Revisit the mysterious 3.5 keV line at the laboratory

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Institute of Modern Physics, Chinese Academy of Sciences (Lanzhou)

June 20, 2024   Volos, Greece

Outline

- Introduction
- Experimental setup
- Results
- Summary

Dark matter detection: an unidentified 3.5 keV X-ray

THE ASTROPHYSICAL JOURNAL, 789:13 (23pp), 2014 July 1 doi:10.1088/0004-637X/789/1/13

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

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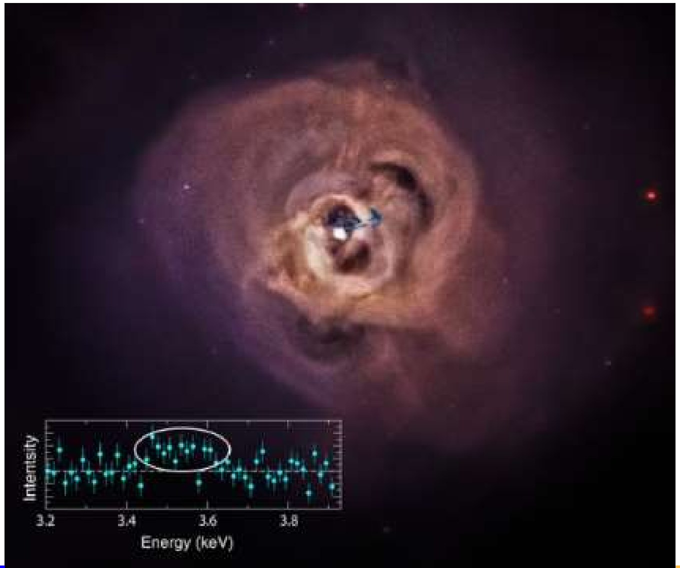
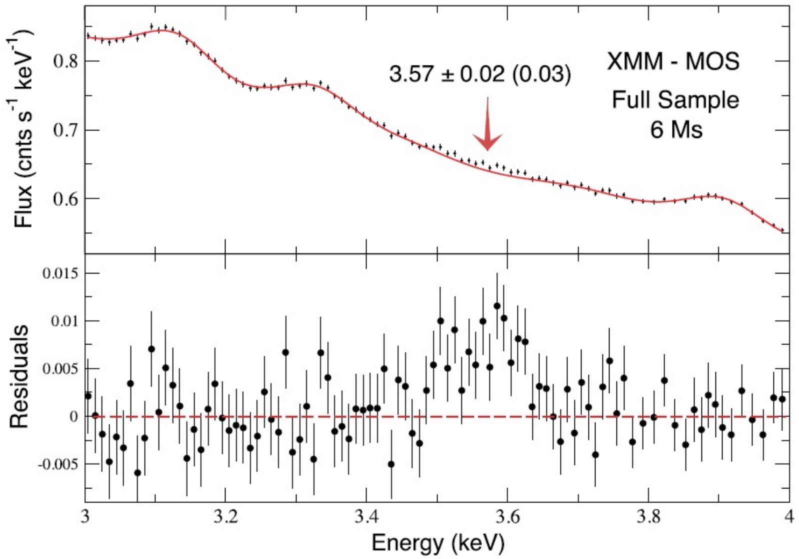
Received 2014 February 10; accepted 2014 April 28; published 2014 June 10

XMM-Newton spectrum

Three subsamples: (Perseus, Centaurus+Ophiuchus +Coma, and all others)





Dark matter detection: an unidentified 3.5 keV X-ray

Selected for a Viewpoint in *Physics*
PRL **113,** 251301 (2014) PHYSICAL REVIEW LETTERS week ending 19 DECEMBER 2014

Unidentified Line in X-Ray Spectra of the Andromeda Galaxy and Perseus Galaxy Cluster

A. Boyarsky,[1] O. Ruchayskiy,[2] D. Iakubovskyi,[3,4] and J. Franse[1,5]
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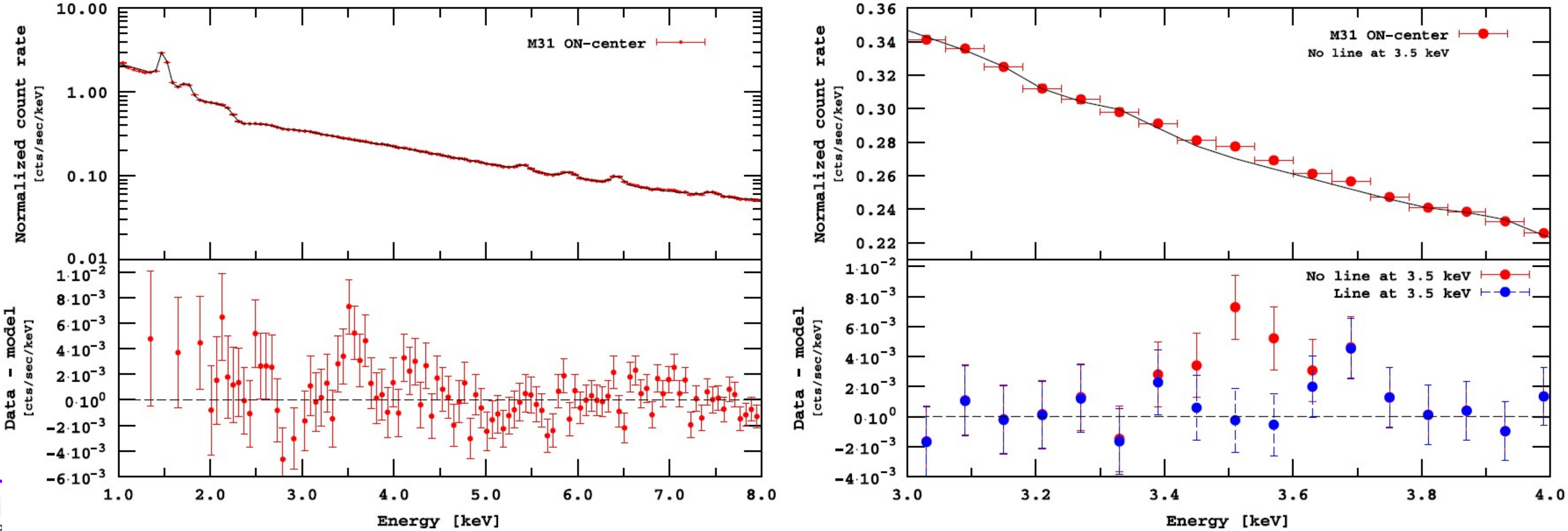

Detection of an unidentified emission line in the stacked X-ray spectrum of galaxy clusters

E Bulbul, M Markevitch, A Foster, RK Smith, M Loewenstein, SW Randall

The Astrophysical Journal, 2014 • iopscience.iop.org

Abstract

We detect a weak unidentified emission line at E=(3.55–3.57)±0.03 keV in a stacked XMM-Newton spectrum of 73 galaxy clusters spanning a redshift range 0.01–0.35. When the full sample is divided into three subsamples (Perseus, Centaurus+ Ophiuchus+ Coma, and all others), the line is seen at> 3σ statistical significance in all three independent MOS spectra and the PN" all others" spectrum. It is also detected in the Cha
Perseus Cluster. However, it is very weak and located within 50–110 e

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Unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

A Boyarsky, O Ruchayskiy, D Iakubovskyi, J Franse

Physical review letters, 2014 • APS

Abstract

We report a weak line at 3.52±0.02 keV in x-ray spectra of the Andromeda galaxy and the Perseus galaxy cluster observed by the metal-oxide-silicon (MOS) and p-n (PN) CCD cameras of the XMM-Newton telescope. This line is not known as an atomic line in the spectra of galaxies or clusters. It becomes stronger towards the centers of the objects; is stronger for Perseus than for M31; is absent in the spectrum of a deep "blank sky" data set. Although for each object it is hard to exclude that the feature is due to an instrumental

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Dark matter detection: an unidentified 3.5 keV X-ray

MNRAS **451**, 2447–2461 (2015) doi:10.1093/mnras/

A *Suzaku* search for dark matter emission lines in the X-ray brightest galaxy clusters

O. Urban,[1,2,3★] N. Werner,[1,2] S. W. Allen,[1,2,3] A. Simionescu,[4] J. S. Kaastra[5] and L. E. Strigari[6]

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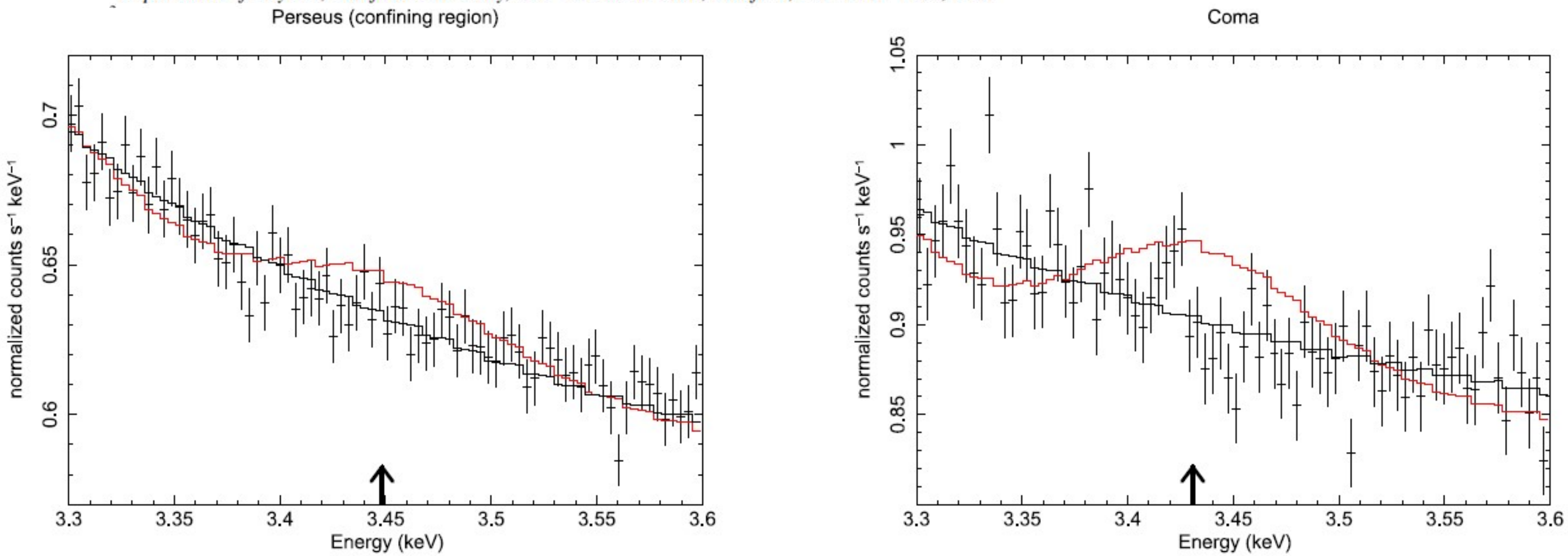
[2] *Department of Physics, Stanford University, 382 Via Pueblo Mall, Stanford, CA 94305-4060, USA*



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PRL **115**, 161301 (2015) PHYSICAL REVIEW LETTERS week ending 16 OCTOBER 2015

Checking the Dark Matter Origin of a 3.53 keV Line with the Milky Way Center

A. Boyarsky,[1] J. Franse,[1,2] D. Iakubovskyi,[3] and O. Ruchayskiy[4]
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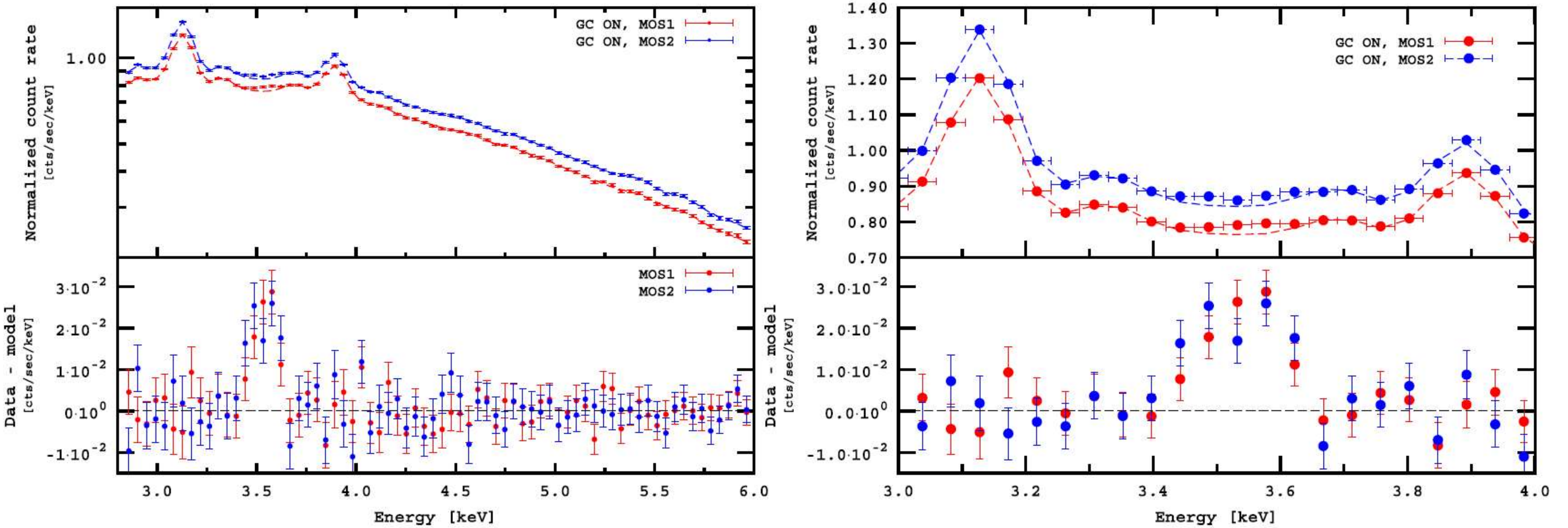


A&A 584, L11 (2015)
DOI: 10.1051/0004-6361/201527634

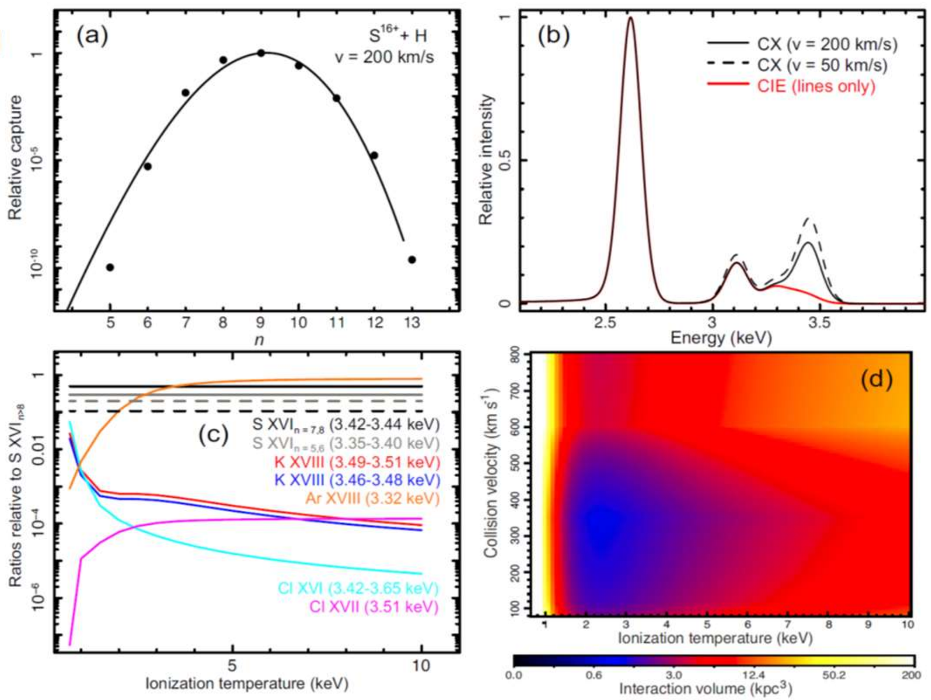
Astronomy & Astrophysics

LETTER TO THE EDITOR

A novel scenario for the possible X-ray line feature at ~3.5 keV

Charge exchange with bare sulfur ions

L. Gu[1], J. Kaastra[1,2], A. J. J. Raassen[1,3], P. D. Mullen[4], R. S. Cumbee[4], D. Lyons[4], and P. C. Stancil[4]



The distinguished line emissions spectral for CIE and charge exchange

Motivated by recent claims of a compelling ~3.5 keV emission line from nearby galaxies and galaxy clusters, we investigate a novel plasma model incorporating a charge exchange component obtained from theoretical scattering calculations. Fitting this kind of component with a standard thermal model yields positive residuals around 3.5 keV, produced mostly by S XVI transitions from principal quantum numbers $n \geq 9$ to the ground. Such high-n states can only be populated by the charge exchange process. In this scenario, the observed 3.5 keV line flux in clusters can be naturally explained by an interaction in an effective volume of ~1 kpc^3 between a ~3 keV temperature plasma and cold dense clouds moving at a few hundred keV^{-1}. The S XVI lines at ~3.5 keV also provide a unique diagnostic of the charge exchange phenomenon in hot cosmic plasmas.

THE ASTROPHYSICAL JOURNAL, 833:52 (7pp), 2016 December 10 doi:10.3847/1538-4357/833/1/52

CrossMark

LABORATORY MEASUREMENTS COMPELLINGLY SUPPORT A CHARGE-EXCHANGE MECHANISM FOR THE "DARK MATTER" ~3.5 keV X-Ray LINE

CHINTAN SHAH[1], STEPAN DOBRODEY[1], SVEN BERNITT[1,2], RENÉ STEINBRÜGGE[1,5], JOSÉ R. CRESPO LÓPEZ-URRUTIA[1], LIYI GU[3], AND JELLE KAASTRA[3,4]
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[2] Institut für Optik und Quantenelektronik, Friedrich-Schiller-Universität, D-07743 Jena, Germany
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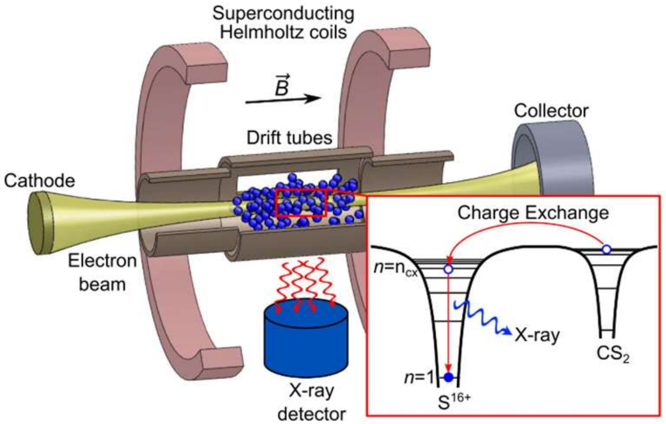
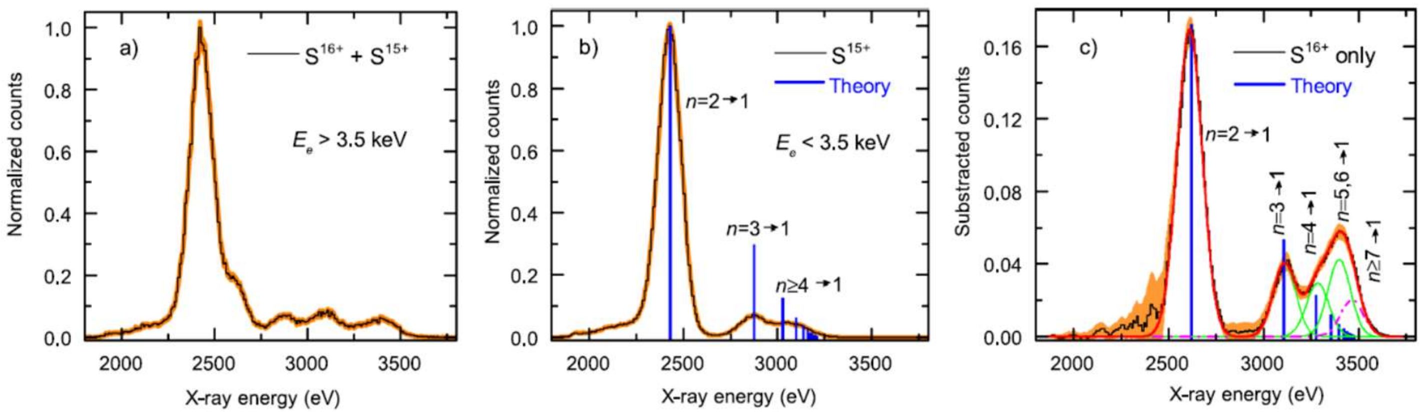
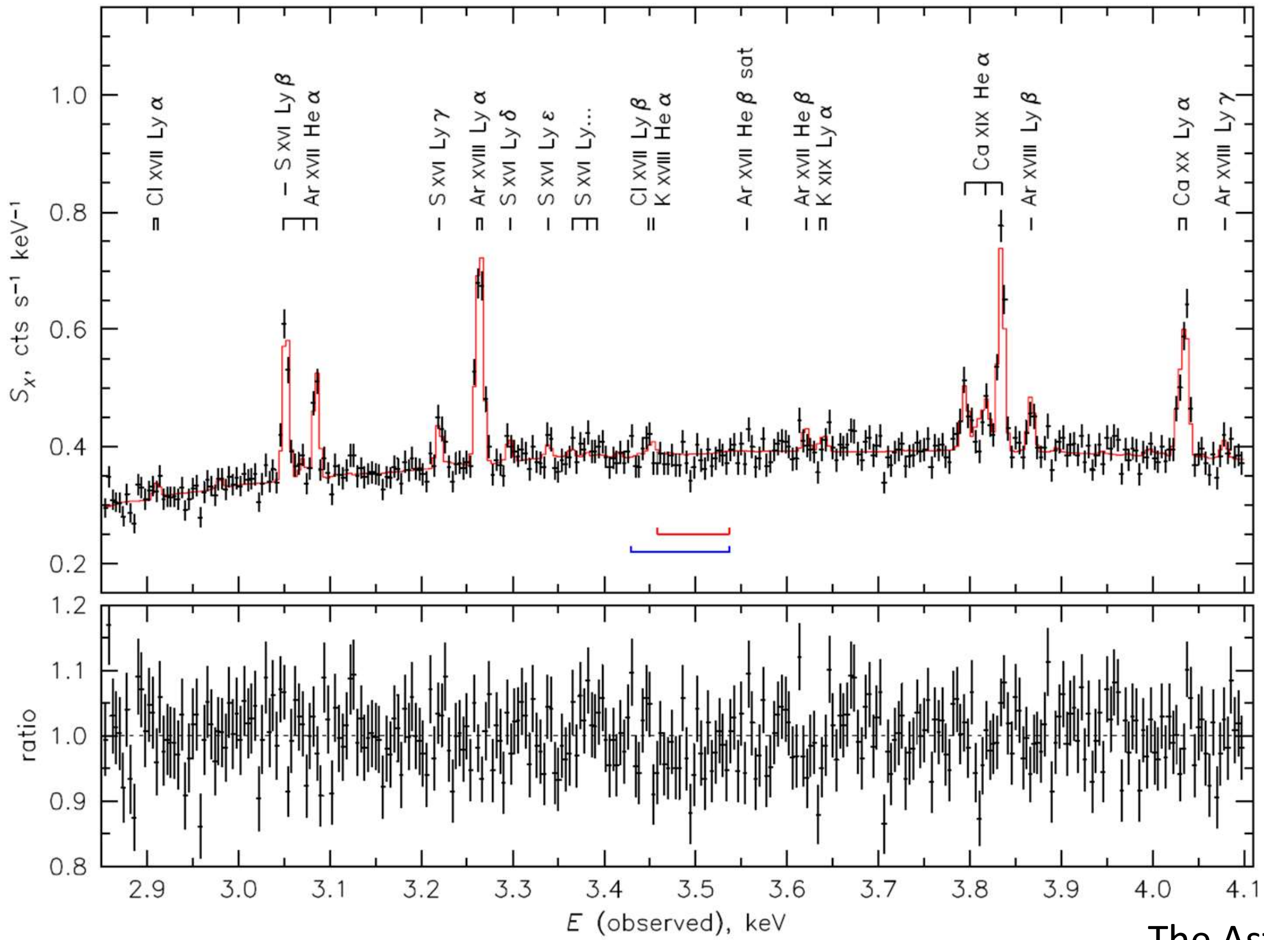
[4] Leiden Observatory, Leiden University, P.O. Box 9513, 2300 RA Leiden, The Netherlands
Received 2016 June 9; revised 2016 August 12; accepted 2016 August 15; published 2016 December 7





SXV SXVI

Hitomi Constraints on the 3.5 keV Line in the Perseus Galaxy Cluster



Important spectral lines:

sulfur and argon

The Astrophysical Journal Letters, 837:L15 (2017)

ASTROPARTICLE PHYSICS

The dark matter interpretation of the 3.5-keV line is inconsistent with blank-sky observations

Christopher Dessert[1], Nicholas L. Rodd[2,3], Benjamin R. Safdi[1*]

Observations of nearby galaxies and galaxy clusters have reported an unexpected x-ray emission line around 3.5 kilo–electron volts (keV). Proposals to explain this line include decaying dark matter —in particular, that the decay of sterile neutrinos with a mass around 7 keV could match the available data. If this interpretation is correct, the 3.5-keV line should also be emitted by dark matter in the halo of the Milky Way. We used more than 30 megaseconds of XMM-Newton (X-ray Multi-Mirror Mission) blank-sky observations to test this hypothesis, finding no evidence of the 3.5-keV line emission from the Milky Way halo. We set an upper limit on the decay rate of dark matter in this mass range, which is inconsistent with the possibility that the 3.5-keV line originates from dark matter decay.

Dessert et al., Science 367, 1465–1467 (2020)

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SciPost Phys. Lect. Notes 53 (2022)

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There are a number of prospects for probing the 3.5 keV line with upcoming experiments:

- The eROSITA X-ray telescope was launched in 2019 and is currently performing an all-sky survey. Its sensitivity after four years should be sufficient to detect or exclude the line [184], although its energy resolution (∼ 120 eV) will not be good enough to resolve the shape of the line.
- eXTP is an X-ray timing and polarimetry mission with a target launch date of 2025. While it is not designed for DM searches, its large field of view and effective area should give it excellent sensitivity to sterile neutrinos [185], although again it will not have the energy resolution to resolve the lineshape.
- The Micro-X sounding rocket program [186,187] offers the possibility of eV-scale energy resolution in the relatively near term. By placing high-resolution X-ray spectrometers on suborbital sounding rockets, this approach would achieve excellent energy resolution – as low as 3 eV – for modest cost. The exposure would be short – 5 minutes – and there would be essentially no pointing information, but the instrument's field of view would be large, with roughly a 20 degree radius. The strategy would be to search for a DM decay signal from the local Galactic halo, rather than from localized targets such as galaxy clusters and the Galactic Center; Micro-X should have the sensitivity to observe the line even with such short flights. Micro-X flew an initial flight (not for a DM search) in 2018.

Was There a 3.5 keV Line?

Christopher Dessert[1,2], Joshua W. Foster[3], Yujin Park[4,5], and Benjamin R. Safdi[4,5]
[1] Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003, USA
[2] Center for Computational Astrophysics, Flatiron Institute, New York, NY 10010, USA
[3] Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
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[5] Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
Received 2023 September 30; revised 2024 January 23; accepted 2024 January 30; published 2024 March 29

The 3.5 keV line is a purported emission line observed in galaxies, galaxy clusters, and the Milky Way whose origin is inconsistent with known atomic transitions and has previously been suggested to arise from dark matter decay. We systematically reexamine the bulk of the evidence for the 3.5 keV line, attempting to reproduce six previous analyses that found evidence for the line. We only reproduce one of the analyses; in the other five, we find no significant evidence for a 3.5 keV line when following the described analysis procedures on the original data sets. For example, previous results claimed 4σ evidence for a 3.5 keV line from the Perseus cluster; we dispute this claim, finding no evidence for a 3.5 keV line. We find evidence for background mismodeling in multiple analyses. We show that analyzing these data in narrower energy windows diminishes the effects of mismodeling but returns
existence of the 3.5 keV line.
to the earlier reliance on local
cibility, all code and data are

The story of the 3.5 keV line is still not over.
Dark Matter or Charge Exchange?

The Astrophysical Journal, 964:185 (2024)

EBIS+COLTRIMS at IMP in Lanzhou

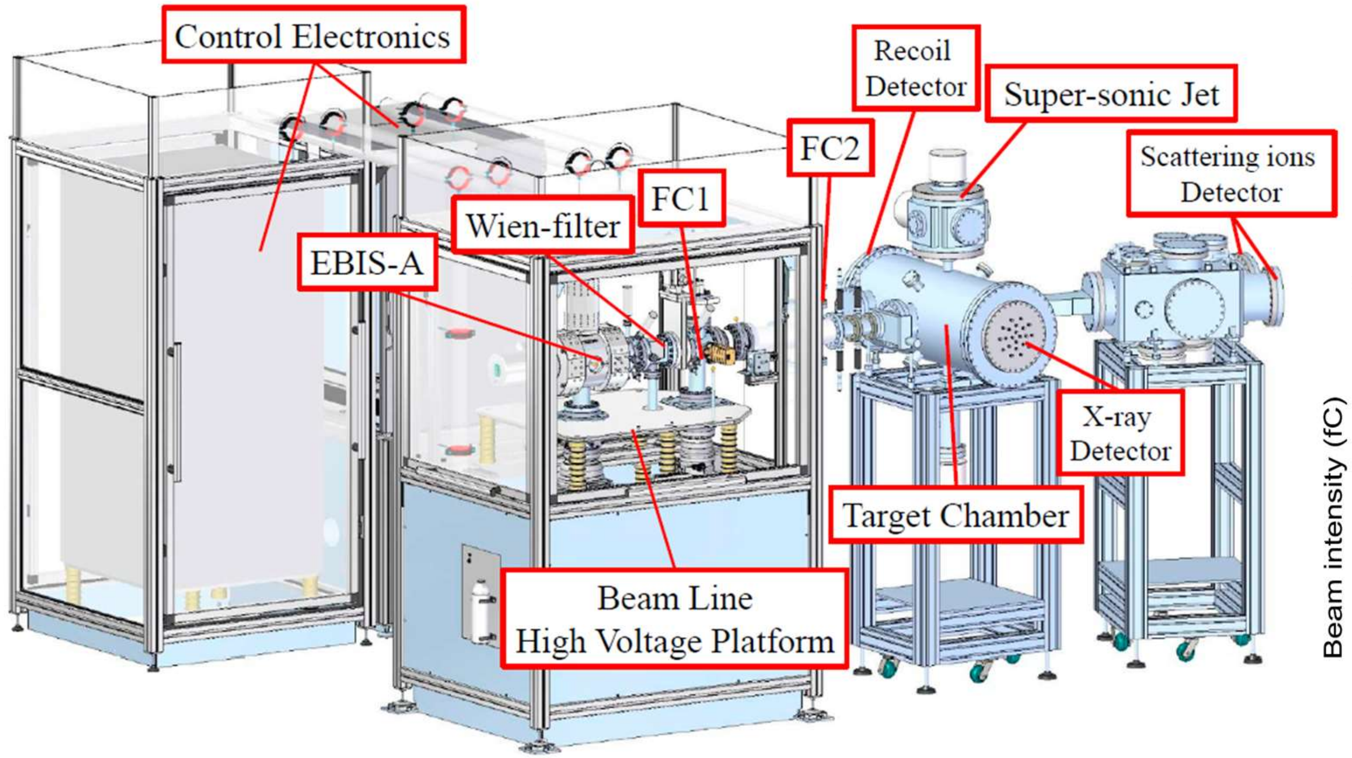
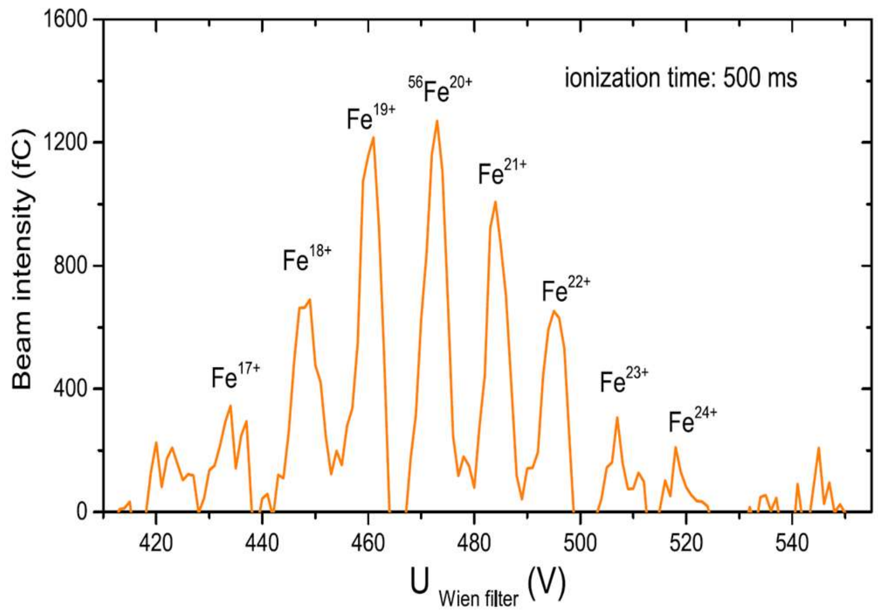


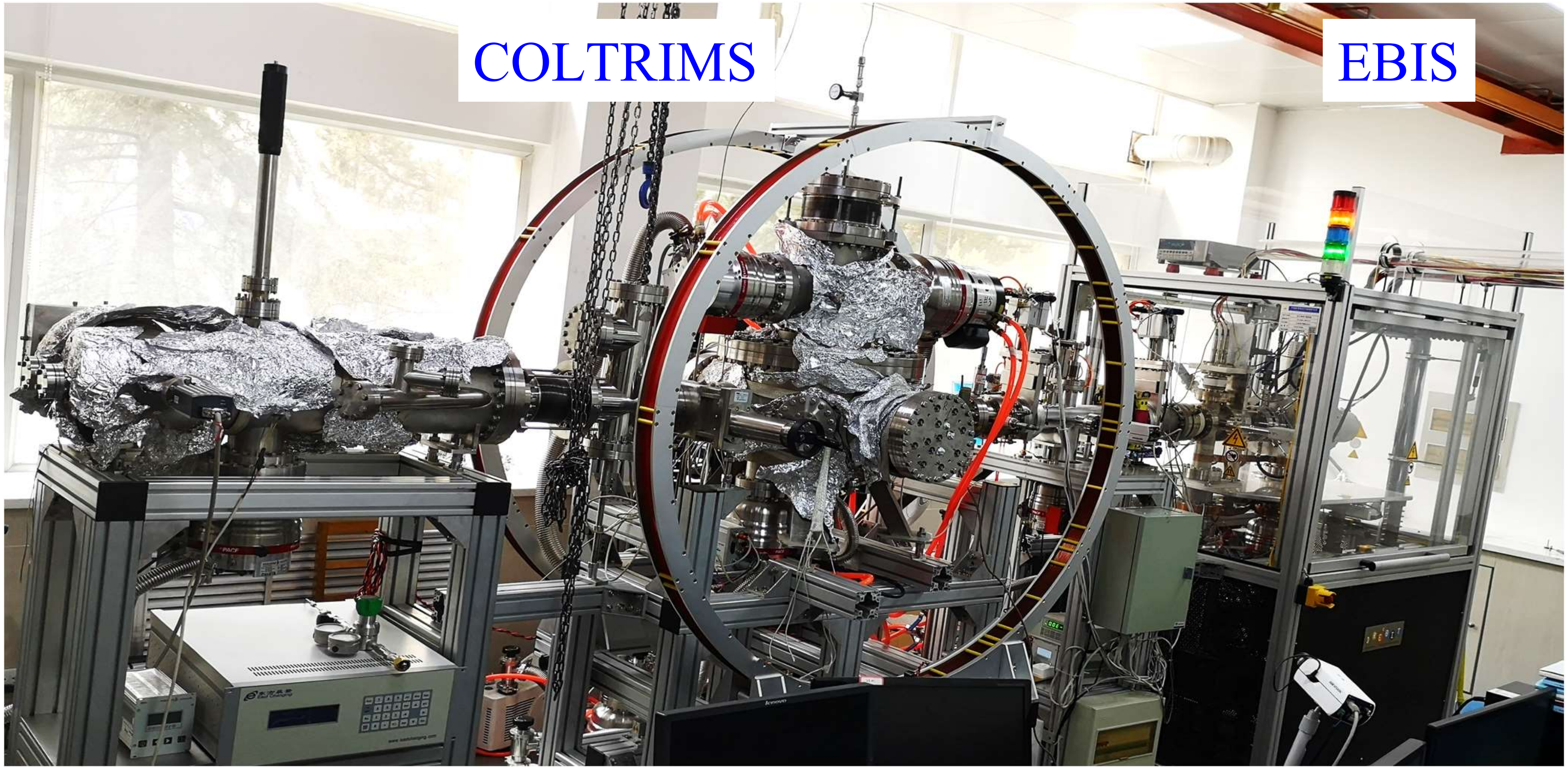
Fig. 1. Sketch of the IMP EBIS-A facility and COLTRIMS at Institute of Modern Physics in Lanzhou.

Nuclear Inst. and Methods in Physics Research B 460 (2019) 224–229

Highly charged ions at solar wind velocity

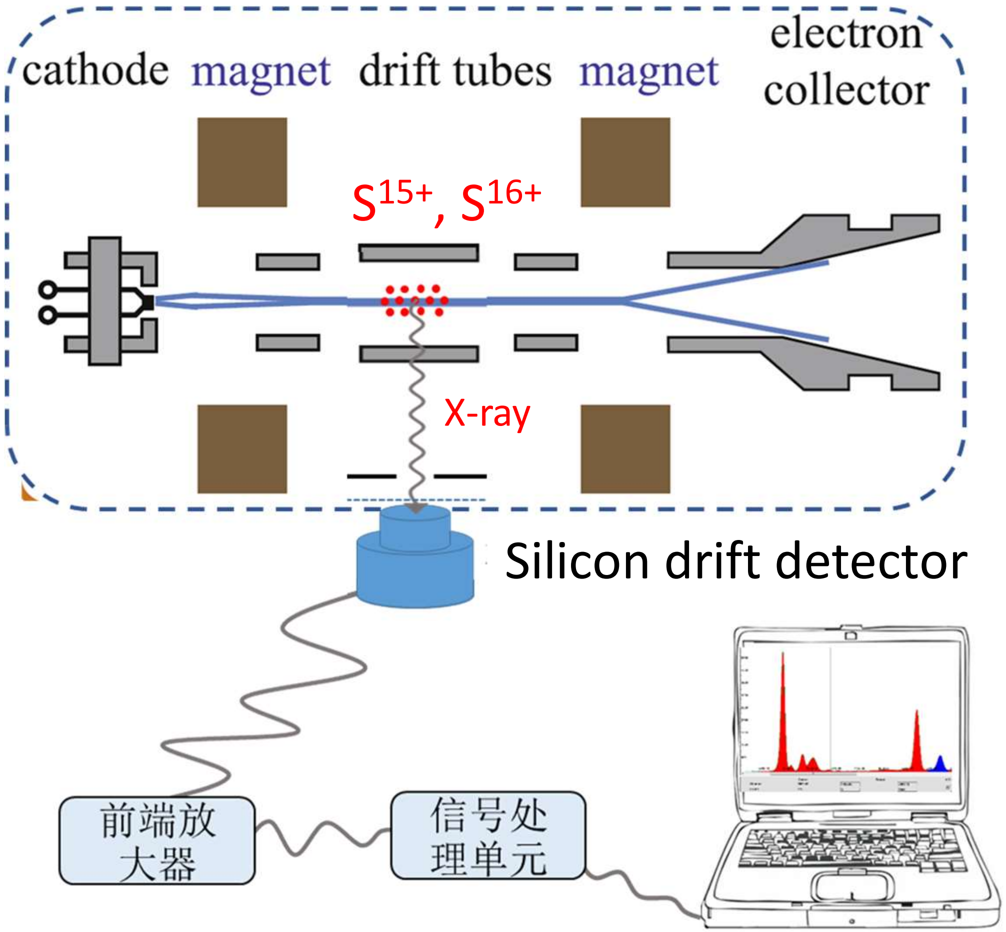
H^{+}, He^{2+}, C^{q+}, N^{q+}, O^{q+}, Ne^{q+}, Si^{q+}, S^{q+}, ……



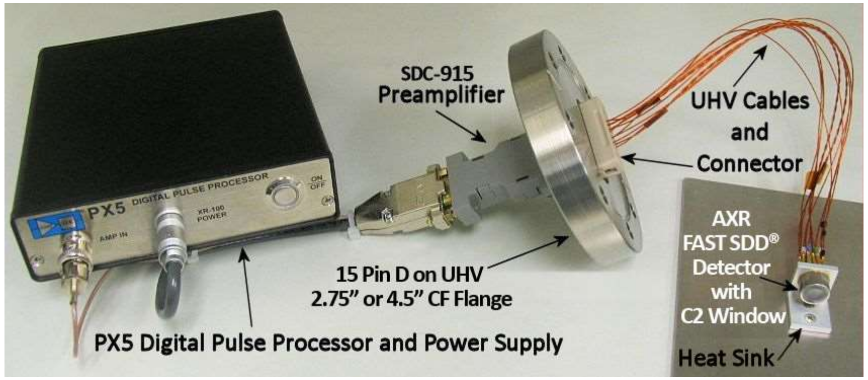


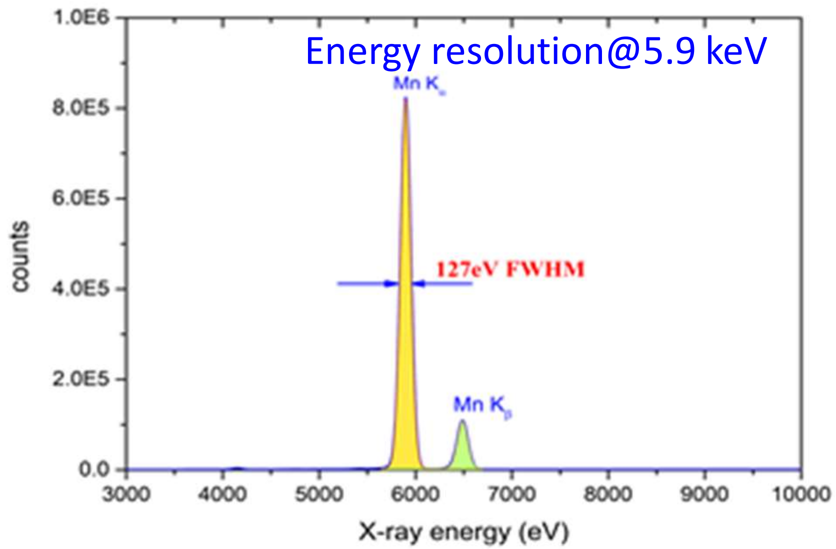
Nuclear Inst. and Methods in Physics Research B 460 (2019) 224–229

EBIS: electron beam ion source

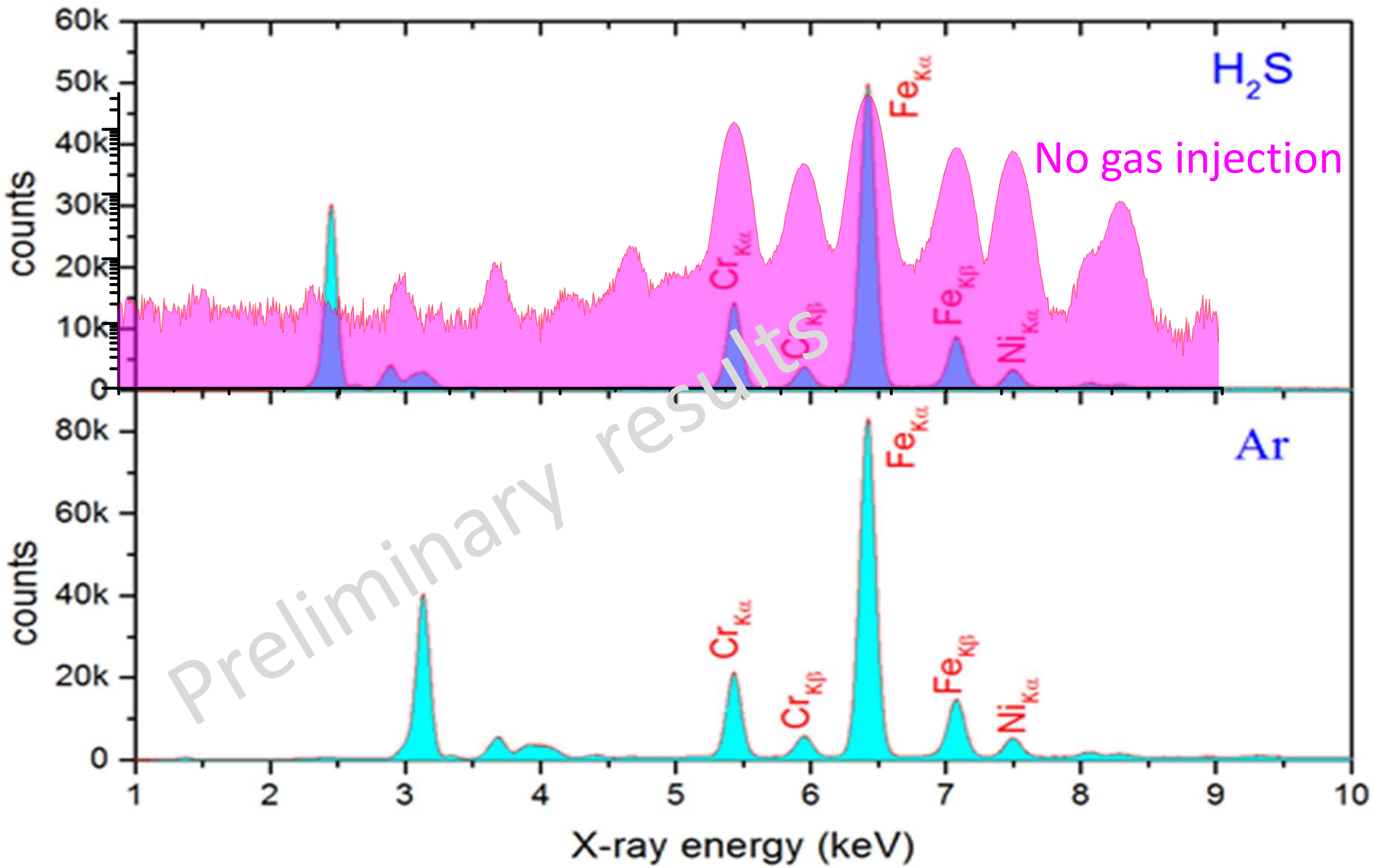


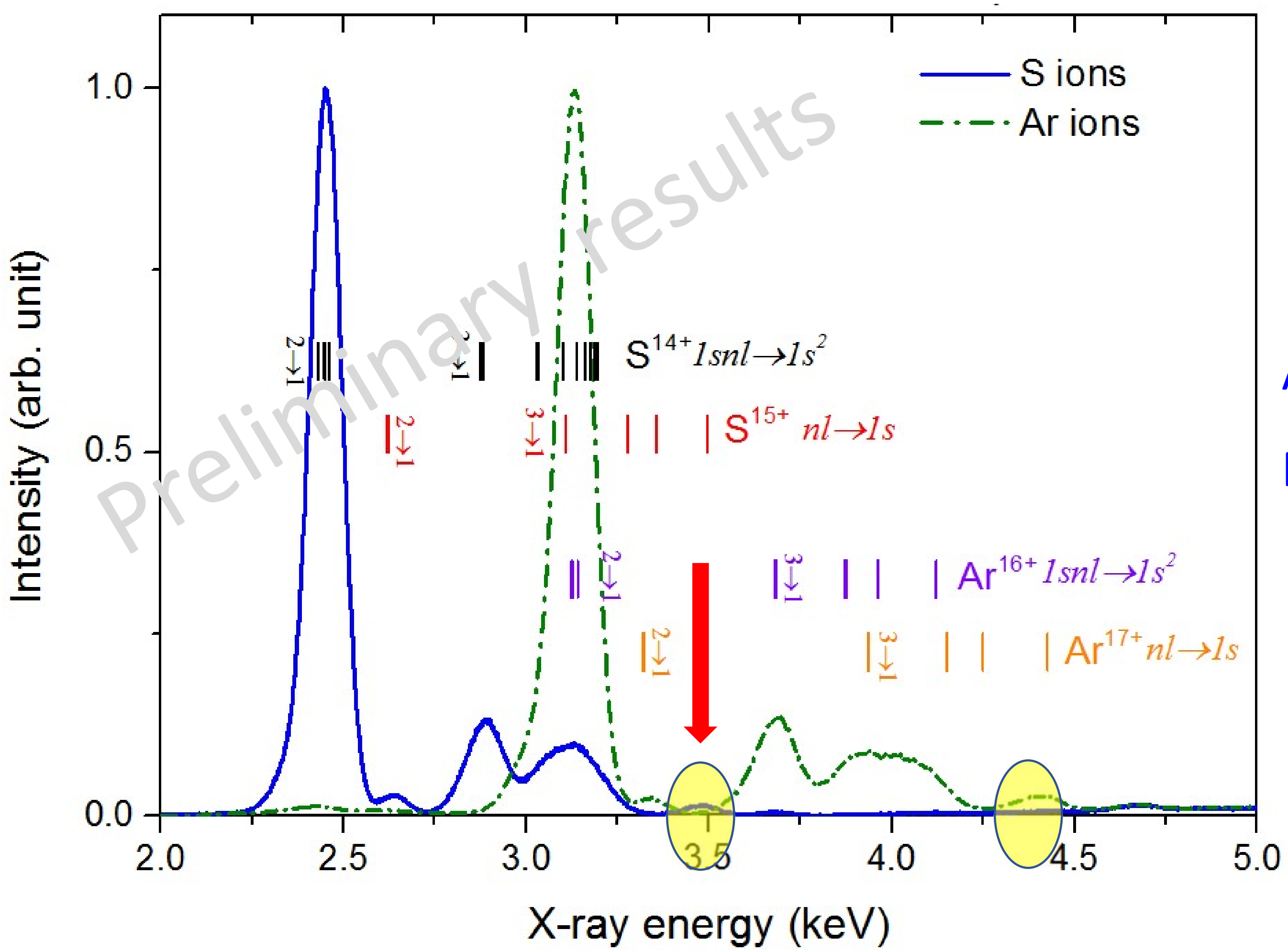
Silicon drift detector@ Amptek





zhuxiaolong@impcas.ac.cn


H2S
No gas injection
Ar
FeKα
CrKα
CrKβ
FeKβ
NiKα
Preliminary results
counts
X-ray energy (keV)



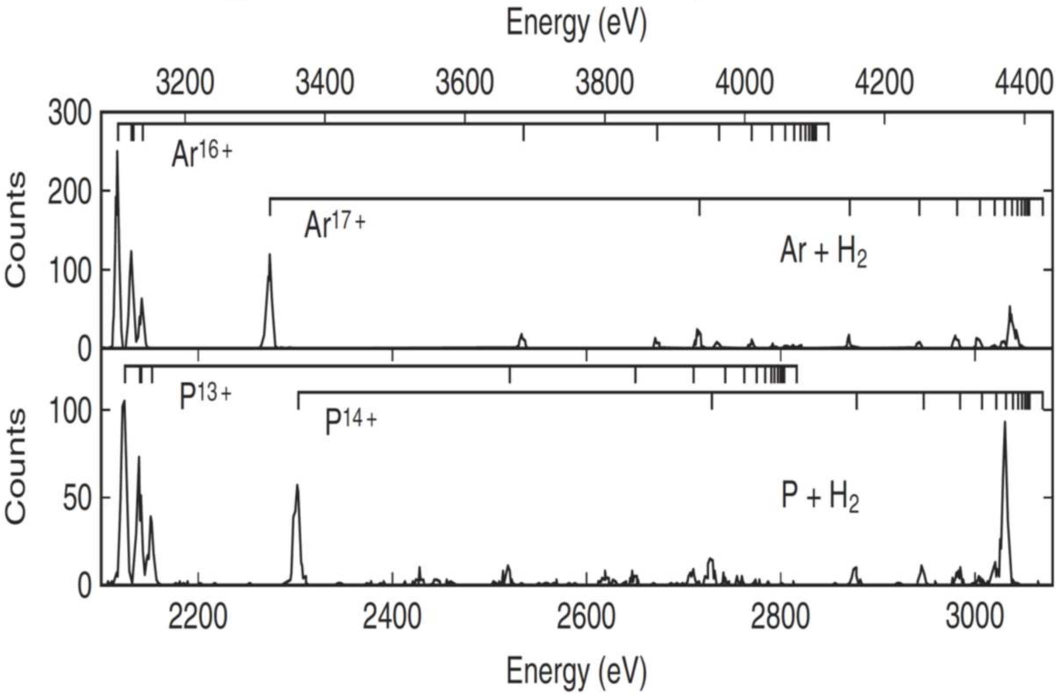
A peak appears at the ionization limit

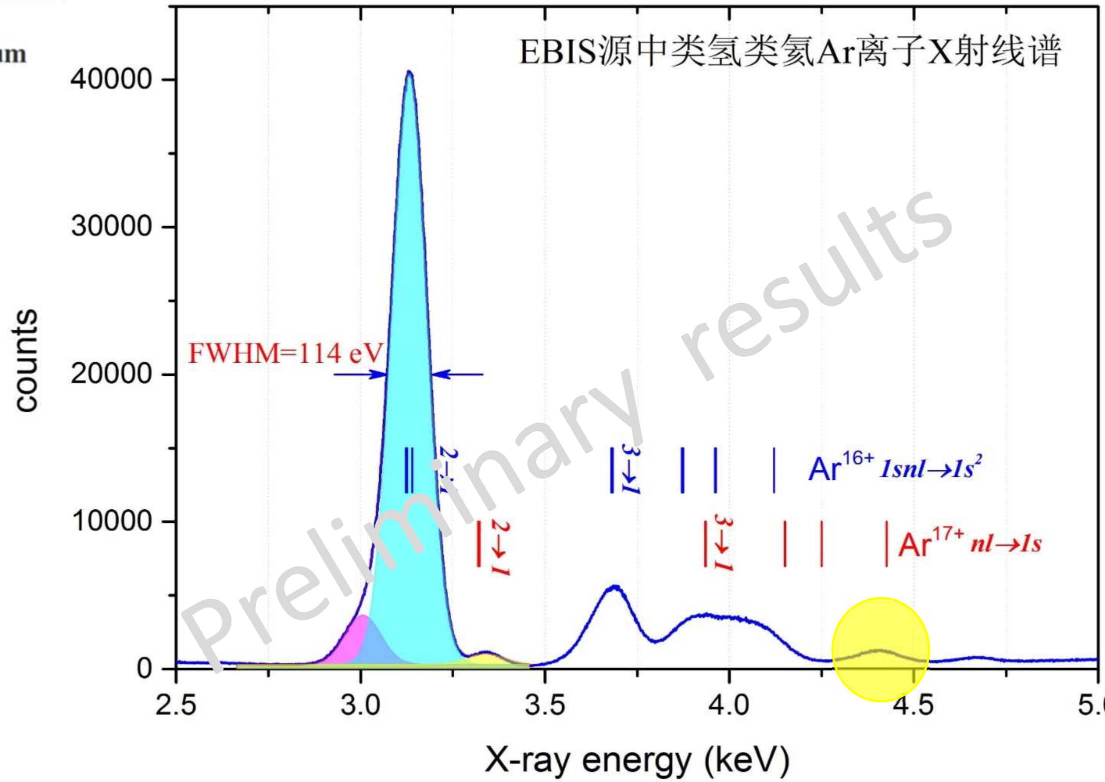
Near 3.5keV line observed for SXVI

PRL 105, 063201 (2010) PHYSICAL REVIEW LETTERS week ending 6 AUGUST 2010

Measurement of Anomalously Strong Emission from the 1s-9p Transition in the Spectrum of H-Like Phosphorus Following Charge Exchange with Molecular Hydrogen

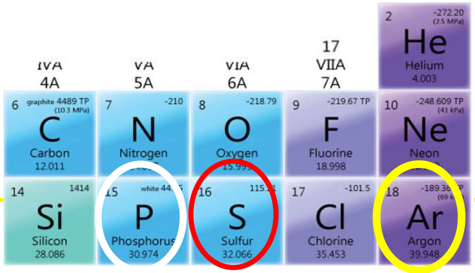
M. A. Leutenegger,[1] P. Beiersdorfer,[2,3] G. V. Brown,[2] R. L. Kelley,[1] C. A. Kilbourne,[1] and F. S. Porter[1]





SuperEBIT electron beam ion trap at LLNL

Argon and Phosphorus

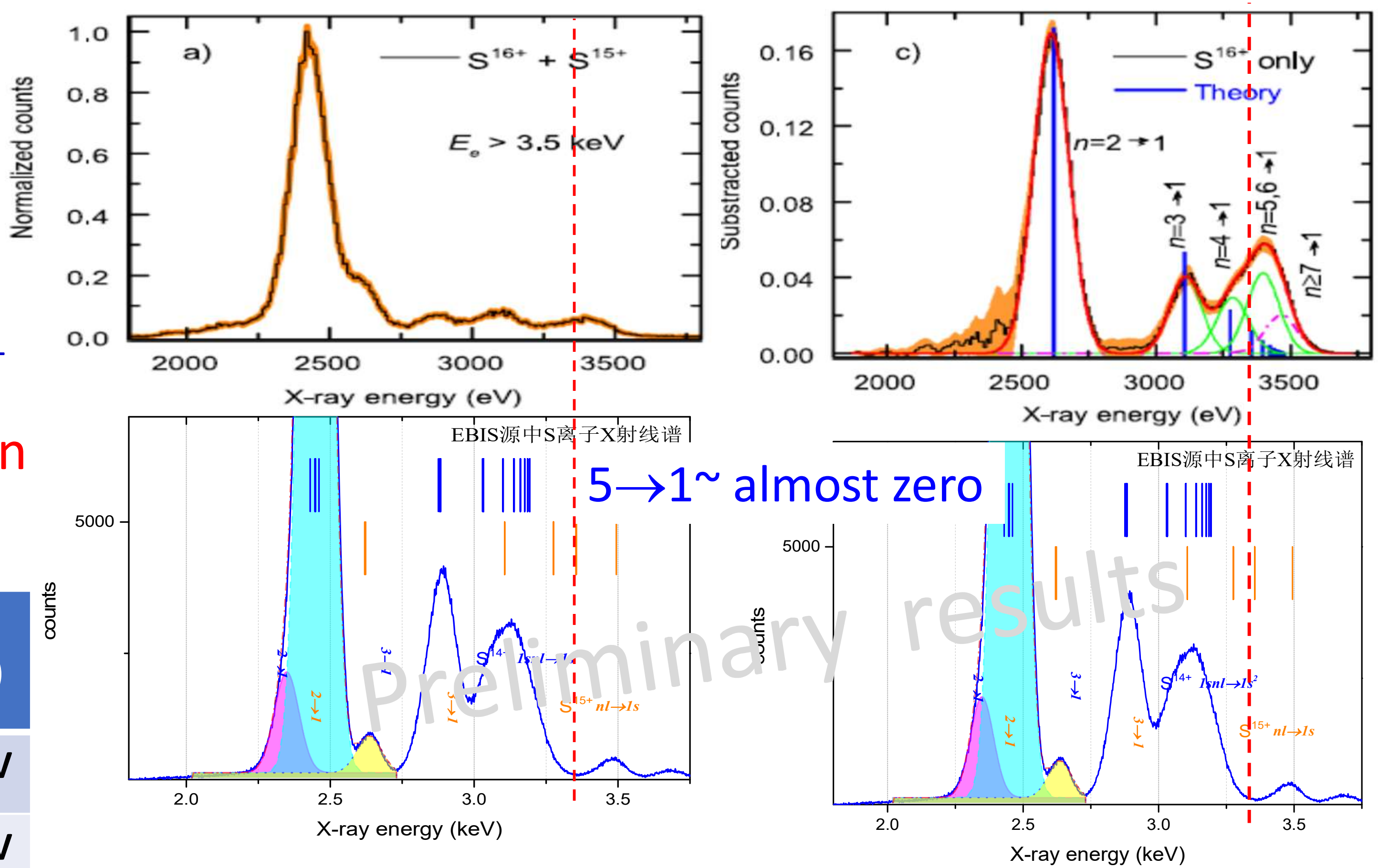


Observation of strong X-ray radiation near the ionization limit of Ar^{17+} ions

Possible sources of S^{15+} spectral lines in EBIS:

1. Electron Ionization excitation of S^{14+}
2. Electron excitation of S^{15+}
3. Charge exchange between S^{16+} with neutral

	Injection gas	Resolution FWHM (eV)
C. Shah et al.	CS_2	150@5.9keV
Present Exp.	H_2S	127@5.9keV



Isolated peak observed near 3.5 keV

it comes from the charge exchange between S^{16+} and neutrals

COLTRIMS： *n*-resolved charge exchange

IMP, Lanzhou, China

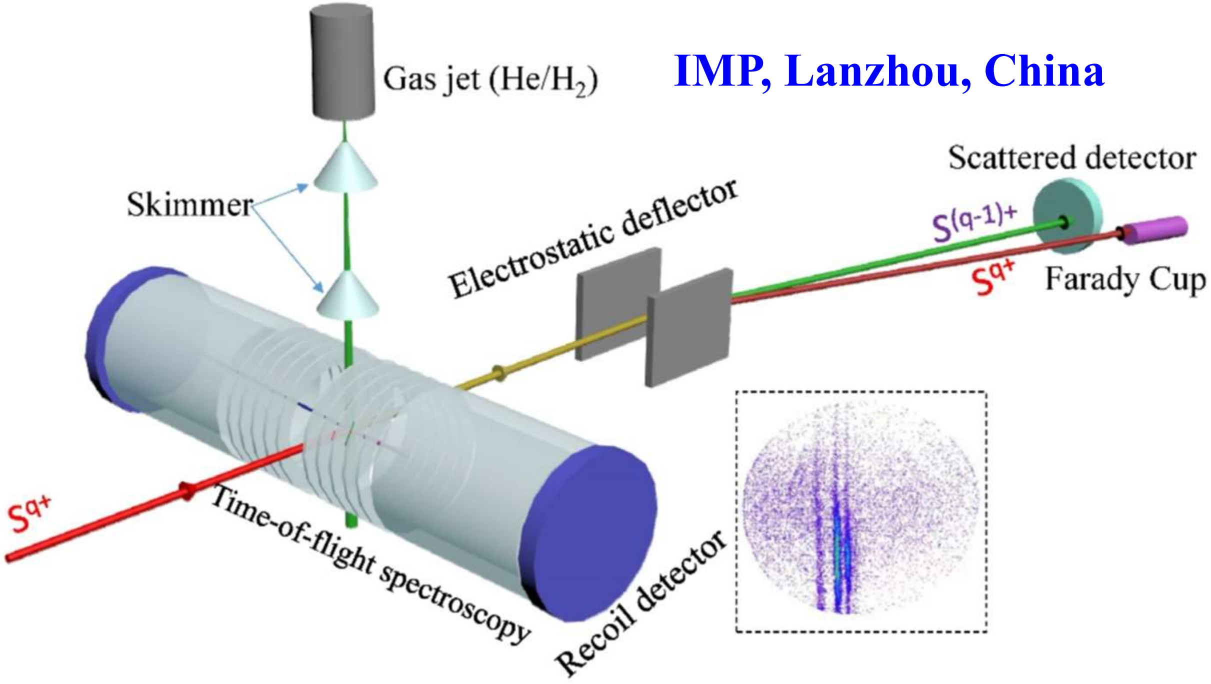
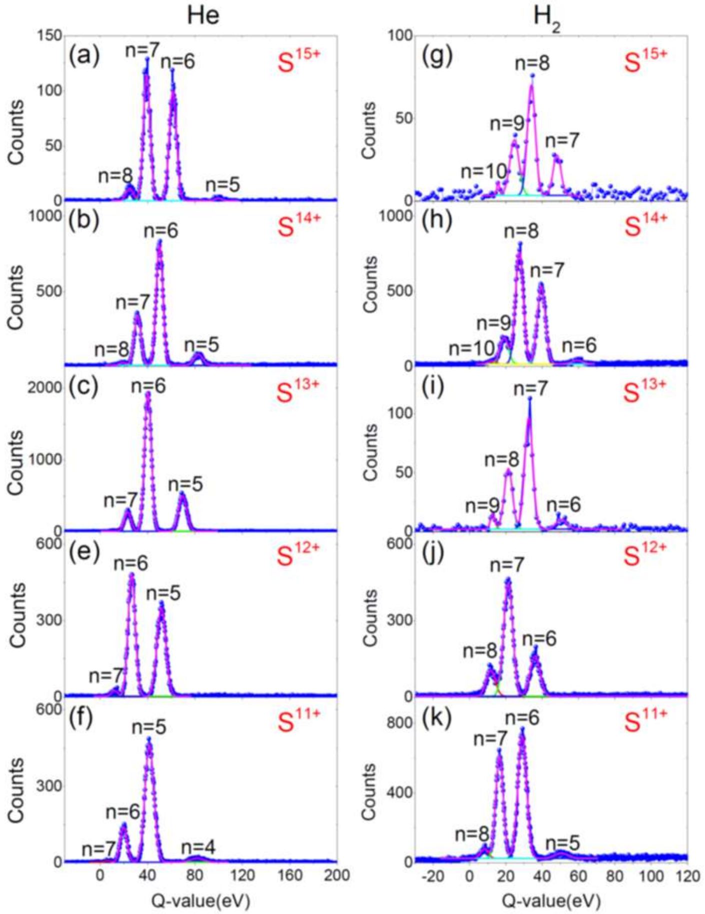


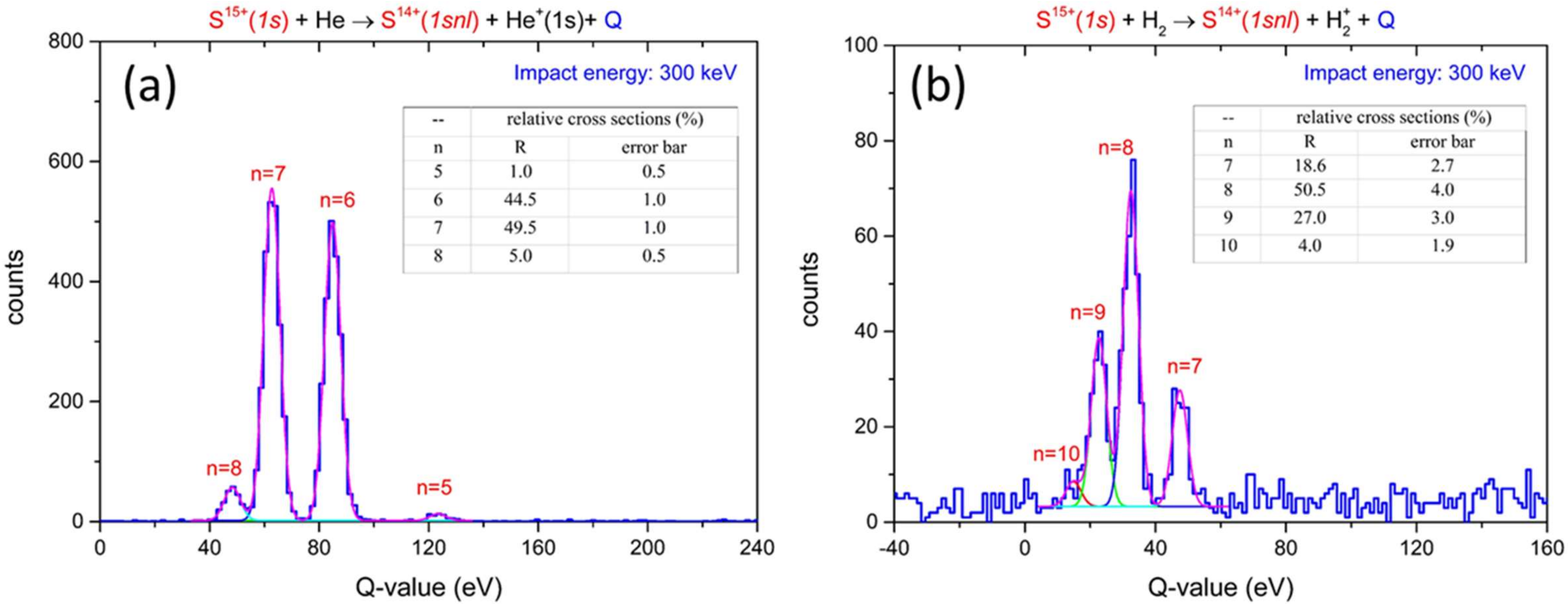
Figure 1. The experimental scheme of COLTRIMS



S^{11+} - S^{15+} @ 20·q keV *Only few n population*

Figure 2. Measured Q-value spectra of SEC in S^{q+}-He and S^{q+}-H_2 collisions at an impact energy of q×20 keV. The left and right panels represent He and H_2 target, respectively. The incident projectile charge state q runs from 11 to 15. Solid blue circles are the experimental measurements and the red lines represent the Gaussian fit.

COLTRIMS： *n*-resolved charge exchange



(a)

--	relative cross sections (%)	
n	R	error bar
5	1.0	0.5
6	44.5	1.0
7	49.5	1.0
8	5.0	0.5

(b)

--	relative cross sections (%)	
n	R	error bar
7	18.6	2.7
8	50.5	4.0
9	27.0	3.0
10	4.0	1.9

The captured electron like to populate into higher principal quantum number *n* in slow highly charged ion collisions

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Table 2. The experimental n population with the prediction of scaling laws.

q	He target				H_2 target			
	n_{exp}	n_O	n_{JW}	n_{OBM}	n_{exp}	n_O	n_{JW}	n_{OBM}
15	6.6±0.2	5.7	5.9	6.4	8.1±1.0	7.2	7.5	8.1
14	6.2±0.1	5.4	5.6	6.1	7.7±0.3	6.8	7.1	7.7
13	5.9±0.1	5.1	5.3	5.8	7.3±0.8	6.4	6.7	7.3
12	5.6±0.1	4.8	5.0	5.4	6.9±0.1	6.1	6.3	6.9
11	5.2±0.1	4.5	4.6	5.1	6.4±0.1	5.7	5.8	6.4

Scaling Laws:

$$n_O = \left(\frac{I_H}{I_t}\right)^{1/2} q^{0.75},$$

$$n_{JW} = q\left(1+\frac{q-1}{\sqrt{2q}}\right)\left(\frac{I_H}{I_t}\right)^{1/2},$$

$$n_{OBM} = \sqrt{2}\left(\frac{q}{Z_t}\right)^{0.75},$$

$$n_{OBM} = \sqrt{2}\left(\frac{q}{Z_t}\right)^{0.75}$$

Expectations: H_2 q=16, $n_{OBM} \approx 8.5$

- Hydrogen-, helium-like ions capture electrons to higher principal quantum numbers *n*, and the emitted spectral lines form a peak near the ionization limit
- Measurements of the hydrogen-like sulfur-ion spectral lines support the idea that the 3.5 keV line comes from charge exchange
- *n*-resolved charge-exchange experiments indicate that the captured electron typically populates into a higher principal quantum number ***n*** for the single electron capture in slow highly charged ion with neutral collisions