RESEARCH OF POSSIBILITY TO USE BEAM POLARIZATION FOR ABSOLUTE ENERGY CALIBRATION IN HIGH-PRECISION MEASUREMENT OF TAU LEPTON MASS AT VEPP-4M

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Abstract

Results of experiments on measurement of a duration of beam polarization existence in VEPP-4M electron-positron collider ring after injection of a polarized beam from VEPP-3 booster at the energy $1.85\ GeV$ and subsequent deceleration down to the energy of tau-lepton production threshold (1.78 GeV) are presented and analysed.

INTRODUCTION

A preparation of the experiment at VEPP-4M electron-positron collider with KEDR detector on the precision measurement of tau-lepton mass near tau production threshold ($E = 1777$ MeV, the beam energy) is underway [1, 2]. In 2001-2002 we achieved an accuracy $\sim 10^{-6}$ in an absolute calibration of VEPP-4M energy using the technique of resonant depolarization (RD) in a new series of measurements of J/Psi- and Psi'-meson masses [3]. There is a basic difficulty of an application of RD in the vicinity of 'tau-threshold' due to a closeness of the integer spin resonance $\nu = k = 4$ ($E \approx 1763$ MeV, $\nu = E$[MeV]$/440.65$ is an effective frequency of spin precession in units of a revolution frequency). Because of a small distance to resonance ($\epsilon_k = \nu - k \approx 0.03$) the depolarizing effect of quantum fluctuations related to field imperfections is significantly strengthened. By this reason one can not obtain the radiative polarization in VEPP-3 booster, which serves as a source of polarized particles for VEPP-4M, at energies close to 'tau-threshold' [4]. The preliminary attempts to avoid depolarization of particles in VEPP-3 while decelerating and crossing the combined spin resonances in the region between 1840 and 1800 MeV at available rates $2 \div 3$ MeV/sec were not succesful. Therefore, the radiative polarization in VEPP-3 is realized at $E \geq 1840$ MeV. Then an injection of the polarized beam into VEPP-4M is executed and, at last, the beam energy is adjusted downwards to the 'tau-threshold'. A 'life time' of beam polarization in a final state may appear rather small due to a high rate of radiative depolarizing processes. In 2002-2003 we performed the experiments on polarization measurement and on application of RD at various spin tunes in the vicinity of 'tau-threshold' [2]. Spin relaxation time, or the polarization life time (PLT), was under study.

POLARIZATION LIFE TIME

The relaxation time of beam polarization is $\tau_r^{-1} = \tau_p^{-1} + \tau_d^{-1}$ [5] where τ_d^{-1} describes a rate of depolarizing processes; τ_p is a design time of radiative polarization. The extent of depolarization can be characterised by the factor $G = \tau_r/\tau_p = P/P_0$ where $P_0 = 0.92$ is the equilibrium degree of radiative polarization in the ideal machine and $P \leq P_0$ is the same quantity in the real machine with imperfections. Quantum emission scatters particle trajectories that is a reason of diffusion of the vertical component of spin vector in presence of spin-orbital coupling (SOC). The latter appears in a machine with non-flat orbits, for instance, in cases of radial magnetic fields (H_x) and its radial gradients ($\partial H_x/\partial x$). SOC can be described by the vector function $d(\vec{\theta})$ periodical with the azimuth θ [5]. G-factor depends upon $d(\vec{\theta})$ as:

$$G =< |\mathcal{K}|^3 >< |\mathcal{K}|^3(1 + 11/18|\vec{d}|^2) >^{-1},$$

where $\mathcal{K}$ is the orbit curvature, $< ... >$ means averaging over the azimuth. As result, the equilibrium extent (P) and the time of relaxation (τ_r) may significantly decline, especially near the machine spin resonances: $\nu + m\nu_x + n\nu_y = k$ Here m, n, k are integer, ν_x and ν_y are respectively the radial and vertical betatron tunes. The parameter τ_p for VEPP-4M is rather large: $\tau_p \approx 72$ hours at $E = 1777$ MeV. If $\tau_d \leq 1$ hour in conditions under consideration, the relaxation process is actually the process of full depolarization ($\tau_d << \tau_p$, $\tau_r \approx \tau_d$, $G << 1$).

POLARIMETER SYSTEM

The system of absolute calibration of the particle energy at VEPP-4M includes a polarimeter based on IBS (Intra-Beam-Scattering) effect and a TEM wave-based depolarizer [3]. The quantity $S = 1 - \dot{N}_2/\dot{N}_1$, the ratio between the counting rates of scattered electrons from a non-polarized bunch ($\dot{N}_2$) and polarized one ($\dot{N}_1$), is measured with the help of system of scintillation counters entered inside the vacuum chamber. The depolarizer's frequency is scanned and at an instant when it coincides with the mean spin frequency a depolarization of the polarized bunch occurs. The related jump in S of the order of 1% is proportional to a square of the polarization degree P and can be a few tens as a statistical error for 50 seconds. The energy is defined through the ratio of the spin frequency measured to the revolution frequency with an accuracy $\delta E \approx \pm(1 \div 2)$

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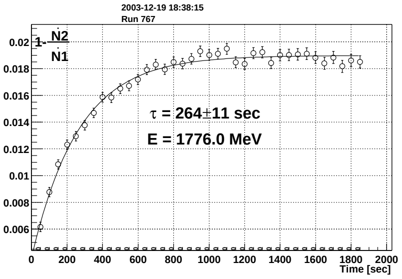

Figure 1: Relaxation of the beam polarization due to radiative depolarization processes ($\tau_r = 2\tau$).

keV. The depolarizer is not needed in the measurement of PLT which is just an observation of an evolution of S in time.

RESULTS OF EXPERIMENTS

Fig.1 shows the process of relaxation of S at the energy slightly below 'tau-threshold'. The corresponding time (τ) of relaxation is determined from fitting the measured data by an exponent and is a half radiative depolarization time ($\tau_r = 2\tau$). The summary result of the measurement of τ at different energies is plotted in Fig.2 as a set of solid circles. Approximately, $\tau_r \propto \epsilon_k^4$, as well as should be in a case of integer spin resonance. Besides, there are two narrow valleys in the energy region studied. One of them is due to a modulation spin resonance depending on a synchrotron oscillation tune ν_γ: $\nu = 4 + 3\nu_\gamma$. It presents a 'fine structure' of the main resonance $\nu = 4$. Admittedly, other is connected with the 3d-order resonance $\nu - \nu_y + \nu_x = 5$. Origin and esimates of both resonances are discussed below. In the special experiment the RF voltage was lowered by 100 kV (10% change of ν_γ) that resulted in the shift by $\sim$ 500 keV of the modulation resonance position and a corresponding increase of τ at a given energy. In measurements performed $\tau \approx 10$ minutes ($\tau_r \approx 20$ minutes) at 1777 MeV. It is just enough to have time for the energy calibration with an accuracy $\sim 10^{-6}$ near the 'tau-threshold' (see Fig.3).

ESTIMATES OF DEPOLARIZING EFFECTS

Statistical model of field errors

We have conducted a numerical simulation [2] of the depolarizing effect of random (uncorrelated) vertical displacements and tilts of VEPP-4M magnets based on the approach [6] for $\vec{d}$ calculation. Fig.4 shows the probability on the set of 4000 samples for realization of the different values of PLT at the variance of the vertical displacements of magnets $\delta z = 100$ μm (a geodesic leveling of VEPP-4M keeps $\delta z \approx 70$ μm) . As it is seen in Fig.4, an expected $\tau_r > 50$ minutes with 100% probability. Note, that the main set of samples corresponds to large relaxation times of the order of several hours and more. Contributions in τ_r^{-1} from random tilts of the bending magnets (H_x) and focusing elements ($\partial H_x/\partial x$) with the typical variance $3 \cdot 10^{-4}$ rad are estimated as appreciably smaller.

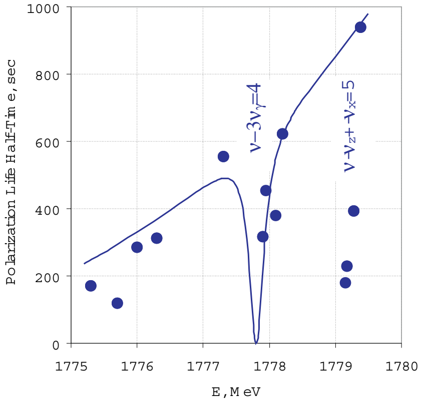

Figure 2: Measured and calculated half-PLT versus a beam energy near the tau-lepton production threshold.

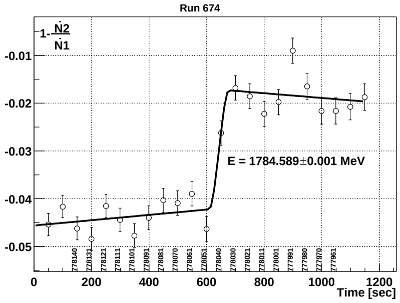

Figure 3: The measurement of the beam energy on a jump in the counting rate of IBS electrons during scanning the frequency of the depolarizer. Energy measured is 1784.589 ± 0.001 Mev.

Spin harmonic of radial field perturbations

Near the resonanse $\nu = k = 4$ the value of $\vec{d}$ is principally determined by a single spin azimuthal harmonic [5] of the radial field perturbations. In case of VEPP-4M this harmonic and G-factor can be written as [6]

$$w_k \approx < H_x F^{\nu=k} \exp\left(-ik\theta\right) >,$$

$$G \approx \left[1 + \frac{11}{18}|w_k|^2 \left(\frac{\nu}{\epsilon_k}\right)^4\right]^{-1}.$$

Here H_x is in units of the mean guiding field; the complex value F^ν is the spin response periodical function in a stor-

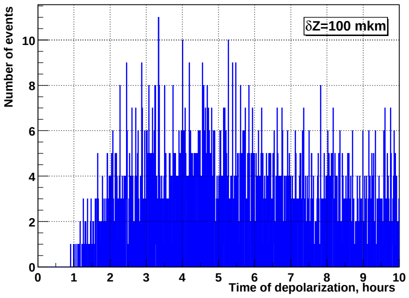

Figure 4: Result of statistical model to account the depolarizing effect of the vertical displacements of focusing magnets of VEPP-4M with a variance 100 μm.

age ring [5] (in VEPP-4M $< |F^\nu|^2 > \approx 12$ at $E = 1777$ MeV). Assuming the measured relaxation time $\tau \sim 30$ minutes to be due to the effect of radial fields we obtain the harmonic amplitude $|w_k| \sim 10^{-3}$. Contribution of Y-correctors into $|w_k|$ may be of the same order at moderate rms (< 1 mm) and maximum (about 2 mm) values of the distortions typical for VEPP-4M. Obviously, one should try compensate the parasitic spin harmonic using Y-correctors to increase PLT.

Synchrotron-oscillation spin satellites

Account of synchrotron oscillations results in occurence of narrow resonant lines in the energy scale (γ) separated by intervals which are multiple to $\nu_\gamma \mu_0/\mu'$ (μ_0 and μ' are the normal and anomal magnetic moments). The following formula [5] should be applied to calculate the depolarization rate in this case:

$$G \approx \left\{ 1 + \frac{11}{18}\nu^2 \sum_{k,m} \frac{|w_k|^2 < J_m^2(\Delta/\nu_\gamma) >}{[(\nu - k - m\nu_\gamma)^2 - \nu_\gamma^2]^2} \right\}^{-1} . \tag{2}$$

Here, w_k is a spin harmonics amplitude in the form like as (1); k and m are respectively a harmonics number and a number of a side-back line corresponding to resonance $\nu - m\nu_\gamma = k$; J_m is Bessel function of the m-th order; $\Delta = \sqrt{2}\nu\sigma_\gamma$ is a spread of the spin tune due to an energy spread σ_γ. The equation (2) is valid if $\nu^2\lambda/\nu_\gamma^3 << 1$ [5], where $\lambda = (f_0\tau_p)^{-1}$, f_0 is a revolution frequency. It is fulfilled for VEPP-4M ($\nu_\gamma \sim 0.01$, $f_0 = 819$ kHz, $\tau_p \sim 80$ hours at $E = 1.8$ GeV). The solid curve in Fig.3 shows the results of calculation of PLT using (2) in the vicinity of the modulation spin resonance with $k = 4$, $m = 3$ and a value of the harmonic amplitude $w_4 \approx 1.2 \cdot 10^{-3}$ estimated from the measured general dependence of PLT upon the energy.

Spin resonance due to sextupoles

The spin resonance $\nu - \nu_y + \nu_x = k + \epsilon$, ($k = 5, \epsilon << 1$) presumably detected in our experiments is due to a presence of the sextupole component $h = \partial^2 H_y/\partial^2 x$. Using the method in [6], we obtain the SOC function in a given case [7] ($d_y \equiv 0$):

$$\left| (d_x + id_z)\frac{\delta\gamma}{\gamma} \right| = \left| \nu \int_\theta^\infty h\delta xyF^\nu e^{-i\nu\theta'} d\theta' \right| .$$

The radial orbit deviation δx is considered as an additional disturbance caused by the energy fluctuation $\delta\gamma/\gamma$; the quantity y is treated as a full vertical oscillation of trajectory in the approximation of weak betatron coupling. Introducing the Fourier amplitude of perturbations

$$w_k = < Rh\sqrt{\beta_x\beta_z}F^\nu e^{i[\mu_z - \mu_x + (\nu_x - \nu_z - k)\theta]} >$$

and applying the averaging over the azimuth and over the beam ensemble one can obtain a width of the resonance defined for the level $G = 0.5$

$$\Delta\epsilon_k \approx \frac{\sqrt{11}}{6} R^{-1}\nu|w_k|\sqrt{\mathcal{E}_y < \mathcal{H} >}.$$

Here $\mathcal{E}_y$ is the vertical emittance and $\mathcal{H} = \beta_x^{-1}[\eta_x^2 + (\alpha_x\eta_x + \beta_x\eta_x')^2]$ is a known function describing an excitation of radial oscillations. In our case, $\mathcal{E}_z \sim 0.05 \cdot \mathcal{E}_x \approx 1.2 \cdot 10^{-7}$ cm·rad, $< \mathcal{H} > \approx 24$ cm. The existing system of sextupole correction of chromaticity yields $R^{-1}|w_k| \approx 6.4 \cdot 10^{-2}$ cm^{-1} at $E = 1780$ MeV, so the full width of the resonance in the energy scale is $\delta E = 180$ keV (R is the mean machine radius). VEPP-4M collider operates at the betatron tunes $\nu_x = 8.53 \div 8.54$ and $\nu_y \approx 7.57 \div 7.58$. To avoid an influence of the resonance in the range $1777 \div 1780$ MeV one should keep a non-integer part of the difference $|\nu_y - \nu_x| > 0.035 \div 0.041$.

SUMMARY

The polarization lifetime in VEPP-4M near 1777 MeV though is limited, but still is sufficient for realization of energy calibration procedure with a high accuracy (10^{-6}). An application of the resonance spin harmonic correction in order to prolong PLT seems neccesary and resonable. The thin structure of spin resonances dependent on the synchrotron and betatron tunes are studied.

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