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ELEMENTARY PARTICLES AND FIELDS
Experiment

Project of Super Charm-Tau Factory

D. A. Epifanov[1),2)*]
(on behalf of SCTF Collaboration)

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Abstract—The Super Charm-Tau Factory project proposed at Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences, in Novosibirsk is discussed. An electron–positron collider with the luminosity of 10^{35} cm^{-2} s^{-1} and energies of 2 to 6 GeV in the beam center-of-mass frame and with a state-of-the-art particle detector arranged at the point of e^+e^- interaction will permit studying, at a new precision level, the physics of charmonium, exotic charmonium-like states, charmed mesons and baryons, and the tau lepton, as well as the production of light hadrons in e^+e^--annihilation processes and in two-photon processes. A longitudinal polarization of the electron beam at the interaction point will provide a number of competitive advantages to the Super Charm-Tau Factory in relation to Super B factories such as Belle II and LHCb.

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1. INTRODUCTION

A project of the Super Charm-Tau Factory was proposed at Budker Institute of Nuclear Physics (BINP, Siberian Branch, Russian Academy of Sciences) [1]. The planned luminosity of the factory at a level of 10^{35} cm^{-2}s^{-1} will make it possible to enlarge by one to two orders of magnitude the amount of experimental information accumulated earlier in the course of the BES III and CLEO-c experiments [2] for energies in the e^+e^--beam center-of-mass (c.m.) frame between 2 and 6 GeV.

Table 1 gives the list of c.m. energies (along with resonances) at which data acquisition is planned, integrated luminosities at each c.m. energy point over the whole time of Super Charm-Tau Factory operation, and physics tasks. The total integrated luminosity of 10 ab^{-1} over the whole time of Super Charm-Tau Factory operation approximately corresponds to 2×10^{10} tau leptons, 10^{10} D mesons, and 5×10^{12} J/ψ mesons.

The physics program of the Super Charm-Tau Factory includes comprehensively studying the physics of charmonia, exotic charmonium-like states, charmed mesons and baryons, and the tau lepton, as well as two-photon physics. Also, it is planned to study, at a new precision level, CP violation in D-meson and tau-lepton decays, as well as lepton-number nonconservation in tau-lepton decays.

Searches for new-physics effects beyond the Standard Model is one of the main tasks of the Super Charm-Tau Factory. Not only will experiments at the Super Charm-Tau Factory compete with the investigations performed at the Large Hadron Collider (LHC) at CERN, as well as at the Belle II Super B-Factory [3], but they will also supplement those investigations.

In order to reach a high luminosity of the e^+e^- collider of the Super Charm-Tau Factory, it is planned to apply the Crab Waist beam-collision scheme, which was discovered recently. Owing to a substantial decrease in the vertical beta function and to the reduction of the impact of collision effects [4], this scheme permits enhancing the luminosity by one to two orders of magnitude without substantially increasing the beam intensity or the dimensions of the setup and without reducing the bunch length. The collider of the Super Charm-Tau Factory will generate a longitudinally polarized electron beam making it possible to perform a number of unique measurements in decays of particles with a nonzero spin [5]. A universal magnetic detector (UMD) [1] is being developed in order ensure fulfillment of the physics program of the Super Charm-Tau Factory. The detector would have high coordinate and momentum/energy resolutions for charged particles/photons, record parameters of the particle-identification scheme [separation of $\pi^\pm$ and $K^\pm$ particles in the momentum range of (0.6–2.5) GeV/c at a confidence level not lower than three standard deviations (3σ) and a good separation of $\mu^\pm$ and $\pi^\pm$ particles up to the momentum value of

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[1)] Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences , Novosibirsk, 630090 Russia.

[2)] Novosibirsk State University, Novosibirsk, 630090 Russia.

[*] E-mail: `epifanov@inp.nsk.su`

Table 1. List of c.m. energies at which data will be collected, integrated luminosities at each point on the energy scale over the whole time of Super Charm-Tau Factory operation, and physics tasks

E, GeV	L, ab^{-1}		
3.097	3.0	J/ψ	Spectroscopy of states formed by light quarks, rare decays
3.554	0.5	$e^+e^- \to \tau^+\tau^-$ threshold	Precision measurements of tau-lepton decays
3.686	1.5	$\psi(2S)$	Spectroscopy of states formed by light quarks, charmonium spectroscopy
3.770	3.0	$\psi(3770)$	Investigation of properties of D mesons
4.170	1.0	$\psi(4160)$	Investigation of properties of D_s mesons
4.650	1.0	maximum of $\sigma(e^+e^- \to \Lambda_c^+\Lambda_c^-)$	Investigation of properties of Λ_c baryons

1.2 GeV/c], a data acquisition system providing data readout with a short dead time up to counting rates of 300 to 400 kHz, and a trigger characterized by a high efficiency with respect to signal events and by a high level of background suppression under conditions of high counting rates.

2. PHYSICS PROGRAM

The physics program of experiments at the Super Charm-Tau Factory is outlined in [1]. A software package intended for simulating physics processes and the detector response is being developed at the present time. On the basis of this package, the physics program of experiments at the Super Charm-Tau Factory is being currently refined with allowance for special features of the detector under construction and the polarization of the electron beam at the interaction point.

2.1. Tau-Lepton Physics

The tau-lepton data sample that is the largest in the world and which comes from the Belle [6] and BABAR [7] e^+e^- B factories, as well as from LHCb [8], opens a new era in performing precision tests of the Standard Model in tau-lepton decays. Considerable advances have been made in those experiments in studying basic properties of the tau lepton—namely, the Michel parameters $\xi\kappa$ and $\bar{\eta}$ in the radiative leptonic decays of the tau lepton were measured for the first time ever, the tau-lepton lifetime was measured to the highest degree of precision in the world, and the tau-lepton mass was measured to a high precision. Moreover, the leptonic universality of the Standard Model could be tested at a new precision level owing to the measurements of the ratios of the coupling constants for the electron, muon, and tau lepton. In addition, the most stringent limits were set on the tau-lepton electric dipole moment and on the branching ratios for lepton-number-violating tau-lepton decays [9].

The vector W boson, which interacts with fundamental left-handed fermions, is the mediator of charged weak interaction in the Standard Model. Owing to this, the weak charged current has the so-called V-A Lorentz structure postulated within the Standard Model. There are two main classes of tau-lepton decay. These are leptonic decays (in which the intermediate W boson decays to leptons: $W^- \to \ell^-\bar{\nu}_\ell,\ \ \ell,\ell' = e,\mu$)—$\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau$, $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau\gamma$, and $\tau^- \to \ell^-\ell'^+\ell'^-\bar{\nu}_\ell\nu_\tau$—and hadronic decays in which W^- boson[3] decays to a quark—antiquark pair, $d\bar{u}$ (Cabibbo-allowed decays) or $s\bar{u}$ (Cabibbo-suppressed decays). Hadronic tau-lepton decays provide unique possibilities for studying QCD at low energies [10], while leptonic tau-lepton decays are the only decay processes where strong-interaction effects do not introduce uncertainties in the investigation of electroweak coupling constants [11]. Owing to this, such decays are a perfect means for studying the Lorentz structure of the weak charged current. In the case where the neutrino and the spin of the final-state lepton are not detected, the predicted energy spectrum of the lepton in the decay process $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau$ is parametrized in terms of four Michel parameters (ρ, η, ξ, and δ) as [11]

$$\frac{d\Gamma(\tau^\mp)}{dx\,d\Omega_\ell} = \frac{4G_F^2 m_\tau E_{\max}^4}{(2\pi)^4}\sqrt{x^2-x_0^2}\bigg(x(1-x) + \frac{2}{9}\rho(4x^2-3x-x_0^2) + \eta x_0(1-x) \mp \frac{1}{3}P_\tau\cos\theta_\ell\,\xi\sqrt{x^2-x_0^2}\bigg[1-x + \frac{2}{3}\delta\Big(4x-4+\sqrt{1-x_0^2}\Big)\bigg]\bigg),$$

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[3] Unless otherwise stated, we are dealing with charge-conjugate decays everywhere in this article.

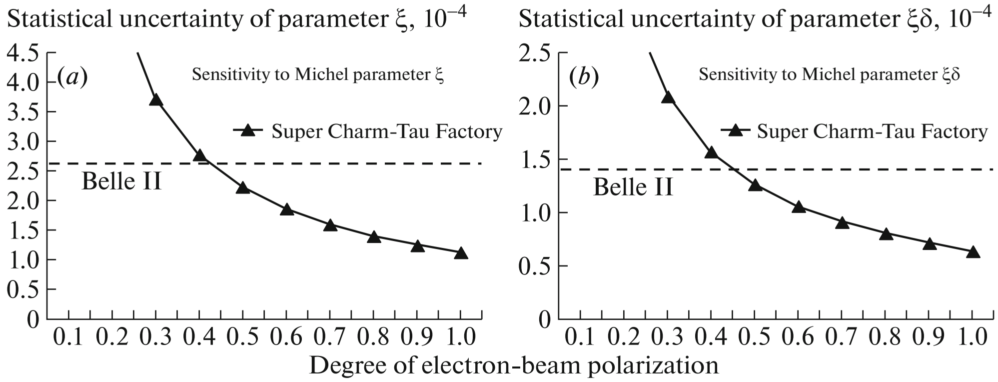

Fig. 1. Dependence of the statistical uncertainties in the Michel parameters (a) ξ and (b) $\xi\delta$ on the degree of the electron-beam polarization at the Super Charm-Tau Factory (closed triangles). The dashed lines represent the parameter values expected in the Belle II experiment.

$$x = E_\ell/E_{\max}, \quad E_{\max} = m_\tau\big(1 + m_\ell^2/m_\tau^2\big)/2,$$
$$x_0 = m_\ell/E_{\max},$$

where P_τ is the degree of tau-lepton polarization, Ω_ℓ is the final-lepton solid angle, and θ_ℓ is the angle between the tau-lepton polarization vector and the final-lepton momentum in the tau-lepton rest frame. The Michel parameters are experimentally measurable bilinear combinations of generalized coupling constants for charged weak interaction and, within the Standard Model, take the values of $\rho = 3/4$, $\eta = 0$, $\xi = 1$, and $\delta = 3/4$. In order to measure the parameters ξ and δ, it is necessary to know the direction of the tau-lepton polarization (spin) vector. In experiments at e^+e^- colliders where the beams used are unpolarized (such as Belle/Belle II and BABAR), the mean polarization of one tau lepton is zero, so that, in order to measure the parameters ξ and δ, one has to employ the correlation between the spins of τ^+ and τ^- leptons in the reaction $e^+e^- \to \tau^+\tau^-$. In doing this, one analyzes the joint distributions of the products of decay of both tau leptons, a signal one and a tagging one, in the multidimensional reaction phase space [12].

The Super Charm-Tau Factory involving a polarized electron beam would permit producing tau leptons whose mean polarization is nonzero, which substantially facilitates measurement of physics observables that depend on the tau-lepton polarization. The sensitivity of the Super Charm-Tau Factory to the Michel parameters versus the degree of the electron-beam polarization was studied in relation to the sensitivity of the Belle II experiment [13]. Although the statistics expected at Belle II (46 billion $\tau^+\tau^-$ pairs) are larger than what is expected from the Super Charm-Tau Factory (21 billion $\tau^+\tau^-$ pairs) by a factor of about 2.2, the sensitivity to the Michel parameters ρ and η is higher at the Super Charm-Tau Factory by a factor of 1.5, while the sensitivity to the Michel parameters ξ and $\xi\delta$ at the Super Charm-Tau Factory becomes higher for electron-beam polarizations of $\mathcal{P}_e > 0.5$ (see Fig. 1). A nonzero mean polarization of one tau lepton at the Super Charm-Tau Factory also allows one to perform a more detailed model-independent search for CP violation in hadronic tau-lepton decays. It is noteworthy that measurement of the dynamics of the hadronic decays $\tau^- \to \pi^-\nu_\tau$ and $\tau^- \to \pi^-\pi^0\nu_\tau$, which have been already studied well, would make it possible to monitor with a high precision (not poorer than 10^{-3}) the degree of electron-beam polarization over a broad range of c.m. energies from the threshold for $\tau^+\tau^-$-pair production to 6 GeV.

2.2. Charmonium and Charmed-Hadron Physics

Over the whole time of Super Charm-Tau Factory operation, 5×10^{12} J/ψ and 5×10^{11} $\psi(2S)$ mesons would be produced in e^+e^- collisions at energies below the $D\overline{D}$-production threshold. The radiative decays of J/ψ and $\psi(2S)$ particles may produce 10^{11} χ_{cJ} and 10^{11} η_c mesons. Further, 4×10^8 h_c and 4×10^8 $\eta_c(2S)$ mesons may originate from the decay processes $\psi(2S) \to h_c\pi^0$ and $\psi(2S) \to \eta_c(2S)\gamma$. This level of statistics would permit systematically studying the properties of low-lying states of charmonia (their masses and total and leptonic widths, as well as the branching ratios for transitions between different states). In this region of c.m. energies, the electron-beam polarization would be monitored to a precision not worse than 10^{-3} by analyzing the dynamics of the decay processes J/ψ, $\psi(2S) \to [\Lambda \to p\pi^-][\bar\Lambda \to \bar p\pi^+]$ [14]. At the Super Charm-Tau Factory, it would be possible to study in more detail the properties of a large number of exotic charmonium-like states.

The Super Charm-Tau Factory will make it possible to produce 10^{10} pairs of charged and neutral D mesons and 10^9 pairs of D_s mesons. These numbers do not exceed D-meson statistics accumulated at the B factories in the $\Upsilon(4S)$-resonance region, but the kinematical and quantum-mechanical features of D mesons produced at the Super Charm-Tau Factory near the $D\bar{D}$-production threshold would make it possible to obtain more precise results in a number of cases. In particular, there are no accompanying hadrons near the $D\bar{D}$-production threshold, so that one can reconstruct neutrinos by the missing mass in studying leptonic and semileptonic decays; also, the double-tagging method, which permits reducing the background level and measuring to a high precision the absolute probabilities for D-meson decays, is applicable. The coherence of the initial $D\bar{D}$ state is used to study the mixing of D^0 and $\bar{D}^0$ states, to perform searches for CP violation, and to measure strong phase shifts and branching ratios for D-meson decays to CP eigenstates. The parameters of D^0–$\bar{D}^0$ mixing can be measured to a higher precision at the Super Charm-Tau Factory than in the Belle II experiment.

Searches for CP violation in D-meson decays is one of the main tasks of future experiments at the Super Charm-Tau Factory. In charmed-hadron decays, the Standard Model predicts a CP asymmetry at a level not higher than 10^{-3}. Recently, the LHCb experiment opened a CP violation occurring in D^0-meson decays and complying with the predictions of the Standard Model[15]. The Super Charm-Tau Factory would make it possible to measure CP asymmetry to a precision not poorer than 10^{-3} for various CP-violation mechanisms.

3. DETECTOR AND ACCELERATOR COMPLEX

The UMD tracking system consists of two parts: an internal tracker for detecting charged particles of low momentum (less than 100 MeV/c) and a drift chamber (DC). Several versions of the internal tracker are being considered. They include a four-layer silicon strip detector, a cylindrical detector based on gaseous electron multipliers, and a time-projection chamber. The expected physical background near the beam-collision region (elastic electron–positron scattering and two-photon reactions) dictates the choice of tracker. Also, two DC projects have been developed. The first project is that of DC featuring a hexagonal cell of size (6.3–7.5) mm; it consists of 41 layers of wires combined into 10 superlayers that involve alternating axial and stereo layers. This DC contains about 11000 signal wires and 29000 field wires; its expected momentum resolution is $\sigma_{p_\perp}/p_\perp \approx 0.4\%$ at $p_\perp = 1$ GeV/c, while the resolution in ionization loss is $\sigma_{dE/dx}/dE/dx \approx 6.9\%$ [16]. The other version is developed in the form of an ultralight drift chamber featuring a rectangular cell 7.2×9.3 mm^2 in size and 64 stereo layers, the total number of ultrathin wires being about 10^5 [17]. Various options of the identification system are being considered. They include Ring-Imaging CHerenkov detectors on the basis of a multilayered Focusing Aerogel (Focusing Aerogel Ring-Imaging CHerenkov detectors, or FARICH detectors), ring-imaging Cherenkov detectors employing total internal reflection, detectors of the propagation time and coordinate of Cherenkov light, and threshold Cherenkov counters. The FARICH detector is considered as a basic version. A simulation of its response and successful tests of its prototype in a beam has demonstrated the possibility of reaching with it quite stringent planned parameters [18]. An electromagnetic calorimeter is one of the basic UMD subsystems. The calorimeter serves to measure the energies and coordinates of photons over a wide energy range, from 10 MeV to 3 GeV; to identify charged particles; and to develop a triggering signal from the detector. A total-absorption calorimeter on the basis of pure CsI scintillation crystals (characterized by a short luminescence time of about 30 ns) was proposed in order to reach high energy and time resolutions, as well as to reduce the pileup noise, which becomes significant at facilities of ultrahigh luminosity. The calorimeter counter consists of a pure CsI crystal, a wavelength-shifter plate featuring luminophores (NOL-9), four silicon avalanche photodiodes (Hamamatsu APD S8664-55) attached to the plate endfaces, and a charge-sensitive preamplifier. A calorimeter prototype formed by 16 counters has been created to date; work on calibrating the prototype counters by means of cosmic-ray particles is being presently performed, and it is planned to study the prototype energy resolution in a photon beam at Budker Institute of Nuclear Physics (Siberian Branch, Russian Academy of Sciences, Novosibirsk) [19]. The muon system is intended primarily for separating muons and hadrons in UMD. Muons are identified by their range in the absorber the role of which is played by the steel yoke of the detector magnetic system. The counters of the muon system are arranged in the gaps of the steel yoke of the magnet; they are grouped into nine detecting layers in the barrel part and eight layers in the endface part. A counter of the muon system is a plastic-scintillator strip with a groove in which a wavelength-shifter optical fiber is glued. Light re-emitted in the fiber is detected by silicon photomultiplier tubes on the two sides of the fiber. A simulation of this muon system reveals that its spatial resolution, about 4 cm, is determined by multiple charged-particle scattering in the yoke of the UMD magnetic system [20].

The concept of the Super Charm-Tau Factory collider was proposed in 2006 [1]; its basic properties were described in [21]. In 2019, the accelerator-complex project was refined [22]—in particular, the perimeter of each storage ring was reduced to 476 m. Further, the beam-collision angle became 60 mrad, while the planned luminosity of the setup at the c.m. energy of $2E = 6$ GeV reached 2.8×10^{35} cm^{-2}s^{-1}. A longitudinal polarization of the electron beam at the interaction point is an important feature of the Super Charm-Tau Factory collider. In [23], it is shown that an electron-beam polarization of about 90% is reachable at low energies in employing a collider scheme that involves three Siberian snakes; at the maximum energy of $2E = 6$ GeV, the polarization will still remain rather high, about 50%.

4. CONCLUSIONS

Owing to the ambitious and versatile research program for the Super Charm-Tau Factory and a number of its competitive advantages over the existing projects in the area of flavor physics, such as Belle II and LHCb, the Super Charm-Tau Factory would become one of the key elements of landscape of future experimental high-energy physics. In 2011, the Super Charm-Tau Factory was approved by the Government of Russian Federation as one of the six leading megascience projects. The most advanced international research centers involved in particle-physics studies, such as CERN, KEK, INFN, and IDA have taken interest in the project and expressed willingness to participate in it. In 2017, this project was included in the plan of implementation of the first phase of strategies for scientific and technological development of Russia. In 2019, the upgraded and extended conceptual design of the Super Charm-Tau Factory was once again sent to the Government of Russian Federation for a further scrutiny. Also, theses of the Super Charm-Tau Factory were included in the European strategy in the realms of particle physics. An international collaboration has been formed, the physics program of experiments at the Super Charm-Tau Factory is being further elaborated, and research studies and engineering development work devoted to the detector subsystems and accelerator complex are being performed at a number of laboratories. An international advisory council was organized, and three international workshops on the development of the Super Charm-Tau Factory project were held.

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