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Study on Spin-precession of Polarized Slow Positrons in Solids

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Abstract

We have investigated spin-precession mechanisms of polarized slow positrons in materials caused by multiple Coulomb scatterings, Bhabha scatterings and bremsstrahlungs. It is found that the degree of the depolarization is strongly dependent on the atomic number of materials, and the depolarizations caused by the Bhabha scatterings and the bremsstrahlungs are negligible comparing with the multiple Coulomb scatterings. The theoretical formulations of the spin-precession due to the three processes are incorporated in a Monte-Carlo simulation program which is successfully applied to obtain the depolarization of polarized slow-positron beams in materials, *i.e.* a target, an absorber and a moderator which are utilized for the slow-positron production facility. The mangnitude of the polarizations thus estimated are in good agreement with that measured by the experiments.

I. INTRODUCTION

Polarized positrons (e^+'s) can be produced by means of β^+ decay of radioisotopes (RI)[1-3] or e^+e^- pair creation from circularly polarized γ rays[3]. It is well known that according to the $V-A$ theory of the weak interaction, e^+'s emitted from β^+ decays are longitudinally polarized and thus possess a helicity of v/c, v and c being velocities of the e^+ and light, respectively. Consequently the e^+ polarization along the beam axis can be thus given by $P = \langle (v_i/c) cos\theta_i \rangle$, where θ_i is an angle between the directions of momentum and the beam axis for the i-th e^+.

As a typical example of the polarized slow-e^+ production, we schematically demonstrate our production system[2,3] of polarized slow-e^+ beams using a compact proton cyclotron which provides proton beams in Fig. 1. Positrons, which are provided from the β^+ decay of ^{27}Si produced by the proton beam via the nuclear reaction $^{27}Al(p,n)^{27}Si$, are moving out of a target of ^{27}Al and then are implanted on a W moderator in which the e^+'s thermalize and are reemitted outside the W moderator with energies of a few eV corresponding to a negative work function of W. In this production system, the e^+'s are moving in the materials of Al and W and thus are necessarily subject to depolarization.

It has been widely argued that higher polarization of slow e^+'s can be achieved by placing a lower density material, *i.e.* Be, between RI and the moderator to absorb low energy part of the β^+-spectrum. In order to offer polarized slow e^+'s to practical applications, we have to know spin-interaction mechanisms of the polaried e^+ with materials at low energy.

In this paper, we investigate spin-precession mechanisms of polarized slow e^+ and attempt first to estimate the depolarization of the slow e^+ in materials arising from three basic processes such as multiple Coulomb scatterings, Bhabha scatterings and bremsstrahlungs. In Sec. II, we formulate the spin rotation of e^+'s under electric and magnetic fields on the basis of relativistic descriptions of spin motion. In Sec. III, we give theoretical description of the depolarizations, and then calculate the depolarizations of slow e^+'s in various materials utilized in the polarized slow-e^+ production

system, *i.e.* the target (Al), the absorber(Be) and the moderator(W, Pt and MgO). We compare our results with those measured by the experiments[1,2]. Section IV is devoted to summary and discussions.

II. SPIN MOTION IN ELECTRIC AND MAGNETIC FIELDS

For a charged particle, the motion of a spin vector $\vec{s}$ in the particle rest-frame is given as

$$\frac{d\vec{s}}{dt} = \frac{ge}{2m}\vec{s} \times \vec{B}^*, \tag{1}$$

where $\vec{B}^*$ is a magnetic field in the rest frame, e the elementary electric charge of the particle, m the particle mass, and g the gyromagnetic ratio.

In the relativistic description, a covariant form of the equation was obtained by Bargmann, Michel and Telegdi[4] as

$$\frac{dS^\alpha}{dt} = \frac{e}{mc}[\frac{g}{2}F^{\alpha\beta}S_\beta + \frac{1}{c^2}(\frac{g}{2}-1)U^\alpha(S_\lambda F^{\lambda\mu}U_\mu]. \tag{2}$$

Here $S^\alpha = (s^0, \vec{s})$ is a four-vector of spin, $U^\alpha = (u^0, \vec{u})$ a four-vector of particle velocity with $u^0 = \gamma$ and $\vec{u} = \gamma\vec{v}$ where $\vec{v}$ is a particle velocity and $\gamma = 1/\sqrt{(1-(v/c)^2)}$ the Lorentz factor, and $F^{\alpha\beta}$ an electromagnetic field tensor. Since in the rest frame of the particle, $\vec{v} = 0$ and $s^0 = 0$, the four-vectors have unit length:

$$U^\alpha U_\alpha = 1, \; S^\alpha S_\alpha = -1, \tag{3}$$

and a following relation is held:

$$S^\alpha U_\alpha = 0, \; or \; s^0 = \vec{s}\cdot\vec{v}. \tag{4}$$

When a relativistic particle moves in electric and magnetic fields, we can semiclassically describe the rotation of the spin direction of the particle as a following time evolution form:

$$\frac{d\vec{s}(t)}{dt} = \vec{s}(t) \times \vec{\Omega}(t), \tag{5}$$

where t is a time measured in the Laboratory frame and $\vec{\Omega}(t)$ an angular velocity of the rotation of the spin vector $\vec{s}(t)$ in the particle rest frame. The behavior of particle

momentum $\vec{p}(t)$ in the electric field $\vec{E}(t)$ and magnetic field $\vec{B}(t)$ is given as

$$\frac{d\vec{p}(t)}{dt} = e[\vec{E}(t) + \vec{v}(t) \times \vec{B}(t)]. \tag{6}$$

Here all quantities are defined in the Laboratory frame. Using Eqs.(2), (5) and (6), the angular velocity of the spin-rotation $\vec{\Omega}(t)$ is obtained as

$$\vec{\Omega}(t) = -\frac{eg}{2mc}[\frac{1}{\gamma^2}\vec{B}(t) + \frac{\gamma-1}{\gamma^2}\vec{l}(\vec{B}(t)\cdot\vec{l})] + [\frac{1}{2}(g-2)\frac{\gamma^2-1}{\gamma} + \frac{\gamma-1}{\gamma}]\vec{\Omega}_0(t), \tag{7}$$

where $\vec{l} = \vec{v}(t)/|\vec{v}(t)|$ represents the unit vector along the direction of the velocity, and $\vec{\Omega}_0(t) = \vec{l} \times \frac{d\vec{l}}{dt}$ the angular velocity of the particle momentum $\vec{p}(t)$. Equation (7) indicates that the spin direction is rotated by the magnetic field and through the change of the particle trajectory.

In absence of the magnetic field, the vectors $\vec{\Omega}(t)$ and $\vec{\Omega}_0(t)$ are parallel(or antiparallel) to each other and are related as

$$\vec{\Omega}(t) = [\frac{1}{2}(g-2)\frac{\gamma^2-1}{\gamma} + \frac{\gamma-1}{\gamma}]\vec{\Omega}_0(t). \tag{8}$$

If the trajectory of the particle in the electric field is a planar curve, $\vec{\Omega}(t)$ is parallel to $\vec{\Omega}_0(t)$, *i.e.* $\vec{\Omega}_0(t) = \Omega_0(t)\vec{n}$ and $\vec{\Omega}(t) = \Omega(t)\vec{n}$ where $\vec{n}$ is the unit vector of $\vec{l} \times \frac{d\vec{l}}{dt}$. If one may assume as in the ordinary case that the Lorentz factor γ is a constant in a single scattering, Eq. (8) can be integrated as

$$\theta = [\frac{1}{2}(g-2)\frac{\gamma^2-1}{\gamma} + \frac{\gamma-1}{\gamma}]\theta_0. \tag{9}$$

This implies that if the particle is scattered with a nucleus or an electron in the material with the angle θ_0, the spin direction will rotate with an angle θ in the scattering plane shown in Fig. 2, $\vec{p}$ ($\vec{s}$) being the momentum (spin) vector of particle (*i.e.* e^+) and the index of i (f) denoting the initial (final) state of the scattering.

III. DEPOLARIZATION IN MATERIALS

A. Basic processes of spin-precession

In order to calculate the angle θ of the spin precession on the basis of Eq. (9), we first consider angular distributions of possible three basic processes of slow e^+'s in materials, *i.e.* Coulomb scatterings, Bhabha scatterings and bremsstrahlungs.

The Coulomb scattering, which plays dominant role in the scattering processes of e^+'s in materials with low energy, is described by the electromagnetic interaction of the e^+ without energy loss in a Coulomb potential generated by a static point charge eZ, where Z represents the charge of a nucleus. Consequently, multiple Coulomb scatterings are series of Coulomb scatterings between a charged particle and nuclei, allowing us to describe the spin precession by Eq. (9). It is well known that the differential cross section of the Coulomb scattering for the e^+ can be described by the Mott scattering formula[5]:

$$\frac{d\sigma}{d\Omega} = \frac{Z^2\alpha^2}{4\beta^4 E^2 sin^4\frac{\theta_0}{2}}\left(1-\beta^2 sin^2\frac{\theta_0}{2}\right), \tag{10}$$

where E is a total energy of the e^+, β a relativistic velocity of the e^+, θ_0 a scattering angle in the e^+ rest frame and α a fine structure constant. For the e^+ with high energy, the scattering angle θ_0 is small resulting in a small depolarization in materials, while for the e^+ with low energy, the spin rotation angle θ becames small for $\gamma \sim 1$, *i.e.* $\theta < 0.02\theta_0$ for the energy less than $10keV$.

Bhabha scattering can be characterized as scattering of e^+ with e^- of atoms through core-e^- and valence-e^- excitations in the materials. The differential cross sections can be described by using Gryzinski's excitaion function[6] as

$$\begin{aligned}\frac{d\sigma(\Delta E)}{d\Delta E} &= \frac{\pi e^4}{(\Delta E)^3}\frac{E_B}{E}\left(\frac{E}{E+E_B}\right)^{\frac{3}{2}}\left(1-\frac{\Delta E}{E}\right)^{\frac{E_B}{E_B+\Delta E}} \\ &\cdot\left\{\frac{\Delta E}{E_B}\left(1-\frac{E_B}{E}\right)+\frac{4}{3}ln\left[2.7+\left(\frac{E-\Delta E}{E_B}\right)^{\frac{1}{2}}\right]\right\},\end{aligned} \tag{11}$$

where ΔE represents the energy loss, and E_B the mean e^- binding energy. Since Eq. (11) gives a only small energy loss in the excitaions, *i.e.* $\Delta E \sim E_B$, the spin precession

in the Bhabha scatterings can also be described well by Eq. (9).

The bremsstrahlung gives rise to the spin flip and thus induces depolarization measured as a difference of counting rates for positive and negative helicities of e^+'s in the final state. Assuming that the inital e^+'s are completely polarized, the depolarization D caused by the bremsstrahlung is given as

$$D = 1 - \frac{d\sigma(\lambda_f=+1)-d\sigma(\lambda_f=-1)}{d\sigma(\lambda_f=+1)+d\sigma(\lambda_f=-1)}, \tag{12}$$

where $d\sigma(\lambda_f=+1)$ and $d\sigma(\lambda_f=-1)$ represent the differential cross sections of the bremsstrahlung processes in which the parameter λ_f stands for the e^+ helicity in the final state. Using the differential cross sections, $d\sigma(\lambda_f=+1)$ and $d\sigma(\lambda_f=-1)$ calculated for a pure Coulomb field in Ref. 7, the depolarization of a completely polarized e^+ is represented as

$$D = \frac{2k^2}{6+3p_i^2+3p_f^2-2(1+p_i^2)^{1/2}(1+p_f^2)^{1/2}}, \tag{13}$$

where k is the energy of the bremsstrahlung radiation and $p_i(p_f)$ the initial(final) e^+ momentum. This implies that the depolarization effect due to bremsstrahlung is not so large for slow e^+'s since the probability of the bremsstrahlung radiation is very small and the energy of the bremsstrahlung radiation k is also very low.

B. A Monte Carlo simulation program

In order to estimate the depolarization of slow e^+ beams in materials, we have developed a simulation program SPPG(Slow Polarized Positron Generation) based on a detector simulation tool GEANT[8]. We attempte to incorporate in SPPG the depolarization effects caused by the multiple Coulomb scatterings, the Bhabha scattings and the bremsstrahlungs in materials described in Sec. III.A. To simulate the multiple Coulomb scatterings of low energy e^+, we use the Molière theory[9], which was later elaborated by Bethe[10]. Since this theory is applicable under limited conditions such as (1) small angular deflection and (2) small energy loss, we are forced to take a small step size in SPPG, namely 10 μm for the Al target and 5 μm for the W moderator. To check the validity of the simulation in the small step size, we compare our calculated results with experimental data[11] of the angular deflections of e^- with $15MeV$

passing through materials of Be and Au. As seen in Table I, the calculation is in good agreement with the measurements.

Since the cut-off energy of particles in GEANT code is $10keV$, the thermalization process cannot be simulated for the moderator. Therefore, we assume that e^+'s slowing down to $25keV$ in the moderator are thermalized within a virtual "skin" of thickness of $1000\mathring{A}$ which covers the surface of the moderator, and are reemitted as slow e^+'s from the moderator. The depolarization in the "skin" is negligible because $\theta < 0.05\theta_0$ in Eq. (9) for the energy of $< 25keV$.

Using SPPG, we simulated the depolarization arising from the multiple Coulomb scatterings of e^+'s with sufficient energy which can pass through $Be(Z = 4)$, $Al(Z = 13)$ and $W(Z = 74)$ with a thickness of $0.2mm$. As shown in Fig. 3, the depolarization is large at low energies, since the number of scatterings increases giving rise to large deflection as the initail energy decreases. The degree of depolarization is strongly dependent on the atomic number of materials. Figure 4 shows the results of the similar calculations carried out for the materials of the fixed thickness of $10mm$ in which the e^+'s lose whole energies and eventually stop. In this case, the depolarization becomes larger with increase of their initial energy and is saturated at the energy $> 4MeV$. These results allow us to conclude that the depolarization of e^+'s in materials is important only at the low energy.

We also calculated the depolarization effects caused by the Bhabha scatterings in Fig. 5 and the bremsstrahlungs in Fig. 6 for the e^+'s passing through the materials with a thickness of $0.2mm$. These depolarizations can be negligible comparing with that due to the multiple Coulomb scattering.

C. Applications in polarized slow-e^+ productions

SPPG can clarify detailed behavior of polarized slow e^+ produced in our apparatus[2,3] shown in Fig. 1. The radioisotope of ^{27}Si with the maximum β^+ energy of 3.85 MeV is produced in the Al target of a $2mm$ thickness via the $^{27}Al(p,n)^{27}Si$ reaction caused by proton irradiation. A portion of β^+'s produced in the Al target with wide energy spread is thermarized in the moderator of a $25\mu m$ thick polycrystal W foil and then are reemitted as slow e^+'s with the energy of $\sim 1eV$. Figure 7 shows the energy distributions

of (a) initial e^+'s produced inside the Al target from the β^+ decay of ^{27}Si and (b) e^+'s passing through the Al target. As shown in Fig. 7, only high energy e^+'s emitted from the β^+ decay of ^{27}Si can pass through the target. Although the e^+'s emitted from the β^+ decay are polarized with a longitudinal polarization of $P = \langle (v_i/c) cos\theta_i \rangle$ as indicated with the dashed lines in Fig. 8, they are depolarized in the Al target by 14% and in the W moderator by 4% as shown with the solid lines in Fig. 8(a) and (b), respectively, resulting in the average polarization of slow-e^+ beam to be 38.1±1.4% which is consistent with the measured value of 36.0±4.9% [2].

In order to check the validity of our simulation with respect to the depolarization and geometry, we estimate the polarization of slow-e^+ beam by inputing the same geometrical structure of devices as those used by the Michigan university group[1]. Figure 9 shows the geometries of each components, *e.g.* a β^+ source of ^{22}Na, a venetian-blind moderator, and a Be absorber with different thicknesses placed between the ^{22}Na source and the moderator. Two types of β^+ sources have been used: ^{22}Na deposited in a 60° half-angle cone drilled in Be holder resulting in emission into π-steradians(sr), and ^{22}Na deposited on an insulin wetting agent in a $0.25mm$ deep and $3.5mm$ diameter cylindrical depression milled in the Be holder resulting in emission into 2π-sr. Figure 10 shows the magnitude of the polarizations obtained from SPPG for the W moderator and 2π-sr source being in good agreement with the experimental results[1]. We also calculate the polarizations for the MgO moderator with the π-sr source and for the Pt moderator both with the π-sr and 2π-sr sources. It is clarified that: (1) the difference of polarizations for the different moderators is negligible because the depolarization in the thermalization process of e^+'s is negligible in these thin moderators; (2) the polarization is independent of the π-sr and 2π-sr sources, since e^+'s emitted backwards from the 2π-sr ^{22}Na source lose most of their energies in the Be holder and are absorbed in the Be holder or the Be absorber.

IV. SUMMARY AND DISCUSSIONS

The spin precession of polarized slow e^+'s has been investigated on the basis of three fundamental processes, *i.e.* multiple scattering, Bhabha scattering and bremsstrahlung. These processes are incorporated in the Monte Carlo simulation program, SPPG, which can simulate successfully the generation and depolarization of polarized slow e^+'s in various materials.

It is found that the depolarization is strongly dependent on the atomic number and the depolarization caused by Bhabha scatterings and bremsstrahlungs are negligible compared with that caused by the multiple scatterings. The magnitudes of the estimated polarizations of slow-e^+ beams are in good agreement with those measured in the experiments[1,2] indicating that our simulator can be a very effective and reliable tool for designing high-quality polarized e^+ beams.

However, there still remain unresolved problems of how to describe quantitatively a thermalization process of polarized slow e^+'s with the kinetic energy of $< 10keV$ in materials. The e^+'s lose cotinuously their energies to thermal energy by free e^- excitations, plasmon scatterings or e^--hole pair excitations, and then diffuse in lattices of materials. In the diffusion process, a dominant process is the e^+-phonon scatterings which cause the depolarization of the e^+'s. It would be highly desired that theoretical description on the fundamental processes is studied to enable more practical and reliable prescription of spin depolarization in the thermalization and diffusion processes.

ACKNOWLEDGMENTS

We thank Dr. M. Washio, Dr. M. Hirose and Dr. Y. Kurihara for valuable suggestions and fruitful discussions. This research was partially supported by a grand in Aid for Scientific Reseach from the Ministry of Education, Science, Sports and Culture of Japan and Proposal-Based Advanced Industrial Technology R&D Program from the New Energy and Industrial Technology Development Organization (NEDO) of Japan.

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Table 1: Comparision the angular deflections of e^-'s passing through Be and Au targets estimated by our simulation with that measured by Hanson *et al*[11].

Material	Be		Au
Thickness (mg/cm^2)	257.00	491.30	18.66
Initial energy of e^-'s (MeV)	15.47	15.24	15.69
Angular deflection ($degree$)			
in experiment[11]	3.01	4.33	2.55
in our simulation	2.94±0.03	4.39±0.04	2.46±0.03

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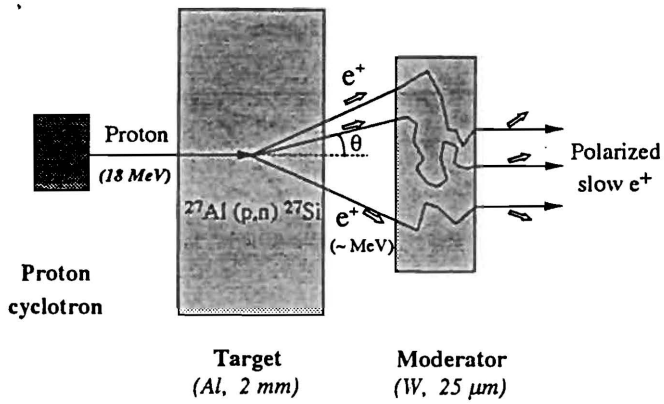

Figure 1: Production of polarized slow e^+'s using proton beams of $18MeV$.

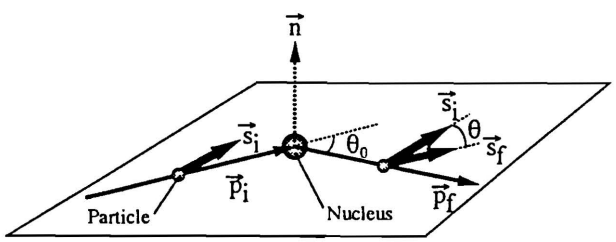

Figure 2: Spin rotation of a charged particle during the Coulomb scattering with a nucleus in materials. Various quantities are defined in the text.

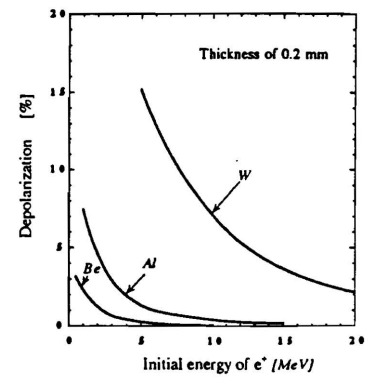

Figure 3: Simulation of the depolarization caused by multiple Coulomb scatterings for the polarized e^+'s passing through materials, *i.e.* W, Al and Be with a thickness of $0.2mm$.

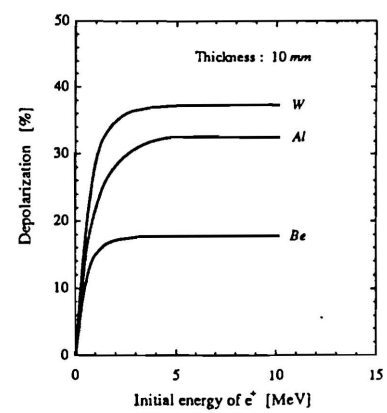

Figure 4: Simulation of the depolarization caused by multiple Coulomb scatterings for the polarized e^+'s stopping in materials, *i.e.* W, Al and Be with a thickness of $10mm$.

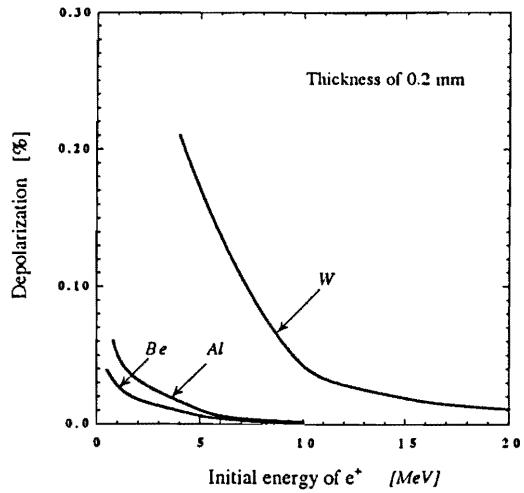

Figure 5: Simulation of the depolarization caused by Bhabha scatterings for the polarized e^+'s passing through materials, *i.e.* W, Al and Be with a thickness of $0.2mm$.

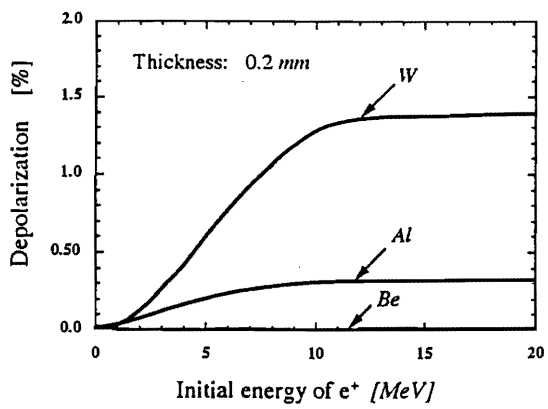

Figure 6: Simulation of the depolarization caused by bremsstrahlungs for the polarized e^+'s passing through materials, *i.e.* W, Al and Be with a thickness of $0.2mm$.

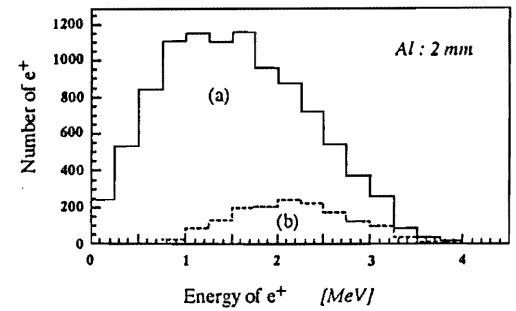

Figure 7: Energy distributions of (a) initial e^+'s produced inside the Al target through the β^+ decay of ^{27}Si and of (b) e^+'s passing through on the Al target in Fig. 1.

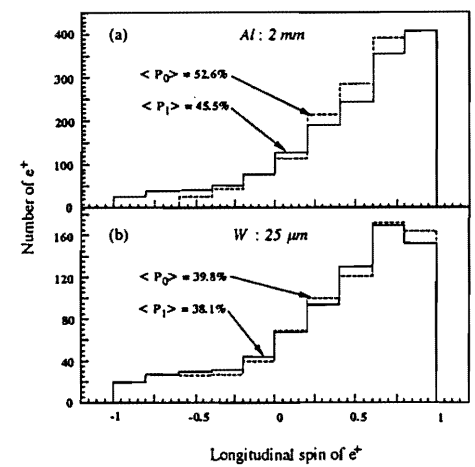

Figure 8: Simulation of longitudinal spins of (a) e^+'s which pass through the Al target and of (b) slow e^+'s which are remitted from the surface of the W moderator. The solid line represents the longitudinal spins P_1 of the e^+'s with depolarization in the Al target or W moderator, while the dashed line represents the longitudinal spins P_0 of the e^+'s without depolarization in the Al target or W moderator. The average values of P_0 and P_1 are also given both for Al and W.

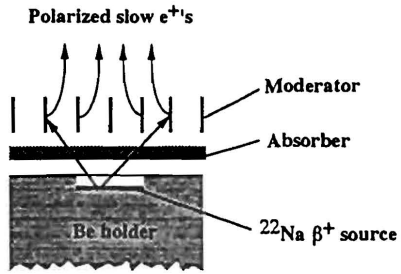

Figure 9: Production of polarized slow e^+'s using a ^{22}Na source.

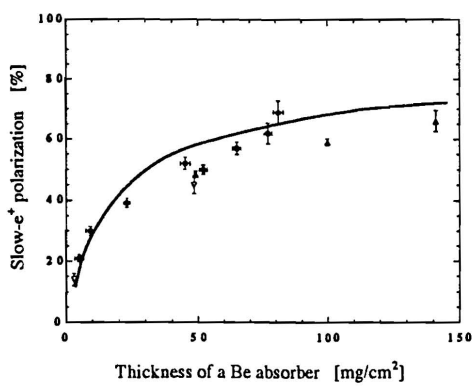

Figure 10: Polarization of slow e^+'s with different thickness of a Be absorber using the production system described in Fig. 9. The dot is measured using the geometries of (1)the π-sr source with the Pt(o) or MgO(•) moderators, and (2)the 2π-sr source with the Pt(▽) or W(△) moderators by the group of Michigan university. The solid curve is estimated by SPPG using the geometries of 2π-sr source with the W moderator.