Observation of the surface states in topological (Kondo) insulator Sm(Yb)B$_6$ and BiTeCl

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ARPES study on the surface states of SmB6 and YbB6

STM study on the surface states of BiTeCl
SmB$_6$ – a “mystery” Kondo insulator?

4f–5d hybridization  Saturated resistivity  Topological Kondo insulator

High T

Low T

Origin of the “in-gap” states?


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SmB$_6$ – recent experiment evidence of TKI

Surface conductivity at low T

Surface hall effect

Point contact


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Sample characterization

X-Ray Diffraction

LEED pattern

Magnetoresistance vs. T

(100) face 1x1

Negative magnetoresistance in low temperature!

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ARPES: Valence band structure

Localized 4f band located at -18 meV, -150 meV and -950 meV.

A parabolic 5d band around X point.

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In-gap states: $\alpha$

25 eV @ 8 K

Fermi surface mapping

Cut along $X$, $\alpha$ band

$\beta$ and $\delta$ bands should be originated from 5d band after hybridization.

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In-gap states: $\gamma$

Surface states??

$\gamma$ bands more observable in 2nd BZ.

Linear dispersion of $\gamma$ bands.

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Negligible $k_z$ dependence for $\alpha$ band.

Surface States!
Chirality of orbital angular momentum in $\alpha$ band.

Intensity inversion between RCP and LCP data in $\gamma$ band.

Possible topological origin!

ARPES: $T$ dependence of $\alpha$ band

$\alpha$ and $\beta$ bands vanish or merge into one 5d band at high temperatures.
Possible TI candidate: $\text{YbB}_6$

Larger band gap than SmB$_6$

$31 \text{ meV}$ vs $10 \text{ meV}$

Metallic behavior in resistivity!

Topological insulator?
Non-dispersive Yb 4f bands are located at around 1 eV and 2.3 eV below Fermi energy.

An elliptical Fermi pocket located around $X$ and a circular Fermi pocket around $\Gamma$ are clearly observed.
Near $E_F$ dispersive states

Both the $\alpha$ band around $\Gamma$ and $\beta$ band around $X$ show almost linear dispersion.

The band top of the $\gamma$ band overlaps with the band bottom of $\alpha$ band in some energy range.
Near $E_F$ dispersive states

Bulk conduction $\delta$ band has been observed around the $X$ point.
Negligible $k_z$ dependence for $\alpha$ band.
Negligible $k_z$ dependence for $\beta$ band.
Summary

- SmB$_6$, identified almost linear dispersive states around $\Gamma$ and $X$;

- Circular dichroism of the surface states indicate their possible topological origin;

- Temperature dependence data shows the hybridization of 4f-5d bands across the Kondo temperature.

- SmB$_6$ is likely a Topological Kondo Insulator.
ARPES study on the surface states of SmB6 and YbB6

STM study on the surface states of BiTeCl
Structure of BiTeCl (Br, I)

BiTeCl (Br, I)

inversion-symmetry breaking

Polarized surface, Rashba p-n junction

M. Sakano et al., PRL110, 107204 (2013)  
Giant Rashba-type splitting in BiTeCl (Br, I)

Possible topological surface states in BiTeCl

Y. L. Chen et al., Nat. Phys. 9, 704 (2013)
Quasi-particle interference on BiTeCl

Scattering direction changes with energy!

-200mV---75mV: along Γ-M direction

Above 75mV: along Γ-K direction
Dispersions of $q$ vectors

$\Gamma$-M direction

$\Gamma$-K direction

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Origin of the two $q$ vectors

$q_1$ along direction is likely from topological surface states, like $\text{Bi}_2\text{Te}_3$, the back scattering is prohibit.

$q_2$ could be a rashba like surface states, in which the back scattering is still possible.
Summary

- Two branch of dispersive surface states are observed at BiTeCl surface.
- One of them is likely to be topological surface states without back scattering
Thank you!
Angle-resolved photoemission spectroscopy


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拓扑表面态是受到时间反演对称性保护的，在表面准粒子散射图像中，表现为非磁性杂质造成的背散射完全被压制。
Conclusion I

线性色散: $q_2$, $\Gamma$-$M$, Dirac cone
抛物线色散: $Q_1$, $\Gamma$-$K$, SCB
抛物线色散: $Q_4$, $\Gamma$-$M$, SCB
Type II: Dirac cone, topological surface state in BiTeCl.
Summary of YbB$_6$

- Identified almost linear dispersive surface states around Γ and X;
- The total number of surface state is odd;
- Circular dichroism of the surface states indicate their possible topological origin;
- The bulk insulating gap might be around 100meV

Unsolved issues
  - Two fold symmetry of circular dichroism in α band?
Angle-resolved photoemission spectroscopy

Kinetic Energy ($E_{kin}$)
Momentum ($\mathbf{k}$)

High energy resolution
Momentum space

$E_{kin} = h\nu - |E_B| - \varphi$
$p_\parallel = \hbar k_\parallel = \sqrt{2mE_{kin}} \sin \theta$

UHV - Ultra High Vacuum ($p < 10^{-7}$ mbar)

Juan Jiang, Fudan University, 2014 ALS user meeting, Berkley, ARPES study on the surface states in hexaborides SmB$_6$ and YbB$_6$. 
Spin polarized topological nontrivial surface states!


Spin polarized topological nontrivial surface states!

Spin polarized

Circular Dichroism ARPES


Spin polarized topological nontrivial surface states!

Odd number of Fermi pockets enclose the Kramers points!

topological nontrivial


Both $\alpha$ and $\gamma$ bands are likely to be topologically non-trivial!

The total number of surface state is odd!
ARPES: T dependence of α band

Juan Jiang, Fudan University, 2014 ALS user meeting, Berkley, ARPES study on the surface states in hexaborides SmB$_6$ and YbB$_6$. 
Linear dispersion of $\alpha$ bands.

$\alpha$ band goes straight through $\phi$ and coexists with $\beta$ band.
Sample 1 @ Hisor

Sample 2 @ SLS
**k\_z dependence of 5d band**

**5d band along cut #1**

Poor k\_z resolution to distinguish the strong k\_z dispersion of the 5d band.
Bulk origin of $\gamma$ band.

Surface States!

$k_z$ mapping

Odd FSs!

Obvious 2D nature of the $\alpha$ and $\beta$ bands, 3D nature of $\gamma$ band.
The energy position of the crossing point shifted about 500 meV.

β’ band is the lower cone of β?  

-320 meV

+180 meV
100 meV band gap!

Juan Jiang, Fudan University, 2014 ALS user meeting, Berkley, ARPES study on the surface states in hexaborides SmB$_6$ and YbB$_6$. 

Schematic band structure of YbB$_6$:
The CD of the $\beta$ pocket shows an anti-symmetric pattern about the $\Gamma$-$X$ axis in the surface BZ.

The CD of the α pocket shows a two-fold symmetry!
The CD both $\alpha$ and $\beta$ can be well fitted by a sine function.

However, the period for $\beta$ is $2\pi$, while that for $\alpha$ is $\pi$.

Chiral OAM!

Surface reconstruction?

1x2 reconstruction

Circular Dichroism ARPES

The spin polarization of the initial state and the helicity of light determines the matrix element and the intensity.
Circular Dichroism ARPES