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HIGH PRECISION EXPERIMENTS IN THE J/ψ, $\psi(2S)$ AND τ SECTOR

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Abstract

High precision experiments in charmonium sector require beam energy calibration. VEPP-4M [1] storage ring with energy measurement by resonant depolarization (RD) method provided high precision mass measurement of J/ψ- and $\psi(2S)$- mesons with KEDR detector with accuracy 2×10^{-6} [2]. This narrow resonances can be used for calibration of energy scale of other accelerators such as BEPC-II or future Super Charm-Tau Factories equipped with Compton backscattering (CBS) energy measurement system.

BEAM ENERGY MEASUREMENT

Resonant Depolarization Method

The resonant depolarization (RD) method [3] is the most accurate technique of beam energy measurement. The accuracy achieved is about 10^{-6}. The method was successfully applied in the high precision measurements of the mass of elementary particles from ϕ-meson to Z-boson.

The method is based on the measurement of the spin precession frequency Ω, which depends on the beam Lorentz factor γ and well-known normal μ_0 and anomalous μ' parts of the electron magnetic moment:

$$\Omega = \omega_r \left(1 + \gamma \frac{\mu'}{\mu_0}\right), \quad (1)$$

where ω_r is the beam revolution frequency in the storage ring. The spin precession frequency is determined by the moment of resonant destruction ($\Omega = n\omega_r \pm \omega_d$, where $n \in \mathbb{Z}$) of the beam polarization in an external electromagnetic field with a frequency ω_d.

The beam polarization could be measured in several ways: using intensity of intra-beam scattering (Touschek effect) [4]; intensity of synchrotron light [5]; asymmetry of Compton backscattering [6]; scattering asymmetry on internal target [7]. At the VEPP-4M beam polarization is determined by intra-beam scattering [8]. The beam is depolarized by a TEM wave which is created by two matched striplines. They are connected to a high frequency generator with tunable frequency, which is computer controlled. The generator frequency ω_d and the VEPP-4M revolution frequency ω_r are stabilized by a rubidium atomic clock with an accuracy 10^{-10}. A polarized beam is prepared in the VEPP-3 booster with polarization time 1.3 hours at E=1.55 GeV or 0.6 hours at E=1.85 GeV then injected into VEPP-4M. In order to suppress beam size and orbit instabilities a relative count rate difference $\Delta = \dot{N}_{pol}/\dot{N}_{unpol} - 1$ of the polarized and unpolarized bunch is under observation.

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The depolarization frequency is measured with an accuracy better then 10^{-6}. Double energy calibrations with opposite directions are performed in order to suppress dangerous side 50 Hz resonances. The determination of center of mass energy at the interaction point (IP) requires taking into account following effects: vertical orbit distortions and spin precession frequency width; solenoid field of the detector; coherent energy loss asymmetry; electron and positron energy difference and beam separation in parasitic IP; β-function chromaticity and beam potential [9, 10]. Corrections and errors are about few kev. Between calibrations VEPP-4M energy is reconstructed [11] by using some parameters of VEPP-4M storage ring: field of bending magnet measured by nuclear magnetic resonance method; environment and storage ring temperatures; beam orbits.

Compton Backscattering

The RD method meets problem with beam polarization near τ-lepton production threshold ($E = 1777\ MeV$) due to close vicinity to $\Omega_s/\omega_r - 1 = 4$ spin resonance [12]. An additional method of energy monitor for τ mass measurement experiment is required. The process of Compton backscattering (CBS) allows one to determine beam energy by measuring maximum energy of scattering photon:

$$E = \frac{\omega_{max}}{2}\left(1 + \sqrt{1 + \frac{m_e^2}{\omega_0 \omega_{max}}}\right), \quad (2)$$

ω_0 is the initial energy of laser photon; m_e is the electron mass. For the first time this method was realized in [13] and firstly applied in particle experiments for tau mass measurement at VEPP-4M [14]. The scattered photons are registered by high purity germanium detector (HPGe). The detector is calibrated by number of well known γ-sources. The achieved accuracy of the method in beam energy range $E = 1.7 - 1.9$ is about 60 keV. Absolute calibration of the CBS method was done via comparison with RD. The experience of system exploitation at VEPP-4M helped with same systems at BEPC-II [15] and at VEPP-2000 [16] colliders.

HIGH PRECISION EXPERIMENTS AT VEPP-4M WITH KEDR DETECTOR

The data analysis of J/ψ and $\psi(2S)$ mass measurement is based on three J/ψ scans with integrated luminosity $0.7\ pb^{-1}$ and on four $\psi(2S)$ scans with integrated luminosity $1.0\ pb^{-1}$ [2]. Each scan has several points with different energies which cover resonance shape. The beam energy is calibrated before and after data acquisition in each scan point. The resonance masses were determined by fitting

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the inclusive hadronic cross sections as a function of the e^+e^- center-of-mass energy. Special investigation were performed to understand stability of VEPP-4M and reliability of energy reconstruction between RD energy calibrations. The total energy drift during day-night is about 50 keV [17]. The energy reconstruction accuracy during the experiments of J/ψ and $\psi(2S)$ mass measurements is about $6-8$ keV [2, 10]. The achieved accuracy of mass measurement is about 2×10^{-6} which is the best in the world and will remain so for decades.

For tau mass measurement we use CBS method as beam energy monitor together with RD technique. For energy calibration by RD we injected polarized beam at $E = 1.85$ GeV and then deaccelerated energy to tau threshold. The energy was reconstructed by using VEPP-4M parameters as mention before and compared with the CBS energy monitor. CBS monitor itself is calibrated at the moment of energy measurement by RD. We achieved best world accuracy at that time [18]. Later this result was improved at BEPC-II collider with BES-III detector [19] where CBS energy measurement system was installed [15] which calibrated by location of J/ψ and $\psi(2S)$ resonances. This year integrated luminocity about 130 pb^{-1} had been collected again to improve accuracy of tau mass measurement. Data analysis is in progress.

Measurement of Γ_{ee} for J/ψ- and $\Gamma_{ee}\times\mathcal{B}_{\mu\mu}$ for $\psi(2S)$-mesons are based on 0.23 pb^{-1} and 6.5 pb^{-1} integrated luminosity respectively. High precision mass measurement of J/ψ and $\psi(2S)$ with beam energy spread determination and RD energy calibration allow us to measure this parameters with best or world comparable accuracy [20, 21]. Measurement of the mass of $\psi(3770)$-meson is based on 2.6 pb^{-1} integrated luminosity. The resonance is located on the $\psi(2S)$ slope and new measurement [22] allowed to discover sufficient role of resonance-continuum interference which affects on resonance shape. With resonant depolarization method the masses of D^0 and D^+ mesons ($\int L = 0.9\,pb^{-1}$) are measured with best accuracy [23] in 2010. A new measurement was done in 2017 and now data analysis is in progress.

SUMMARY

The resonant depolarization method of beam energy calibration at VEPP-4M allows us to measure masses of the J/ψ- and $\psi(2S)$- mesons with high accuracy (2×10^{-6}). Moreover we had measured masses of τ lepton, D^+-, D^0-mesons, parameters of the $\psi(3770)$-mesons and leptonic width of the J/ψ and $\psi(2S)$ mesons. Together with Compton backscattering method of beam energy calibration this lays the foundation of high precision experiments at other e^+e^- colliders.

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