(1 - e^{-t/r_f T}) + r_i e^{-t/r_f T} \qquad (5)$$

where r_f and r_i are constants and T is the usual radiative polarization build-up time, which for SPEAR is given by:

$$T = 9870/E^5 \text{ (GeV) minutes} \quad .$$

r_i is related to the initial beam polarization existing when the observation period begins. r_f is the desired quantity which describes the depolarization strength during the observation period. $r_f = 1$ signifies no depolarization; $r_f = 0$ is complete depolarization of the beam. As described in Ref. 1, the SPEAR polarimeter can follow the time evolution of r(t) and the data can be fitted to determine r_f.

After determining the approximate location of resonance (3) by scanning in energy, a single beam of positrons was stored into a SPEAR configuration with the following parameters (SYNCH values):

$$\beta_y^* = 0.20 \text{ m} \qquad \nu_y = 5.189 \text{ (variable)}$$

$$\beta_x^* = 1.21 \text{ m} \qquad \nu_x = 5.266$$

$$\eta = 0.00 \text{ m} \qquad \nu_s = 0.043$$

During the entire fill, E_{vmon}, ν_x, and $2\nu_s$ were monitored and held fixed within the following values:

$$E_{vmon} = 3.6061 \pm 0.0002 \text{ GeV}$$

$$\nu_x = 5.277 \pm 0.001$$

$$2\nu_s = 0.083 \pm 0.001 \ .$$

Starting at $\nu_y = 5.185$, ν_y was lowered in steps of 0.001 to 5.178, then raised to 5.186 and finally lowered to 5.1845. ν_y was changed by varying the Q3-trim current. Whenever the limit of the Q3-trim range was reached, the Σ5 computer was commanded to vary ν_y and Q3-trim was brought back into its operating range. Both ν_y and ν_x were monitored by chart recordings; typical scans are displayed in Fig. 1. It can be seen from Fig. 1a that there is a rather large spread in ν_y, presumably coming from power supply ripple. The value of ν_y assigned to each polarimeter run was chosen to be the most probable value of the ν_y distribution.

At each setting of ν_y, the up-down asymmetry was measured in a series of five or six three-minute runs. This was sufficient to give a good indication of r_f when it was small ($\lesssim \frac{1}{2}$), the most important case when trying to determine resonance positions. In offline data analysis, the series of polarimeter data were fitted to the expected time dependence an adjacent ν_y settings were linked together as discussed in Ref. 1.

The resulting values of r_f are plotted versus ν_y in Fig. 2. The vertical error bars represent the statistical errors on the fitted values of r_f. The horizontal error bars are meant to indicate the spread in ν_y. The data are plotted at the most probable value of ν_y and the error bars correspond to the half-height of the ν_y signal on the chart recorder. A clear resonance dip between $\nu_y = 5.180$ and 5.185 is evident. Judging the results shown in Fig. 2 both from the central values of ν_y and from the tune-spread of ν_y, we estimate that the central value of the resonance is given by

$$\hat{\nu}_y = 5.1835 \pm 0.0015 \quad .$$

Hence, the spin-precession frequency for this setting of SPEAR is $\nu = 8.1835 \pm 0.0015$. From Eq. (2) it follows that $E = (3.6061 \pm 0.0007)$GeV.

During these runs, the average value of E_{vmon} calculated by the Σ5 central program was in fact 3.6061 GeV, but this agreement is fortuitous since E_{vmon} is not corrected for saturation properties of all magnet families and other effects mentioned below. The flip coil should provide the most reliable absolute measurement. During these runs the typical reading was 1.16660 V-sec. Using a calibration constant of 3.087 GeV/V-sec for coil No. 1 (which has been in place since January 11, 1977), taking into account the different saturation properties of the four families of SPEAR bending magnets (see Table I) and applying corrections[2] for orbit errors, trim fields, and the earth's magnetic field, this gives E = 3.6052 GeV. This value differs from the spin-precession measurement presented here by less than 1 MeV, well within the estimated ± 0.1% systematic uncertainty in the overall SPEAR energy calibration.

It has been pointed out by Newman et al[3] that measurements of the magnetic anomaly of particles at different energies constitute a test of special relativity. A more general discussion of the relevance of such measurements to tests of special relativity has been given by Combley et al.[4] If we use the absolute magnetic measurements for SPEAR (reliable to better than ± 0.1%), then the present measurements of ν can be used to determine the positron anomaly a_{e^+} at high energy, $\gamma = 7055 \cdot 7$. The value obtained is $a_{e^+} = (1.1599 \pm 0.0012) \times 10^{-3}$ to be compared with the best value for a_{e^-} measured near rest[5], $a_{e^-} = 1.15965241(20) \times 10^{-3}$.

Cooper et al[6] presented a high-γ measurement of a_{e^-} and set limits on a possible special relativity breakdown parameter which they call C_1. Their value was $C_1 = (-1.0 \pm 8.0) \times 10^{-10}$. The value for this parameter determined from the results presented here (assuming $a_{e^+} = a_{e^-}$) is $C_1 = (-0.4 \pm 1.6) \times 10^{-10}$. Even though the γ in this measurement is a factor of three lower than that used in Ref. 6, the higher precision on the measurement of the magnetic anomaly allows us to set a more stringent limit on C_1.

We wish to thank the SPEAR operations staff for providing the careful control of the machine necessary for these measurements.

REFERENCES

1. D. B. Gustavson et al., SLAC PUB-2338, to be published in Nucl. Inst. Meth. (1979).

2. From B. Autin and Y. Marti, CERN ISR-MA/73-17, the orbit correction was calculated as

$$\frac{\Delta p}{p} = \sum_i \eta_i x_i / \sum_i \eta_i^2$$

where the position monitor readings x_i and the associated momentum compaction factors η_i were read from the SYNCH output. For these runs, the correction was about -0.9 MeV. The trim fields were also taken from the SYNCH output and gave a small correction of +0.14 MeV. The earth's field was assumed to have a vertical component of 0.42 Gauss over the region of the ring not shielded by magnets, yielding a small correction of +0.20 MeV.

3. D. Newman et al., Phys. Rev. Letts. 40, 1355 (1978).

4. F. Combley et al., Phys. Rev. Lett. 42, 1383 (1979).

5. R. S. Van Dyck, Jr., P. B. Schwinberg, and H. G. Dehmelt, Phys. Rev. Lett. 38, 310 (1977).

6. P. S. Cooper et al., Phys. Rev. Lett. 42, 1386 (1979).

TABLE I

Current	Approx. Energy	Ratio*
300 A	0.5 GeV	1.00025
600 A	1.0 GeV	1.00011
900 A	1.5 GeV	1.00031
1200 A	2.0 GeV	1.00059
1500 A	2.5 GeV	1.00064
1800 A	3.0 GeV	1.00113
2100 A	3.5 GeV	1.00124
2400 A	4.0 GeV	1.00093

*Ratio of the average magnetic strength of the actual ring magnets to that of the reference magnet.

FIGURE CAPTIONS

1. a. Wave analyzer output signal versus driving frequency for measuring vertical betatron frequency ν_y.

   b. Wave analyzer output signal versus driving frequency for measuring horizontal betatron frequency ν_x.

2. Ratio of backscattered up-down asymmetry to maximum possible asymmetry versus vertical betatron frequency for fixed E_{vmon} = 3.6061 GeV.

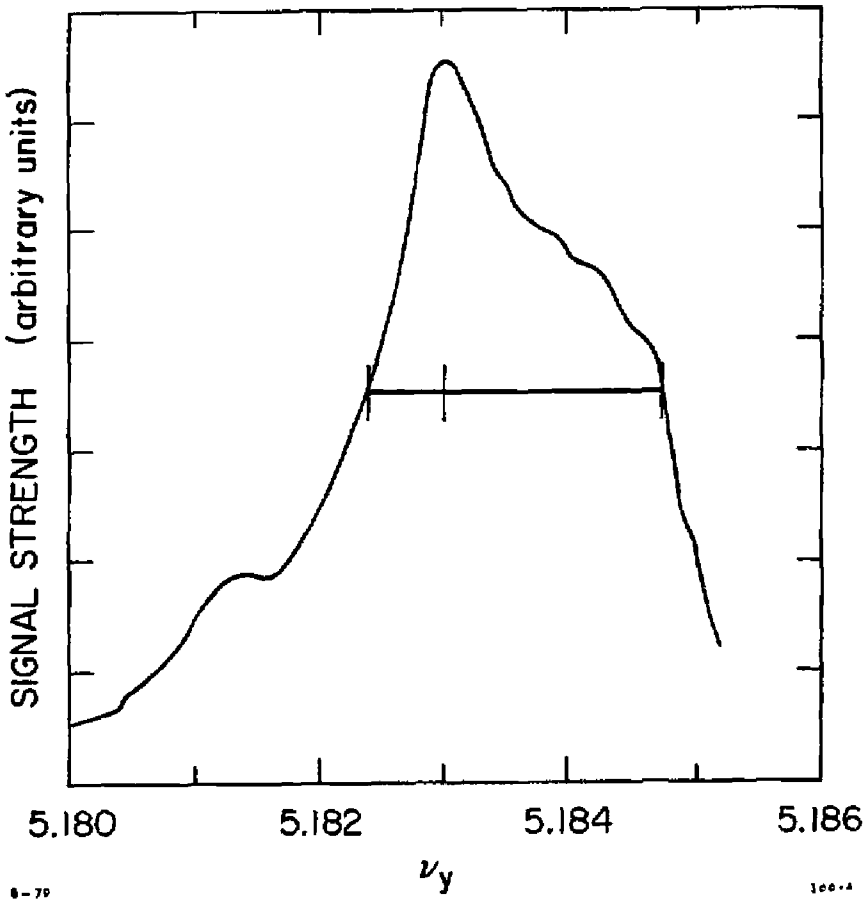


Fig. 1a

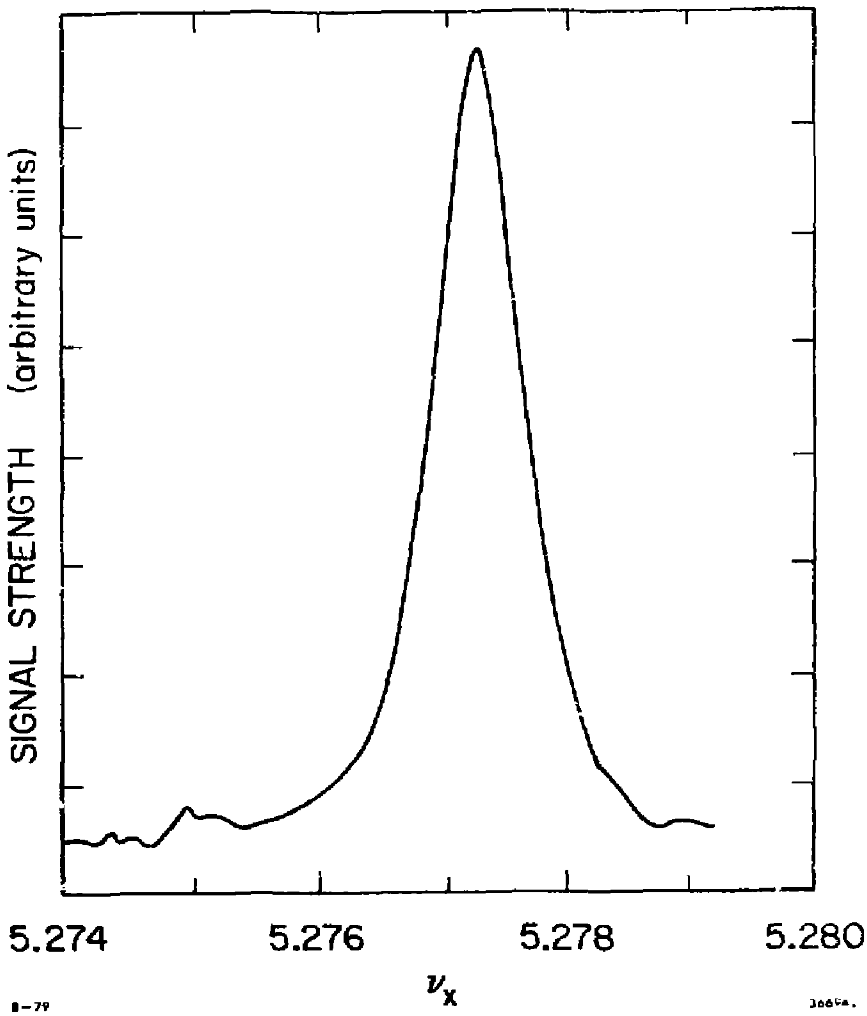
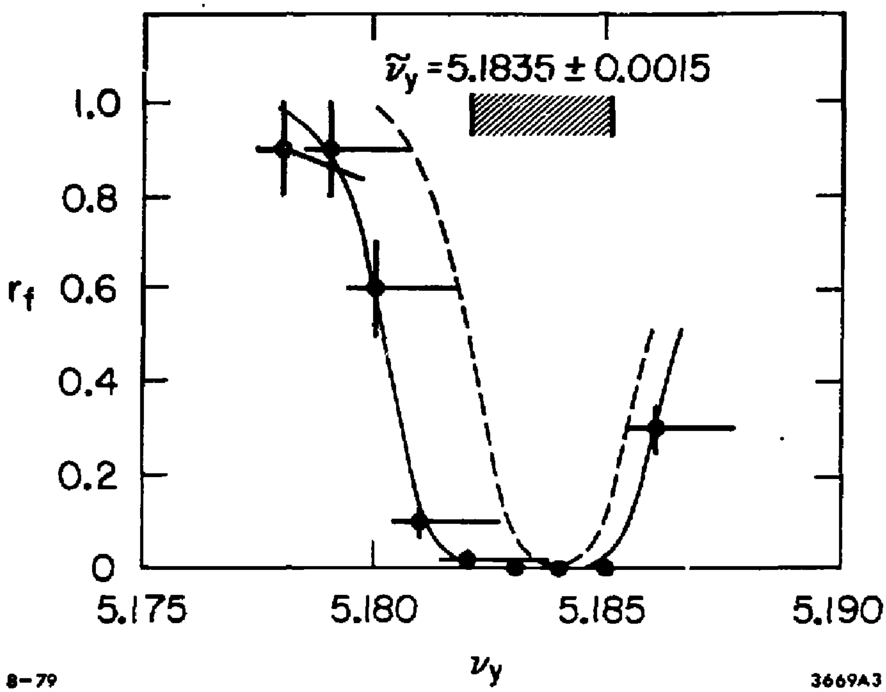
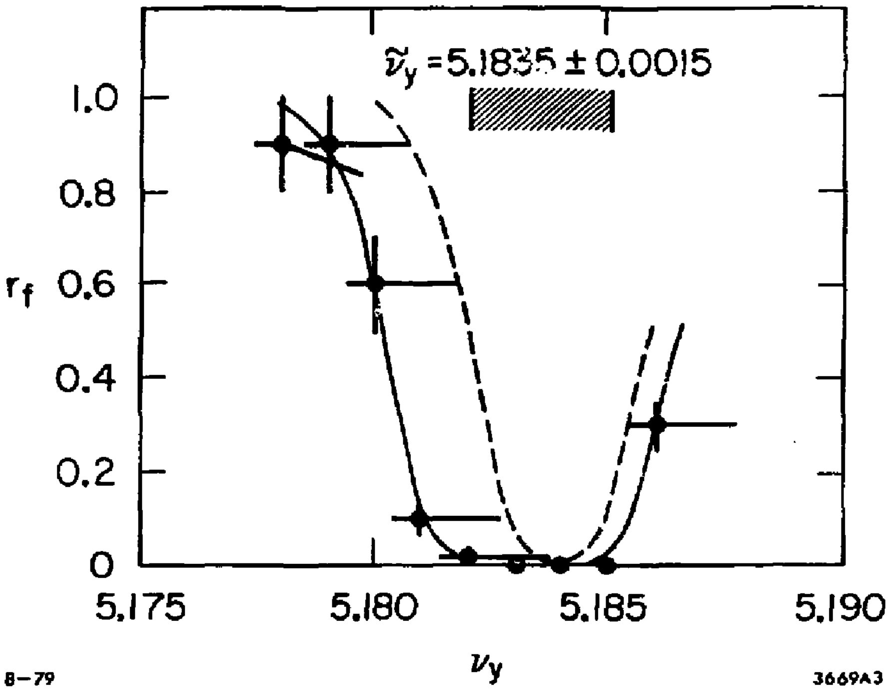


Fig. 1b



$\tilde{\nu}_y = 5.1835 \pm 0.0015$
1.0
0.8
r_f
0.6
0.4
0.2
0
5.175
5.180
5.185
5.190
ν_y
8-79
3669A3

Fig. 2



$\tilde{\nu}_y = 5.1835 \pm 0.0015$
1.0
0.8
r_f
0.6
0.4
0.2
0
5.175
5.180
5.185
5.190
ν_y
8-79
3669A3

Fig. 2