High Energy Physics and Nuclear Physics

Volume 21, Number 3

Study on Beam Polarization and the Design of a Polarimeter in BEPC

Deng Jingkang[1], Shang Rencheng[1], Zhu Shengjiang[1], Xu Wang[1], Zhang Juping[1], Jin Qingzhen[1], Zhu Henian[1], Xia Shaojian[2], Yan Yonglian[2], and Guo Yanan[2]

[1](Department of Physics, Tsinghua University, Beijing, China)
[2](Institute of High Energy Physics, the Chinese Academy of Sciences, Beijing, China)

The necessity and possibility of beam polarization in the Beijing electron-positron collider (BEPC) and the methods for beam polarization measurements are introduced briefly. The design of a Compton scattering polarimeter used for the measurements of beam polarization of BEPC beam via a synchrotron radiation pipeline and the experiments under way are presented.

Key words: BEPC electron beam, beam polarization, polarization measurement.

1. INTRODUCTION

A great deal of research has been carried out on J/ψ, ψ', D_s, and the τ lepton since the completion of Beijing electron-positron collider (BEPC), which, particularly in its use for the study of the accurate measurement of τ-mass, has been highly regarded in the world. Recently, high energy physicists have paid close attention to the developments of BEPC and the related physics in the next few years. Our suggestion for the polarization study on BEPC has attracted the attention of the high energy community. In this paper, we discuss the possibility of the polarization in BEPC, the principles and the methods of polarization measurements, and briefly describe the design of a Compton scattering polarimeter using a synchrotron radiation pipeline.

Received on June 28, 1996.

2. GENERAL DESCRIPTION OF BEAM POLARIZATION AND RELATED PHYSICS

In a particle system, if the distribution of spin directions (different magnetic quantum states) in the space are not isotropic, the system is said to be polarized. The polarization includes the vector polarization and tensor polarization. The particles of 1/2 spin can only have vector polarization, and the magnitude of the polarization is

$$P = \frac{N_+ - N_-}{N_+ + N_-}, \tag{1}$$

where N_+ and N_- are the numbers of particles with +1/2 and −1/2 projection of spin along the quantum axis, respectively. The direction of vector polarization is the one in which the magnitude of the polarization is maximum. For the particles with spin greater than 1, there is also tensor polarization except vector polarization.

The direction of the transverse polarization is perpendicular to the momentum of the beam. The direction of longitudinal polarization is parallel or antiparallel to the momentum of the beam. It is more difficult to realize longitudinal polarization in a storage ring; on the other hand, many interesting high energy physics phenomena are associated with the longitudinal polarization. For the complete longitudinally polarized beam, all particles have the same helicity. As for the partial longitudinally polarized beam, the particles have two different helicities.

At present, the beam energy in BEPC is measured with parameters of the accelerator and the energy of some resonance states requires the results obtained by others as references. Therefore, an absolute energy calibration system for more precise measurement of the beam energy is needed. In a real storage ring the spin vector of the polarized beam processes around the magnetic field. Through the application of a weak radial RF-magnet field, the perturbation from RF-magnet will reduce the equilibrium degree of the polarization. If the perturbation is in phase with the spin precession, the polarization will be completely destroyed after many turns. This phenomenon is called resonant depolarization. The accuracy of energy determined using this method can attain the order of 10^{-5}. For example, the mass of the Z boson was measured at LEP to be 91.177 ± 0.021 GeV without polarization [1]. If the polarization introduced only at some special run time, the uncertainty of energy measurement could be reduced to ±5 MeV. In the case of a collision with polarized beams, the accuracy will attain ±1 MeV.

For the unpolarized beam, the cross section in a reaction needs to sum over the final states and to average the initial states. The spin information in a basic reaction process is therefore lost, and the differential cross section is only dependent on the polar angle θ, but independent on the azimuthal angle φ. If the transverse polarized e^+ beam collides with an e^- beam, the differential cross section is related to transverse polarization $P_\perp$ and the azimuthal angle φ. The dependence of a reaction on the spin is shown as that of the differential cross section on the spin, which is very useful in experimental measurements. In particular, it is worth noting that the experiment at SPEAR, using an electron beam with a transverse polarization of 70%, confirmed that the hadron jets originated from the generated spin 1/2 partons by measuring the azimuthal modulation production of all the hadrons with $\chi > 0.3$ [2].

The beam polarization will be built up when BEPC runs at some conditions, which will bring about to the dependence of the cross section of e^+e^- and $\mu^+\mu^-$ production on the azimuthal angle φ. This subject is currently being studied at Tsinghua University in cooperation with IHEP.

3. POLARIZATION OF ELECTRON BEAM ON BEPC

Polarized electrons can be obtained in linear accelerators by means of a polarized electron source (PES). PES has been developed for a long time, and was widely used in surface physics, biophysics, atomic and molecular physics, and nuclear and particle physics [3]. However, for the circular accelerator, Ternov, Loskutov, and Korobina, the physicists of the former USSR, pointed out in 1962 that the electron beam can gradually become polarized [4]. This is due to the solution of the Dirac equation, in an uniform magnetic field, showing a weak asymmetry for different initial spin states. The polarization is transverse with electrons being antiparallel to the bending field and the positrons being parallel to it. According to the natural radiative Sokolov-Ternov mechanism, the build-up of the polarization can be described with an exponential function,

$$P(t) = -\frac{8}{5\sqrt{3}}\,(1 - e^{-t/\tau_P}) = -92.4\%\,(1 - e^{-t/\tau_P}), \tag{2}$$

τ_P being the build-up time,

$$\tau_P = \frac{5\sqrt{3}}{8}\left(\frac{c\lambda\!\!\!^{-}_C r_0 \gamma^5}{\rho^3}\right)^{-1}, \tag{3}$$

where C is the velocity of light, $\lambda\!\!\!^{-}_C$ and r_0 are the Compton wavelength and the classical electron, radius, respectively. ρ is the radius of curvature of the beam orbit in the magnets, and γ is the relativistic factor of the electron energy. Equation (2) describes the build-up of the polarization at a circular accelerator. The final polarization without a depolarizing effect is

$$P_\infty = -92.4\%, \tag{4}$$

where the minus denotes that the polarization direction of the electron is antiparallel to the bending field.

Equation (3) is for the ideal circular accelerators. As for a noncircular orbit accelerator, such as BEPC, it needs to be corrected by factor R/ρ where R is the average radius of the orbit. For any shape

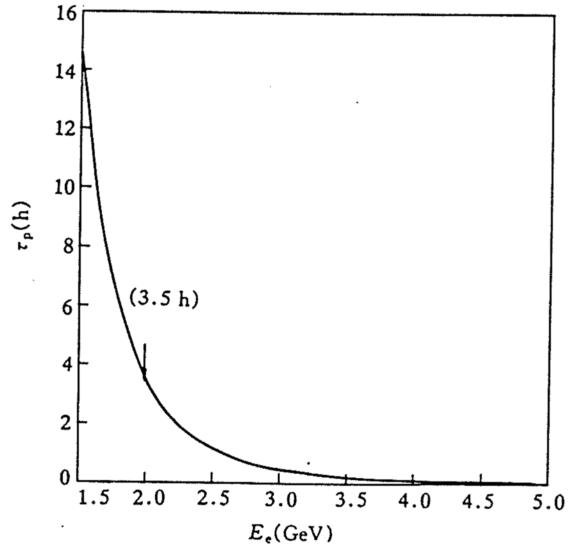

Fig. 1
The built-up time depending on the energy of beam.

orbits, we have

$$\tau_{\mathrm{P}} = \frac{5\sqrt{3}}{8} \left(\frac{c\lambda\!\!\!^{-}_{\mathrm{C}} r_0 \gamma^5}{S} \oint \frac{\mathrm{d}S}{|\rho|^3} \right)^{-1} = 98.7 \frac{\rho^2 R}{E_{\mathrm{e}}^5} , \qquad (5)$$

where S and R are the circumference and the mean radius of the orbit, respectively. And the integral is along the orbit ring.

It can be found from Eq.(5) that the polarization build-up time is inversely proportional to the fifth power of the beam energy. The lower the energy, the longer the build-up time. So someone predicted that it is very difficult to realize polarization in the accelerators with energy below 5 GeV. However, considering that the radius of curvature of the electron orbit on BEPC is relatively small, the defect of the lower energy could be compensated to a certain degree. We calculated the relation of the build-up time dependence on the beam energy, as shown in Fig. 1. The build-up time at the energy required in some typical physics experiments on BEPC is listed in Table 1. The lifetime of the electron beam in BEPC is about 6-7 hours with collision and more than 10 hours without collision. From Table 1, we can see that the build-up time is longer when running at lower energy. However, except for the J/ψ experiment, the polarized beam could be obtained by the natural synchrotron radiation at other energy.

In a real storage ring, there is a depolarizing effect which limits the attainable polarization of the electron beams. The main source of the depolarization is the emission of the synchrotron radiation which statistically excites oscillations by the orbits. The real magnetic field is not exactly perpendicular to the orbit plane, and the spin axis can be tilted by a small inclination, e.g., tens of milliradians. In the presence of stochastic orbit motion a diffusion of the spins could be caused according to the Bargmann-Mickel-Telegdi (BMT) equation [5,6], which leads to a depolarization of the electron beams. The depolarizing effect is obvious when the spin tunes are coupled with the orbit oscillations. At the present running conditions of BEPC, the spin tunes at some typical energy are given in Table 2.

In some interesting experiments (excepting the $\tau^{\pm}$ threshold), most are far from resonance points at present conditions of BEPC. Moreover, the parameters of the orbit oscillations could be adjusted if necessary for a special experiment. The polarization can be improved by correcting the closed orbit, which needs to construct a fast on-line polarimeter to measure the polarization of the electron beams so that we can adjust the parameters of the orbit to improve the polarization.

4. MEASUREMENTS OF BEAM POLARIZATION ON BEPC

The fast and accurate measurements of the beam polarization are the precondition of realizing the polarized beam and studying the high energy polarization physics. Only through the use of a specially designed polarimeter could we determine the polarization accurately. And through the use of the fast polarimeter inosculated with adjusting orbit parameters, a higher polarization could be obtained. An accurate absolute calibration for the beam energy could be done using the fast polarimeter and the RF resonance depolarizing device. Only with accurate real-time monitoring of the polarization could the experiments on particle physics related to polarization be performed. Most of the world's high energy accelerators have long-term groups working on the measurement of beam polarization. The measurement of polarization is an arduous and challenging task and someone noticed that the polarimeter works like a small high energy detector.

The polarization of BEPC built by synchrotron radiation is transverse. We plan to construct a Compton scattering polarimeter to measure the polarization of the electron beams. The laser-Compton polarimeter utilizes the polarized photons scattering on the high energy electrons. In the laboratory frame the photons are backscattered into a narrow cone centered around the direction of the initial electrons. The energy of the encounter electrons also changes. There are two methods to measure the

Table 1

The build-up time for several typical experiments in BEPC.

Typical experiment	J/ψ	$\tau^{\pm}$	ψ'	D_s	$\sigma_{\max}(\tau^{\pm})$	Max. energy
$\sqrt{S}$ (GeV)	3.097	3.56	3.77	4.03	4.174	5.6
τ_P (h)	12.5	6.25	4.7	3.4	2.83	0.65

Table 2

The spin tunes in several typical experiments in BEPC.

Typical experiment	J/ψ	$\tau^{\pm}$	ψ'	D_s	$\sigma_{\max}(\tau^{\pm})$	Max. energy
E_e (GeV)	1.548	1.77	1.88	2.015	2.087	2.8
ν (Hz)	3.51	4.017	4.27	4.57	4.74	6.35

polarization: one is to analyze the momentum of the outgoing electrons [7], the other is to detect the backscattered photons. The longitudinal component of polarization can be obtained from the energy spectrum of backscattered photons [7,8], and the transverse from the asymmetry of the scattered photons [8-11].

The energy distribution of the scattered photons in the laboratory frame can be calculated with

$$E_\gamma = \frac{E_e(\cos\theta^* - 1)}{\cos\theta^* - 1 - 1/K_i}, \tag{6}$$

where θ^* is the angle between the directions of scattered photons and initial electrons, and K_i is the momentum of the laser photon in the electron rest frame. The energy distribution of the scattered photons were simulated by means of the Monte Carlo method, under the conditions of beam energy $E_e = 2.0$ GeV and the laser photon energy $h\nu = 2.33$ eV, and the results of the simulation are shown in Fig. 2. The angle distribution of the scattered photons is also calculated and the results show that the photons are scattered in a narrow cone with half an angle of $1/\gamma$ centered around the direction of the initial electron beams.

The intensity of backscattered γ-ray, N, is given by

$$N = fL, \tag{7}$$

where f is the number of collisions between the laser pulses and the electron bunches per second, and L is the number of γ-photons generated in the scattering of each beam bunch collided with laser pulses,

$$L = \sigma_C n_e \lambda_r L_t f_s, \tag{8}$$

where n_e is the number of electrons in each bunch and $n_e = 1.5 \times 10^{11}$ for BEPC. σ_c is the Compton cross section and $\sigma_c = 630$ mb as a frequency-doubled YAG laser ($h\nu = 2.33$ eV, $\lambda = 532$ nm) is proposed for use. λ_r is the density of the laser beam and $\lambda_r = 4.4 \times 10^{14}$ photon/cm^3 for 50 mJ light pulses generated by the frequency-doubled YAG laser with a pulse width of 10 ns and repetition rate of 10 Hz. f_s is the spatial overlapping factor which equals to the ratio of the overlapped area of the electron beam with the laser beam to the cross section of the laser beam times the ratio of the

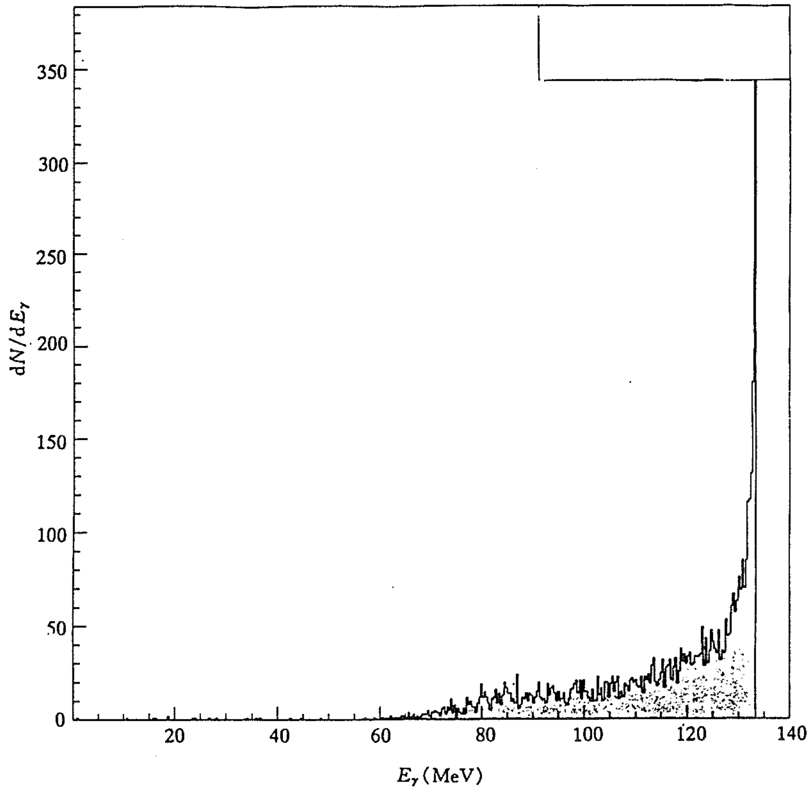

Fig. 2

The energy distribution of the scattered photons calculated under the conditions of $E_e = 2.2$ GeV and $h\nu = 2.33$ eV.

overlapped area to the cross section of the electron beam. The cross section of the electron beam is an ellipse with $a = 0.6$ mm and $b = 4$ mm, and the f_s factor is estimated to be about 20% at the optimal conditions. L_e is the effective length of interaction of the laser beam and the electron beam. When the laser beam, with a diameter of the light spot of about 1 mm, interacts with the electron beam at an angle of 0.9 mrad, then L_e is about 1.1 meters. From these parameters, $L = 910$ and then $N = 9.1 \times 10^3$ γ-photon/second can be obtained, which determine the accuracy and the rate of the polarization measurements.

The measurements of transverse polarization consist in measuring a shift $\Delta\langle y\rangle$ of the center of gravity of the vertical profile of the γ-rays when reversing the circular polarization of light from left to right,

$$\Delta y(E_\gamma) = \frac{\langle y\rangle_L - \langle y\rangle_R}{2} = \Delta S_3 P_y \mathit{\Pi}(E_\gamma), \tag{9}$$

where $\mathit{\Pi}(E_\gamma)$ is the analyzing power which can be calculated from theory. Figure 3 shows the dependence of analyzing power $\mathit{\Pi}$ on the energy E_γ. Further results calculated for $\mathit{\Pi}$ depending on the energy of electrons and the angle of scattered γ-photons are shown in Fig. 4.

The measurements of polarization on high energy accelerators usually use an X-shaped pipe with a laser-in window and a laser-out window, which is inserted in the storage rings. However, as it is

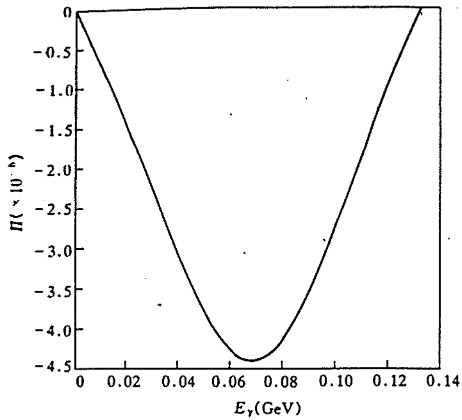

Fig. 3
The analysis power Π depending on the energy E_γ of photons from BEPC (E_λ = 2.33 eV, E_e = 2.0 GeV).

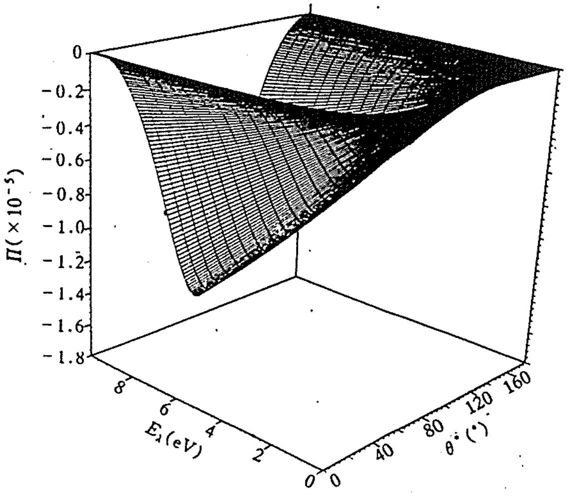

Fig. 4
The analysis power Π depending on the energy E_γ of photons and the angle of scattering photons in the electron rest frame (E_λ = 2.33 eV, E_e = 2.0 GeV).

more economical and has no influence on the normal operation of the BEPC accelerator, we use a synchrotron radiation pipeline which is newly designed and installed. The layout of the polarimeter used on the BEPC is shown in Fig. 5. A transitive section with a mirror to reflect the laser beam is inserted into this synchrotron pipeline while setting the reflector outside the scope of synchrotron radiation. The reflected laser is transported into the interaction point (I.P.) against the direction of the synchrotron radiation. The laser I.P. is chosen to be outside of the Wiggner magnet with a distance of about 2 meters downstream to the synchrotron I.P., but it is still in the linear section of the storage ring. The distance from the reflecting mirror to the laser I.P. is 18.6 meters. At the time of the construction of the synchrotron pipe the needs of the polarization measurements have already been considered, and all the apertures on the pipe have been expanded correspondingly so that the laser can

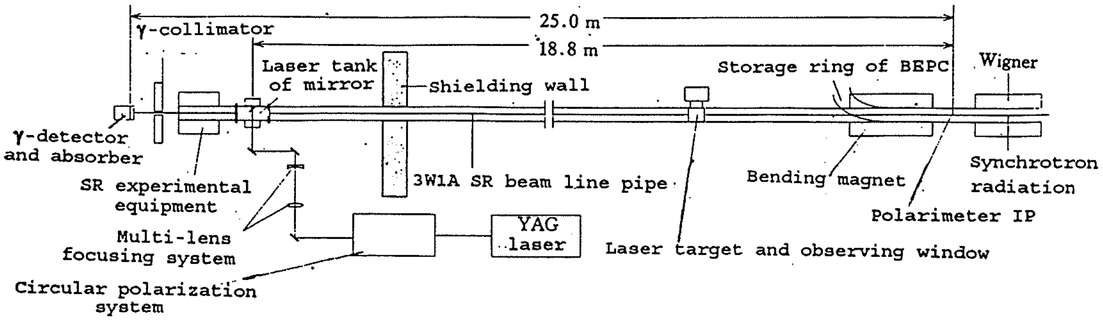

Fig. 5
The layout of the Compton polarimeter proposed to be used in BEPC.

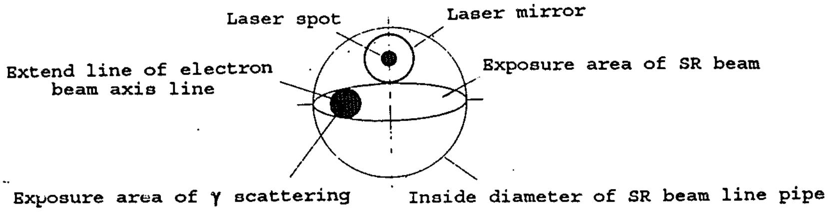

Fig. 6
The profiles of the inward laser beam, scattered high energy γ, and synchrotron radiation at the reflecting mirror.

pass through. The profiles of these lights at the reflecting mirror are shown in Fig. 6. Although the high energy γ-photon and synchrotron radiation overlapped partially in the space, the overlap's influence on the measurements is ignorable as the difference between the energies is about 5 orders of magnitude. There is also an observing target at a distance of a few meters to the laser I.P. In the initial adjustment of the laser beam, if necessary, the target could be dropped down to observe the alignment of the laser beam by a CCD camera. At ordinary running time, the target lifts up from the center of pipeline so that there is no obstacle in the light path of the synchrotron radiation.

A pulsed YAG laser of a pulse width of 10 ns, a pulse energy of 50 mJ, a pulse repetition rate of 10 Hz, and a beam diameter of 6 mm at the out-window will be used in the polarimeter for the measurement of the beam polarization. The diameter of laser beams at I.P. is focused to 1-2 mm by a multi-lens focusing system with long focus length. A laser circular polarization system was specially designed for this polarimeter so that, potentially, a 99% circular polarization can be achieved. To reduce the depolarization effects caused by birefringence, the single-mirror reflections are all replaced by double-mirror reflections.

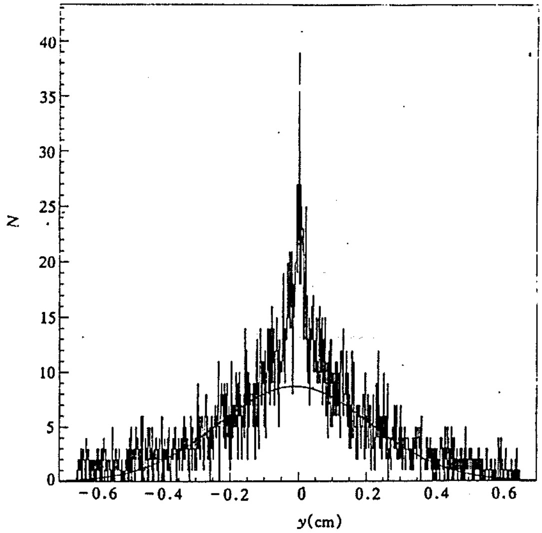

Fig. 7
The distribution of scattered γ along the y direction simulated with the Monte Carlo method.

A compact γ-detector composed of a high density converter and a silicon detector will be used to resolve the vertical asymmetry of the backscattered γ-rays. Manufactured by the Hamamatsu Company, the proposed silicon detector is a one-dimensional position sensitive silicon detector with an active area of 13×13 mm^2 and a spatial resolution of 6 μm. The high density converter is made up of tungsten or lead for developing the γ-shower and to filter out most of the synchrotron radiation flux. To obtain the optimal position resolution and efficiency, a Monte Carlo simulation was performed through the use of the GEANT programs for the γ-ray energy spectrum and the γ-ray position distribution along the direction perpendicular to the plane of the electron orbit. The simulations were also done for the distributions of the showers when different converters are used. The results show that the center of the γ-ray profile could deviate 90 μm from the electron orbit when the right or left circular polarization laser beams are used.

ACKNOWLEDGMENTS

We would like to express our gratitude to Profs. Wu Yingzhi, Zhang Chuang, Guo Zhiyuan, Wang Dong *et al.* of IHEP for their valuable suggestions during the development of the proposal.

REFERENCES

[1] E. Fernandez, in "Neutrino 90," *Nucl. Phys.*, **B666**(1990), p. 1.
[2] R.F. Schwitters *et al.*, *Phys. Rev. Lett.*, **35**(1975), p. 1320.
[3] R.J. Celotta and D.T. Pierce, in: *Advances in Atomic and Molecular Physics*, edited by Sir David R. Bates, **16**(1980), p. 102.
[4] L.M. Ternov, Yu.M. Loskutov, and L.I. Korvina, *Sov. Phys. JETP*, **14**(1962), p. 921.
[5] L. Thomas, *Philos. Mag.*, **3**(1927), p. 1.
[6] V. Bargmann, L. Mickel, and V.L. Telegdi, *Phys. Rev. Lett.*, **2**(1959), p. 435.
[7] M. Swartz *et al.*, *Nucl. Instr. Meth.*, **A363**(1995), p. 526.
[8] K. Nakajima, *Phys. Rev. Lett.*, **66**(1994), p. 1697.
[9] R. Assmann *et al.*, CERN SL/93-02 (BI).
[10] D.B. Gustavson *et al.*, *Nucl. Instr. Meth.*, **165**(1979), p. 177.
[11] D.P. Barber *et al.*, *Nucl. Instr. Meth.*, **A329**(1993), p. 79.