

Positron and Spintronics

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When both positrons and electrons are spin-polarized, electron-positron momentum distribution exhibits asymmetry upon their mutual spin reversal. Annihilation of positronium formed on metal surface also shows spin-reversal asymmetry. These properties are demonstrated to be useful in studying ferromagnetic band structure and surface magnetism, respectively. Here, we call positron annihilation spectroscopy, which particularly uses the spin dependent annihilation process, spin-polarized positron annihilation spectroscopy (SP-PAS). In the spintronics field, SP-PAS will be a potential tool in revealing spin-related phenomena, such as magnetoresistance, current-induced spin polarization, spin-injection, vacancy-induced magnetism, half-metal band structures and so on. To promote spintronics study with SP-PAS, spin-polarized positron beam is needed. In this talk, I will report the development of spin-polarized positron beam, some fundamental aspect of SP-PAS and its applications to spintronics study performed so far.

陽電子とスピントロクス

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陽電子と電子の両方がスピン偏極している場合、電子-陽電子運動量分布は互いのスピン反転に対して非対称性を示す。金属表面で形成されるポジトロニウムの消滅も、同様にスピン反転非対称性を示す。これらの特性は、強磁性バンド構造や表面磁性の研究に有用であることが示されている。ここで、スピンに依存した陽電子消滅過程を利用する陽電子消滅法を特にスピン偏極陽電子消滅法と呼ぶことにする。近年急速に進展しているスピントロクス分野において、スピン偏極陽電子消滅法は各種のスピン現象（磁気抵抗、電流誘起スピン分極、スピン注入、空孔誘起強磁性、ハーフメタルバンド構造など）を解明する上で、有用なプローブになると期待される。スピン偏極陽電子消滅法を用いてスピントロクス研究を推進するためには、スピン偏極陽電子ビームが必要である。本講演では、スピン偏極陽電子ビームの開発、及び、スピン偏極陽電子消滅法の基礎とこれまで講演者等が行った幾つかの応用研究について報告し、将来の展開を模索したい。

JAEA

陽電子+スピトロニクス Positron and Spintronics

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- ◆ About SP-PAS
- ◆ Our Research and Development
- ◆ 3d and 4f ferromagnets
- ◆ Spin Hall effect on Pt surfaces
- ◆ Summary

◆ About SP-PAS

Historical background
 > ACAR : Ferromagnetic band structures since 1957 (USA, Netherland, Switzerland, UK, India, Japan ...)
 > Surface Ps : Surface magnetism in 1980 (USA)

Present needs in materials science

Spintronics R & D

Bulk/Thin film

Half Metals

Vacancy-induced magnetism

DMS, SnO₂, CeO₂...

Surface/Interface

Magnetoregistance

Spin Hall effect

Spin-injection

◆ About SP-PAS

Case A Internal annihilation

After Berko 1967
 MD in positive and negative fields

$$N_{\text{ann}}(p_z) = \frac{1}{4} \sum_{\lambda} \left[\frac{(1 \pm P) N_{\lambda}^+(p_z)}{\lambda^2} + \frac{(1 \mp P) N_{\lambda}^-(p_z)}{\lambda^2} \right]$$

Spin dependent lifetime
 $\lambda^{\pm 1/2} = \frac{1}{2} \sum_{\lambda} [v_{\lambda}^{\pm 1/2} + \lambda_z (v_{\lambda}^{\pm 1/2} + 2v_{\lambda}^{\pm 1/2})]$

Wavefunction overlapping
 $v_{\lambda}^{\pm 1/2} = \int |\psi_{\lambda}^{\pm 1/2}(p, \lambda)|^2 dp$

Differential MD between maj. and min. bands
 $\sum_{\lambda} [N_{\lambda}^+(p_z) - N_{\lambda}^-(p_z)] \propto \Delta N + P \frac{\lambda^+ - \lambda^-}{\lambda^+ + \lambda^-} \Sigma N$

$$\approx \Delta N + P^2 \Sigma N$$

Asymmetry on Momentum Distribution
 $\Delta N(p) = N_+(p) - N_-(p) \neq 0$

Annihilation Lifetime
 $\Delta L(t) = L_+(t) - L_-(t) \neq 0$

Lifetime spectra in positive and negative fields
 $L_{\text{ann}}(t) = \frac{1}{4} \sum_{\lambda} [v_{\lambda}^+(1 \pm P) \exp(-\lambda^2 t) + v_{\lambda}^-(1 \mp P) \exp(-\lambda^2 t)]$

◆ About SP-PAS

Case B Surface Ps annihilation c.f. Gidley 1980

vacuum e+ sample

More S=1
 More 3-γ decay

Less S=1
 Less 3-γ decay

Asymmetry on 3-γ annihilation probability
 $\frac{F_{P_2}^{3\gamma}(+)}{F_{P_2}^{3\gamma}(-)} - \frac{F_{P_1}^{3\gamma}(+)}{F_{P_1}^{3\gamma}(-)} \neq 0$

Surface polarization directly determined

$$F_{P_3}^{3\gamma} = (1 - P_z P_s \cos \phi) / 4$$

$$F_{P_1}^{3\gamma} = (1 - P_z P_s \cos \phi) / 4$$

$$F_{P_2}^{3\gamma} = (1 + P_z P_s \cos \phi + P_z P_s \cos \phi) / 4$$

$$F_{P_1}^{3\gamma} = (1 - P_z P_s \cos \phi + P_z P_s \cos \phi) / 4$$

Total 3γ fraction
 $F_{P_2}^{3\gamma} = \varepsilon(1)(F_{P_3}^{3\gamma} + F_{P_1}^{3\gamma}) + \varepsilon(0)F_{P_2}^{3\gamma}$

Doppler meas. Lifetime meas.
 $R = \frac{(1 - F_{P_2}^{3\gamma})R_0 + F_{P_2}^{3\gamma}R_1/P_0}{1 - F_{P_2}^{3\gamma} + F_{P_2}^{3\gamma}P_1/P_0}$

Asymmetry of 3γ fraction
 $A = \frac{\Delta R(+)-\Delta R(-)}{\Delta R(+)+\Delta R(-)} = \frac{I_{\text{slow}}(+)-I_{\text{slow}}(-)}{I_{\text{slow}}(+)+I_{\text{slow}}(-)}$

◆ Our R&D

Spin-Polarized Positron Source & Beam

- Highly Spin-Polarized Positrons
- ²²Na P=70%
- ⁶⁸Ge-⁶⁸Ga P=94%
- Energy tunability
- 10eV(0.1nm) - 10keV(100nm)
- Polarization switchability
- Longitudinal/Transverse

Foundation of SP-PAS method

- Influence of magnetic field on positron annihilation
- Theoretical calculation
- 3d(Fe, Co, Ni), 4f(Gd, Tb, Dy)...
- First principles calculation

Application of SP-PAS to Spintronics Studies

- Spin Hall effect
- Spin-injection
- Heusler alloys
- Vacancy-induced magnetism
-etc

DBAR measurement

◆ Our R&D

Energy selector Electrostatic lenses Sample chamber

EB spin rotator

⁶⁸Ge-⁶⁸Ga / ²²Na

Flux ~ 5x10¹³ e⁺/s
 P: 30~35%

Polarization Transverse Longitudinal

Electric deflection Magnetic deflection

◆ SP-PAS on 3d and 4f ferromagnets

Field reversal asymmetry of momentum distribution

$$N_+(p_z) - N_-(p_z) = \frac{P}{2} \sum_{\lambda} \left[\frac{N_{\lambda}^+(p_z)}{\lambda^2} - \frac{N_{\lambda}^-(p_z)}{\lambda^2} \right]$$

Diagram showing pole pieces, sample, source, detector, and differential spectrum.

◆ SP-PAS on 3d and 4f ferromagnets

AN(p) (arb. units)

Electron momentum p (10⁻² m₀c)

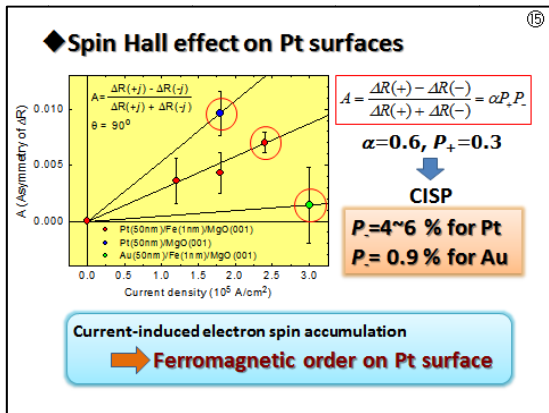
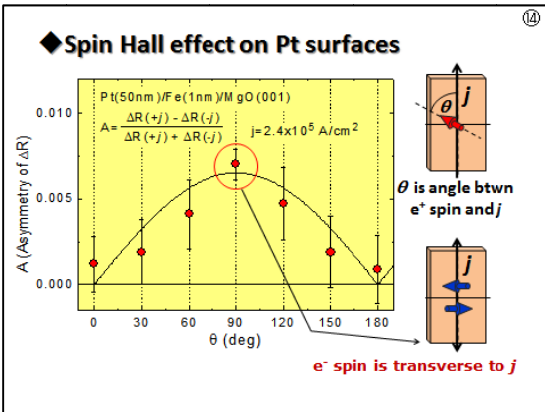
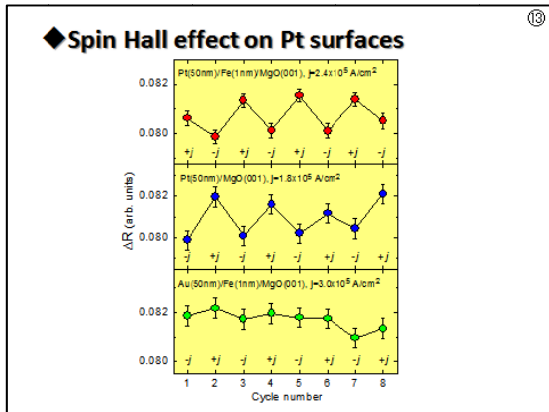
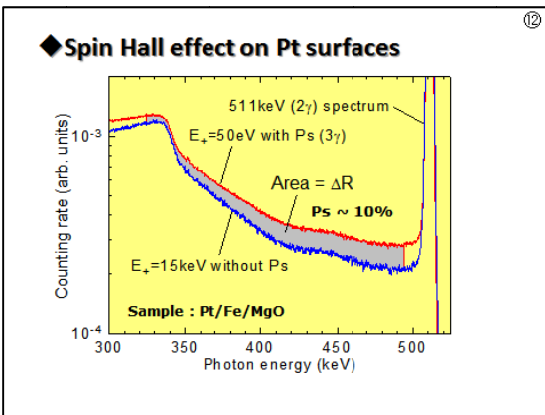
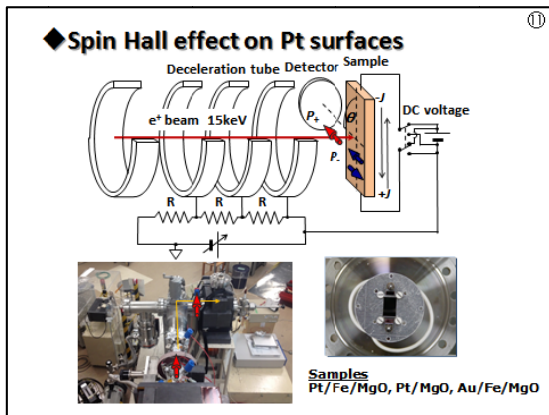
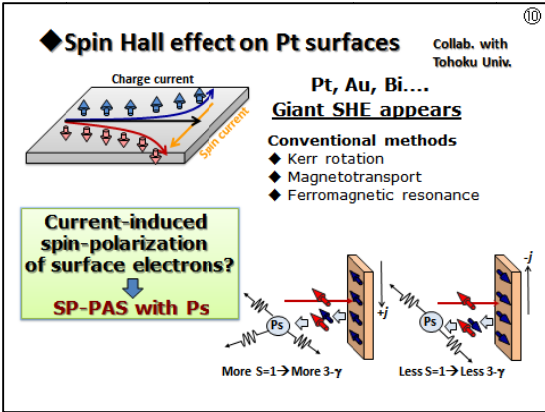
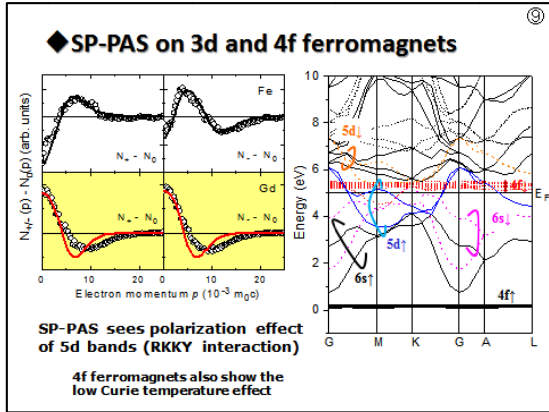
Electron momentum p (10⁻² m₀c)

Intensity 2.2 : 1.6 : 0.4
 M_S (μ_B) 2.2 : 1.7 : 0.6

Fe > Co > Ni

Ferromagnetic band structure

PR883(2011)100406(R). PR885(2012)024417.



◆ Summary

▶ We are developing spin-polarized positron source & beam.

▶ We demonstrated SP-PAS experiments for simple 3d and 4f ferromagnets and current-induced spin accumulation on Pt surfaces.

▶ SP-PAS will be an unique method in spintronics study.

Spin-polarized Spatially-focused Short-pulsed Intense

Ultimate Positron Beam

Many applications in spintronics
Half-Metals
Surface magnetism
Vacancy-induced magnetism
Spin accumulation / transportation
...ETC