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Development of polarized slow e+ beam for future linear colliders

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abstract

We have so far been developing a new method to create slow polarized e+ beam by using β^+ decay of radioactive neuclei with short life-time produced with a proton cyclotron. Here we describe technical details on productions of polarized e+ and measurements of the polarization. The experiments of producing polarized e+ will soon start. Although the e+ intensity is not sufficiently high, we will acquire lots of know-how for further development of polarized e+ sources with high quality which will possibly be applied to future linear colliders.

Physics with polarized e+ beam

From the point of view of high energy physics, the polarized e+ beam should play important roles in next generation e+e- colliders.

First, we discuss cases that we study physics of the Standard Model in which e- and e+ always interact in the helicity combination of $e_R^+ e_L^-$ (RL) and $e_L^+ e_R^-$ (LR), except in the case of two photon interaction. If e+ beam is not polarized, half of e+ in the beam cannot interact because half of collisions occurs in the "wrong" combination, such as $e_R^+ e_R^-$ (RR) and $e_L^+ e_L^-$ (LL). Then polarization of e+ beam gives us a factor two increase of an effective luminosity if both e- and e+ beams have 100% polarization. In addition, the polarization of both e+ and e- beams will suppress drastically the systematic error on measurement of the left-right asymmetry of a cross section $A_{LR} = \{\sigma(LR) - \sigma(RL)\} / \{\sigma(LR) + \sigma(RL)\}$.

In studying new physics beyond the Standard Model, the polarization of an e+ beam would play much essential roles, because some models allow interactions in "wrong" combinations (RR and LL). The super-symmetric extension of the Standard Model, for example, allows reactions such as, $e_L^+ e_L^- \to \tilde{e}_R^- \tilde{\chi}^+ \bar{\nu}_e$, and $e_R^+ e_R^- \to \tilde{e}_R^+ \tilde{\chi}^- \nu_e$, where $\tilde{e}^\pm$ and $\tilde{\chi}^\pm$ stand for a scaler electron and a chargino, respectively. Thus, by choosing the helicities of e- and e+ beams as RR or LL, we can study these interactions free of the backgrounds from the Standard Model interactions.

Production of polarized e+'s using a compact cyclotron

It is well known that e^+ emitted through β^+ decays are longitudinally polarized with the helicity v/c, v and c being the velocities of e^+ and light. Since numbers of e^+ from isolated radioisotopes used in off-line manner is quite limited, it is necessary to develop new methods to generate large amount of polarized e^+. Our method is to use β^+ decay from radioisotopes which are produced through (p,n) interaction by means of on-line usage of a compact proton cyclotron resulting in possible utilization of radioisotopes with short life-time. A proton beam with an energy of 18 MeV irradiates an aluminum target with thickness of 2mm and the radioisotope ^{27}Si is produced in the reaction $^{27}Al(p,n)^{27}Si$. The large maximum energy of 3.85MeV for the β^+ rays emitted from ^{27}Si favors to achieve large helicity of e^+ because of large magnitude of v/c. The β^+ rays with wide energy spread are converted to slow e^+ with good energy resolution at a moderator.

The slow e^+ generated from the moderator are transported to the polarimeter set 27m downstream using a 100G magnetic field produced by solenoid coils. The e^+ intensities of 2×10^6 e^+/s and 5×10^5 e^+/s have been obtained for the proton current of 30μA after the transportation of 10 m and 27 m, respectively, .

Measurement of the e^+ polarization

We now discuss methods of the polarization mesurement, applicable to slow e^+ under keV. In order to establish the reliable method to measure e^+ polarization, we attempt to construct measuring devices based on two different methods as described below.

(1)Polarization measurement using a ferromagnetic target

In the case of free annihilations of unpolarized e^+ and e^- at rest, the branching ratio $B_{3\gamma/2\gamma}$ of 3γ to 2γ annihilation is represented as $B_{3\gamma/2\gamma} = \lambda_{3\gamma}/\lambda_{2\gamma} = 1/372$, where $\lambda_{2\gamma}$ and $\lambda_{3\gamma}$ are the decay rates of 2γ and 3γ annihilations for unpolarized e^+ and e^-. For e^+e^- annihilation at rest, spin states of e^+ and e^- in parallel (which is called triplet state) annihilates into 3γ, while anti-parallel spin states (which is composed of the singlet(50%) and triplet(50%) states) annihilate into 2γ and 3γ, respectively. The numbers of 3γ and 2γ annihilation events change by reversing the direction of e^+ spin or e^- spin. The asymmetry A is represented as

$$A = \frac{R_{\mathrm{para}} - R_{\mathrm{anti\text{-}para}}}{R_{\mathrm{para}} + R_{\mathrm{anti\text{-}para}}} \approx \frac{4}{3} P_{e^+} P_{e^-}$$

(for $\frac{4}{3} P_{e^+} P_{e^-} << 1$), where R_{para} is the ratio of 3γ to 2γ annihilations of e^+ and e^- with parallel spins and $R_{\mathrm{anti\text{-}para}}$ that with the anti-parallel spins. The quantities P_{e^+} and P_{e^-} stand for the polarization of e^+ and e^-, respectively. We utilize a ferromagnetic iron-foil as a polarized e$^-$ targetin which $3d$-electrons are fully polarized under an external magnetic field of 100G. The parallel and anti-pallarel spin states are realized by changing the direction of the external magnetic field.

(2) Ortho-Positronium quenching in magnetic field

The basic idea of the polarization measurement using ortho-positronium quenching in magnetic field is described in *Phys. Rev. A29, 96 (1984)* and references therein. In the external magnetic field B, the singlet state of a positronium (para-Ps state) ψ_s and a sub-state of the triplet state (ortho-Ps state) ψ_t (m=0) are perturbed to form two mixed states (ortho-like-Ps and para-like-Ps states), while other triplet sub-states, $\psi_t(m=\pm 1)$ are not perturbed. The time spectrum of Ps decays in the magnetic field B can be written as

$$\frac{dN(t)}{dt} = N_0 \{ \frac{1}{2} \lambda_t e^{-\lambda_t t} + \frac{1}{4}(1-\varepsilon P_{e^+} \cos\phi)\lambda'_t e^{-\lambda'_t t} + \frac{1}{4}(1+\varepsilon P_{e^+} \cos\phi)\lambda'_s e^{-\lambda'_s t} \}.$$

Here, N_0 is the total number of generated Ps, $1/\lambda_t$, $1/\lambda'_t$, and $1/\lambda'_s$ are the life times of ortho-Ps ($1/\lambda_t$=140nsec), ortho-like-Ps, and para-like-Ps, respectively and $\varepsilon = x/\sqrt{1+x^2}$ for x=0.0276B[kG]. The life time of the perturbed states, $1/\lambda'_t$ and $1/\lambda'_s$ are also functions of the magnetic field B. The quantity P_{e^+} in the above equation is the e$^+$ polarization, and ϕ is the angle between the e$^+$ spin direction and $\vec{B}$. Number of the generated ortho-like-Ps, $N_{\text{ortho-like}}(0)$, can be determined from the shape of the time spectrum. Since $N_{\text{ortho-like}}(0)$ is related to the polarization P_{e^+}; $N_{\text{ortho-like}}(0)/N_0 = (1-\varepsilon P_{e^+}\cos\phi)/4$, the e$^+$ polarization P_{e^+} can be evaluated from $N_{\text{ortho-like}}(0)$ for the known strength of the magnetic field by fitting the time spectrum of Ps decays. For this experiment, a magnet with holes in both sides of the pole pieces is designed to locate the e$^+$ beam pipe in the holes and the magnetic flux density is changed in the range between 2kG and 8kG in the gap of the pole pieces to reduce systematic errors in the polarization measurement.

To examine depolarization of e$^+$ through the beam transportation from the moderator to the target where e$^+$e$^-$ annihilation takes place, we developed a program POEM (POlarized beam simulator in Electric and Magnetic fields) based on GEANT to simulate the trajectory and polarization of the slow e$^+$ in statical electric and magnetic fields.

Discussions

The experiment of measurement of the e$^+$ polarization will soon starts. If the proton beam current and the conversion efficiency of the moderator are improved up to 1mA and 10^{-3}, e$^+$ beam intensity of the order of 10^9 e$^+$/s can be achieved. To obtain 10^{14} e$^+$/s required in future linear colliders, we need to develop a high current proton linac, a high efficiency moderator and a beam buncher. The technical details are described in KEK preprint 95-92.