SEARCHING FOR THE 3.5 keV LINE IN THE STACKED SUZAKU OBSERVATIONS OF GALAXY CLUSTERS

ESA BULBUL1, MAXIM MARKOVITCH2, ADAM FOSTER3, ERIC MILLER4, MARK BAUTZ5, MIKE LOEWENSTEIN2, SCOTT W. RANDALL2, AND RANDALL K. SMITH3

1 Kavli Institute for Astrophysics & Space Research, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA; ebulbul@mit.edu
2 NASA Goddard Space Flight Center, Greenbelt, MD, USA
3 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

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ABSTRACT

We perform a detailed study of the stacked Suzaku observations of 47 galaxy clusters, spanning a redshift range of 0.01–0.45, to search for the unidentified 3.5 keV line. This sample provides an independent test for the previously detected line. We detect a 2σ-significant spectral feature at 3.5 keV in the spectrum of the full sample. When the sample is divided into two subsamples (cool-core and non-cool core clusters), the cool-core subsample shows no statistically significant positive residuals at the line energy. A very weak (~2σ confidence) spectral feature at 3.5 keV is permitted by the data from the non-cool-core clusters sample. The upper limit on a neutrino decay mixing angle of \( \sin^2(2\theta) = 6.1 \times 10^{-11} \) from the full Suzaku sample is consistent with the previous detections in the stacked XMM-Newton sample of galaxy clusters (which had a higher statistical sensitivity to faint lines), M31, and Galactic center, at a 90% confidence level. However, the constraint from the present sample, which does not include the Perseus cluster, is in tension with previously reported line flux observed in the core of the Perseus cluster with XMM-Newton and Suzaku.

Key words: dark matter – galaxies: clusters: general – large-scale structure of universe – line: identification

1. INTRODUCTION

The detection of an unidentified emission line near 3.5 keV in the stacked XMM-Newton observations of galaxy clusters, and in the Perseus cluster, has received significant attention from astrophysics and particle physics communities (Bulbul et al. 2014a, Bu14a hereafter). The detection was also reported in the outskirts of the Perseus cluster and the Andromeda galaxy observed with XMM-Newton (Boyarsky et al. 2014, Bo14 hereafter), as well as in Suzaku observations of the Perseus cluster core (Urban et al. 2015; Franse et al. 2016; see, however, a non-detection by Tamura et al. 2015). An emission line at a consistent energy was detected in the XMM-Newton and Chandra observations of the Galactic center, and in eight other individual clusters (Boyarsky et al. 2015; Iakubovskyi et al. 2015; Jeltema & Profumo 2015).

Although the line was detected by several X-ray detectors in a variety of objects, the origin of the line is unclear. Bu14a discussed potential astrophysical origins of this line, e.g., an emission line from the nearby weak atomic transitions of K XVIII and Ar XVII dielectronic recombination (DR); they found that these lines have to be 10–20 times above the model prediction. Jeltema & Profumo (2015) and Carlson et al. (2015) suggested that a large fraction of cool gas with \( T < 1 \text{ keV} \) in cluster cores may produce lines from K XVIII stronger than those Bu14a allowed for. We commented in Bulbul et al. (2014b; hereafter, Bu14b) that ratios of the observed lines from other elements exclude significant quantities of such cool gas. Recently, Gu et al. (2015) suggested that charge exchange between sulfur ions and neutral gas, a process not included in Bu14a, may produce excess near 3.5 keV. These, as well as some other recent spatially resolved studies, are reviewed by Franse et al. (2016).

A more exotic possibility that is interesting to consider is that the observed line is a signal from decaying dark matter particles (Abazajian 2014; Horiuchi et al. 2016). In previous studies, they reported that the flux of the line is consistent across objects of different mass (Andromeda galaxy, stacked galaxy clusters, and Galactic center) when the mass scaling in decaying dark matter models are taken into account (see Boyarsky et al. 2015). Although it is challenging to test this hypothesis with the current CCD (100–120 eV) resolution X-ray telescopes, the radial distribution of the line in a well-exposed galaxy cluster may provide further information on its origin. Franse et al. (2016) examined the flux distribution of the 3.5 keV line, as a function of radius in the Perseus cluster. However, the observed line flux from the Perseus core \( (r \lesssim 1') \) appears to be in tension with detection from other objects, assuming the decaying dark matter model (Bu14a, Franse et al. 2016). Franse et al. (2016) found that the profile of the line is consistent with a dark matter origin, as well as with an unknown astrophysical line. Recently, Ruchayskiy et al. (2015) have analyzed a very deep XMM-Newton observation of the Draco dwarf galaxy. They found no line signal in the spectrum from the MOS detectors and a 2.3σ-significant hint of a positive signal at the right energy in the independent PN spectrum, both findings consistent with the previous detections within uncertainties.

Bu14a laid the framework for stacking X-ray observations at the rest frame and successfully applied this method to a large sample of XMM-Newton observations. In this work, we take a step further to search for the unidentified line in the stacked Suzaku observations of 47 galaxy clusters. This paper is organized as follows. Section 2 describes the data processing and spectra stacking. In Sections 3 and 4, we provide our results and conclusions. All errors quoted throughout the paper correspond to 68%(90%) single-parameter confidence intervals; upper limits are at 90% confidence, unless otherwise stated. Throughout our analysis, we used a standard ΛCDM
cosmology with $H_0 = 71\, \text{km}\, \text{s}^{-1}\, \text{Mpc}^{-1}$, $\Omega_M = 0.27$, and $\Omega_{\Lambda} = 0.73$. In this cosmology, 1' corresponds to $\sim$0.11 Mpc at redshift of 0.1.

2. SAMPLE SELECTION AND DATA REDUCTION

In an attempt to smooth the instrumental and background features related to the Suzaku XIS detectors, we select a sample of galaxy clusters based on the number of X-ray counts in their 2–10 keV band. To be able to smear the instrumental features, by blue-shifting the spectra to the source frame, we select clusters covering a large redshift range of $0.01 < z < 0.45$. A significant number of on-axis X-ray observations of galaxy clusters have been performed by Suzaku since its launch in 2005. We selected observations with a minimum of 10,000 counts in $z < 0.2$ per cluster, and 5000 counts per cluster for clusters with redshifts $0.2 < z < 0.44$. The final sample includes 51 Suzaku X-ray observations of 47 galaxy clusters. The details of the observations are summarized in Table 1, along with the filtered exposure times. The filtering process is described below. We note that the Perseus cluster, which is the brightest cluster in terms of X-rays, has the longest observations (1Ms) available in the Suzaku archive. However, to avoid the final stacked spectrum being dominated by this cluster, we exclude it from our sample. The flux distribution of the 3.5 keV line out to the virial radius of the Perseus cluster has already been studied in great detail by Franse et al. (2016).

The details of Suzaku data reduction are described in Bulbul et al. (2016) and Franse et al. (2016). Here, we provide a summary of the steps we follow in the data analysis. After the calibrated data is filtered from the background flares, source images in the 0.4–7.0 keV band are extracted from the filtered event file. These images are used to detect point sources within the Suzaku field-of-view (FOV) using the CIAO’s tool wavdetect. The detected point sources are excluded from the further analysis.

The source and particle background spectra are extracted from the filtered event file and filtered night-time Earth data using the FTOOL xisnxbgen. The spectra are extracted within the overdensity radius $R_{500}$, if the estimated $R_{500}$ falls within FOV of XIS.

The overdensity radii ($R_{500}$) are calculated using the mass-temperature scaling relation for each cluster (Vikhlinin et al. 2009). The temperatures used in these estimates are obtained from previously published results in the literature. For some of the nearby clusters, $R_{500}$ is larger than the XIS FOV. For those, we use the largest possible region (a circle with a radius of 8′3) that encompasses the cluster center while avoiding the detector edges. The extraction radii for the full sample are given in Table 3. Redistribution matrix files (RMFs) and ancillary response files (ARFs) are constructed using the FTOOLS addarf and addrmf, while mathpha is used to produce stacked source and background spectra. At the end of the stacking processes, we obtain a total of 5.4 Ms FI and 2.7 Ms BI galaxy cluster observations in the full sample. These count-weighted response files are used in modeling the continuum and the known plasma emission lines (see Section 3).

3. RESULTS

As in B14a, We fit the background-subtracted stacked source spectra with line-free multi-temperature apec models to represent the continuum emission with high accuracy. Gaussian models are added to account for individual atomic lines in the 1.95–6 keV energy band. Our total model includes the following lines at their rest energies: Al XII (2.05 keV), Si XIV (2.01, 2.37, and 2.51 keV), Si XII (2.18, 2.29, and 2.34 keV), S XV (2.46, 2.88, 3.03 keV), S XVI (2.62 keV), Ar XVII (triplet at 3.12, 3.62, 3.68 keV), Cl XVI (2.79 keV), Cl XVII (2.96 keV), Cl XVIII (3.51 keV), K XVIII (triplet at 3.37, 3.49 and 3.51 keV), K XIX (3.71 keV), Ca XIX (complex at 3.86, 3.90, 4.58 keV), Ar XVIII (3.31, 3.93 keV), Ca XX (4.10 keV), and Cr XXIII (5.69 keV).

After the first fit iteration, the $\chi^2$ improvement for the inclusion of each of these lines is determined, and the lines that are detected with $< 2\sigma$ are removed from the model. Additionally, a power-law model, with an index of 1.41 and free normalization, is added to the total model to account for the contribution of the cosmic X-ray background (CXB). We note that Galactic halo emission is negligible in this energy band; hence, it is not included in the model. The best-fit temperatures, normalizations of the line-free apec models, and the fluxes of S XV, S XVI, Ca XIX, and Ca XX lines are given in Table 2.
It is crucial to accurately determine the fluxes of the nearby atomic lines of K XVIII, Cl XVII, and Ar XVII in order to be able to measure the flux of the unidentified line at 3.5 keV. The line ratios of S XV at 2.46 keV to S XVI at 2.62 keV and Ca XIX at 3.9 keV to Ca XX at 4.1 keV are good diagnostics tools for estimating plasma temperature, especially valuable for detecting the presence of cool gas (Bu14b). Following the same method presented in Bu14a, we determine the plasma temperature based on the measured fluxes of helium-like S XV at 2.46 keV, hydrogen-like S XVI at 2.63 keV, and helium-like Ca XIX and hydrogen-like Ca XX lines at 3.90 keV and 4.11 keV from the spectral fits. However, the band where S XV and S XVI are located is crowded with strong Si XIV lines. Therefore, we tie the fluxes of Si XIV

### Table 1

| Cluster        | R.A.  | Decl.  | ObsID         | FI Exp (ks) | BI Exp (ks) | zbest | Sub-sample |
|----------------|-------|--------|---------------|-------------|-------------|-------|------------|
| Fornax         | 3 38 33.48 | −35.0 29 30.5 | 10020010 | 137.5 | 68.7 | 0.004 | CC |
| Antlia         | 10 30 2.21  | −35.0 19 39.7  | 80030510 | 112.5 | 56.2 | 0.012 | NCC |
| Centaurus      | 12 48 48.29 | −41 18 47.5 | 80000140 | 61.4 | 30.7 | 0.008 | CC |
| A1060          | 10 36 41.86 | −27.0 31 51.6 | 80000300 | 64.9 | 32.4 | 0.012 | CC |
| A3627          | 16 14 16.13 | −60.0 50 59.6 | 80030200 | 87.7 | 43.8 | 0.017 | NCC |
| AWM7           | 2 5 29.5  | 43 18 34 | 80103510 | 32.1 | 16.0 | 0.014 | CC |
| A262           | 1 52 46.13 | 36.0 9 32.8 | 80020100 | 67.6 | 33.8 | 0.017 | CC |
| A3581          | 14 07 37.99 | −27.0 01 11.6 | 80702600 | 129.4 | 64.7 | 0.022 | CC |
| Coma           | 12 57 33.43 | 26.0 55 34.0 | 80019700 | 326.3 | 163.1 | 0.021 | NCC |
| Ophiuchus      | 17 12 26.23 | −23.0 22 44.4 | 80204600 | 162.8 | 81.4 | 0.029 | CC |
| A2199          | 16 28 46.13 | 39.0 29 24.6 | 80105600 | 35.5 | 18.0 | 0.031 | CC |
| A496           | 04 33 38.4 | −13 15 33.0 | 80037300 | 68.68 | 34.4 | 0.032 | CC |
| A3571          | 13 47 26.98 | −32.0 51 8.6 | 80089400 | 69.8 | 34.9 | 0.038 | NCC |
| Triangulum Australis | 16 38 29.4 | −64.0 20 51.7 | 80032800 | 138.8 | 69.4 | 0.048 | NCC |
| A754           | 09 08 50.71 | −9.0 38 10.0 | 80026300 | 182.8 | 91.4 | 0.054 | NCC |
| A2665          | 23 50 51.86 | 6.0 8 6.7 | 80107600 | 23.1 | 11.5 | 0.099 | NCC |
| A3667          | 20 12 33.84 | −56.0 47 50.6 | 80096010 | 40.4 | 20.2 | 0.055 | NCC |
| AS1101         | 23 13 59.02 | −42.0 45 33.0 | 80109300 | 107.0 | 53.55 | 0.055 | CC |
| A2256          | 17 4 3.31 | 78.0 40 43.0 | 80106100 | 188.7 | 94.3 | 0.055 | NCC |
| A1831          | 13 59 12.17 | 27.0 58 9.5 | 80107700 | 32.7 | 16.3 | 0.078 | NCC |
| A1795          | 13 48 53.78 | 26.0 36 3.6 | 80012100 | 19.6 | 9.8 | 0.063 | CC |
| A3112          | 03 17 59.57 | −44.0 15 2.5 | 80068600 | 109.9 | 54.9 | 0.075 | CC |

**Note.** Columns are coordinates (R.A., decl.), Suzaku observation ID, exposure in front-illuminated (XIS0+XIS3) and back-illuminated (XIS1) observations, best-fit redshifts obtained from fits of Fe–K band of FI observations, and the category and subsample of the cluster as determined based on the state of the core. NCC stands for non-cool core sample, while CC stands for cool-core sample.
The measured plasma temperatures are calculated based on S line ratios. Measured Values: Ar XVII DR line at 3.62 keV. The implied plasma temperatures are calculated based on S line ratios. Estimated Values: Ar XVII DR line at 3.62 keV. The implied plasma temperatures are calculated based on S line ratios.

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Table 2

| Parameters | Full Sample | BI | Cool Core Clusters | FI | BI | Non Cool-core Clusters | FI | BI |
|-----------|-------------|----|-------------------|----|----|------------------------|----|----|
| KT (keV)  | 5.9 ± 0.3   | 4.8 ± 0.4 | 6.8 ± 0.4 | 3.0 ± 0.6 | 3.1 ± 0.3 | 2.9 ± 0.2 |
| N (10^{-2} cm^{-5}) | 1.2 ± 0.2 | 1.9 ± 0.3 | 1.5 ± 0.6 | 1.4 ± 0.7 | 1.3 ± 0.2 | 1.6 ± 0.3 |
| KTF (keV) | 8.3 ± 0.3 | 9.56 ± 0.6 | 8.3 ± 0.6 | 9.7 ± 1.5 | 15.1 ± 1.23 | 17.1 ± 3.5 |
| N (10^{-2} cm^{-5}) | 1.0 ± 0.2 | 2.5 ± 0.4 | 1.5 ± 0.2 | 2.9 ± 0.4 | 2.9 ± 0.7 | 2.2 ± 0.9 |
| KT (keV)  | 9.9 ± 0.4 | ... | ... | ... | ... | ... |
| N (10^{-2} cm^{-5}) | 1.2 ± 0.2 | ... | ... | ... | ... | ... |
| S XV (10^{-6} phs cm^{-2} s^{-1}) | 9.9 ± 1.2 | 7.8 ± 2.0 | 167 ± 1.4 | 11.7 ± 4.3 | 1.4 ± 1.1 | 3.2 ± 0.1 |
| S XVI (10^{-6} phs cm^{-2} s^{-1}) | 26.6 ± 1.1 | 24.2 ± 1.8 | 321 ± 1.3 | 28.7 ± 1.9 | 15.6 ± 2.5 | 16.7 ± 3.2 |
| Ar XVII (10^{-6} phs cm^{-2} s^{-1}) | 9.5 ± 1.1 | 7.6 ± 1.5 | 132 ± 1.3 | 9.1 ± 1.6 | 5.3 ± 2.0 | 6.6 ± 2.8 |
| Ca XIX (10^{-6} phs cm^{-2} s^{-1}) | 4.6 ± 2.4 | 4.6 ± 2.0 | 7.1 ± 2.8 | 6.1 ± 4.1 | 4.8 ± 1.4 | 4.9 ± 2.4 |
| Ca XX (10^{-6} phs cm^{-2} s^{-1}) | 5.0 ± 0.7 | 6.07 ± 1.1 | 5.5 ± 0.9 | 5.5 ± 1.2 | 3.3 ± 1.2 | 3.5 ± 2.1 |

Note. Best-fit Temperature and normalizations of line-free apec Model in 1.95–6 keV fit to the stacked XIS FI/BI spectra for various samples. The line fluxes of the S XV, S XVI, Ar XVII, Ca XIX, and Ca XX are at rest energies 2.51, 2.63, 3.12, 3.90, and 4.11 keV. Ninety percent uncertainties are given. Lower panel shows the estimated maximum fluxes of the atomic lines in 3–4 keV band (before they are multiplied by a factor of 3) including K XVIII at 3.51 keV, Cl XVII at 3.521 keV, and Ar XVII DR line at 3.62 keV. The implied plasma temperatures are calculated based on S line ratios.

4 The temperatures and line fluxes for NCC sample are determined from the Ca line ratio.

The maximum fluxes of the K XVIII triplet (3.47:3.49:3.51 keV) with the ratios of (1:0.5:2.3) are then estimated using AtomDB, as described in Bu14a, Cl XVII Lyβ is also included in the fits, and the flux is tied to 0.15x that of the Lyα line at 2.96 keV. We note that the Cl XVII Lyα line is not detected significantly in any of our samples; therefore, the Cl XVII Lyβ line is removed from our model after the first fit iteration. The maximum flux of the Ar XVII DR line flux at 3.62 keV is determined from the measured flux of Ar XVII triplet line at 3.12 keV. The expected flux of the Ar XVII DR line is <1% of the Ar XVII triplet at 3.12 keV for 3–5 keV plasma. The estimated fluxes of nearby lines (K XVIII at 3.51 keV, Cl XVII at 3.50 keV, and Ar XVII DR at 3.62 keV), as well as plasma temperatures based on S and Ca line ratios are given in Table 2, bottom panel. As in Bu14a, the lower and upper limits of the fluxes of K XVIII complex, Cl XVII, and Ar XVII DR lines are set to 0.1–3 times of the maximum predicted fluxes (estimates shown in Table 2 are before the multiplication) to account for abundance variance between different ions.

3.1. Full Sample

A total of 5.06 × 10^6 source counts in the 5.4 Ms FI observations and 2.9 × 10^6 source counts in the 2.7 Ms BI observations of the full sample are obtained in the 1.95–6 keV energy band. The count-weighted redshift of this sample is z ~ 0.12. After the first fit iteration with line-free apec and Gaussian models, we obtain a good fit to the stacked FI observations with χ^2 of 1032.3 for 1069 dof. The best-fit parameters of the model are given in Table 2. The predicted plasma temperature indicated by the S XV to S XV line ratio is KT ~3.1 keV for this sample.

To explore the 3–4 keV band in the full sample (although the fit is performed in a wider 2–6 keV band), we add an Gaussian with a fixed energy at 3.54 keV (the best-fit energy of the line detected in the Suzaku observations of the Perseus cluster). The line width is fixed to zero because we do not expect that the line width is resolved with CCD-type detectors, regardless of its origin. The Suzaku FI and BI detectors have energy resolutions of 110–120 eV (similar energy resolution to EPIC detectors on XMM-Newton).

Here, we explore the possible interpretation of the 3.54 keV line as a decay feature of dark matter particles; therefore, we use the properly weighted response files to reflect the physical properties of each cluster and the stacked sample. We note that the proper X-ray counts-weighted response files are used to model the continuum and known atomic transitions, as described in Section 2.

The contribution of each cluster to any flux due to dark matter decay in the stacked sample is related to the mass of decaying dark matter particles within the FOV. Following the same formulation laid out by Bu14a, the weight of each cluster in the full Suzaku sample is;

\[ \omega_{i,\text{dm}} = \frac{M_{\text{proj}}^{\text{DM}}(<R_{\text{crit}})(1 + z_i)}{4\pi D_L^2} \frac{e_i}{e_{\text{tot}}}, \]

where \( z_i \) is the redshift of the \( i \)th cluster, \( e_i \) and \( e_{\text{tot}} \) are the exposure of the \( i \)th cluster and the total exposure time of the sample, \( M_{\text{proj}}^{\text{DM}} \) is the projected dark matter mass within the spectral extraction region (\( R_{\text{crit}} \), which is either \( R_{500} \) or \( R_{200} \)), and \( D_L \) is the luminosity distance. We use the the Navarro–Frenk–White profile (Navarro et al. 1997) to determine the dark matter mass within the FOV. The steps in these calculation are described in detail in B14a. The calculated weight of each
table 3

| Cluster     | $R_{\text{ext}}$ (Mpc) | $M_{\text{DM}}^{\text{proj}}$ $(10^{14} M_\odot)$ | $M_{\text{DM}}^{\text{proj}}/D_s^2$ $(10^{10} M_\odot \, \text{Mpc}^{-2})$ | $\omega_{\text{DM}}$ $(10^{-2})$ | $\omega_{\text{DM}}$ $(10^{-2})$ |
|-------------|-------------------------|---------------------------------|---------------------------------|-----------------|-----------------|
| Coma        | 0.23                    | 1.81                            | 18.42                           | 0.31            | 1.64            |
| Australis   | 0.27                    | 2.76                            | 10.18                           | 0.18            | 0.16            |
| A2199       | 0.29                    | 2.03                            | 1.26                            | 1.40            | 0.37            |
| A496        | 0.31                    | 1.34                            | 0.71                            | 1.52            | 0.37            |
| A3571       | 0.38                    | 2.79                            | 0.98                            | 1.56            | 0.21            |
| Triangulum  | 0.48                    | 5.38                            | 1.12                            | 4.33            | 0.11            |
| A2246       | 1.15                    | 6.86                            | 0.99                            | 0.33            | 0.36            |
| A1246       | 1.50                    | 15.40                           | 0.18                            | 0.94            | 0.38            |
| A2219       | 1.94                    | 4.83                            | 0.21                            | 0.21            | 0.25            |
| A2218       | 1.20                    | 7.63                            | 0.11                            | 0.46            | 1.07            |
| A2142       | 1.57                    | 21.20                           | 0.18                            | 1.44            | 0.67            |
| A2390       | 1.32                    | 11.73                           | 0.05                            | 0.34            | 0.27            |
| A115        | 1.58                    | 20.15                           | 0.09                            | 0.98            | 0.35            |
| A975        | 1.30                    | 11.36                           | 0.05                            | 0.82            | 0.91            |
| A2061       | 0.72                    | 3.89                            | 0.33                            | 0.15            | 0.17            |
| A754        | 0.52                    | 5.68                            | 1.04                            | 0.20            | 0.93            |
| A2665       | 0.51                    | 4.30                            | 0.79                            | 0.84            | 1.43            |
| A2219       | 0.53                    | 1.45                            | 0.24                            | 2.73            | 1.07            |
| A2537       | 0.54                    | 4.98                            | 0.80                            | 1.46            | 1.07            |
| A2218       | 0.58                    | 1.87                            | 0.26                            | 0.86            | 1.58            |
| A1875       | 0.58                    | 4.07                            | 0.55                            | 0.16            | 1.30            |
| A3112       | 0.68                    | 3.42                            | 0.32                            | 0.86            | 0.76            |
| A1800       | 0.69                    | 2.41                            | 0.22                            | 0.37            | 1.57            |

Note. Columns (1) and (6) show the spectral extraction radius in Mpc, columns (2) and (7) are the estimated projected dark matter masses in the spectral extraction radii $M_{\text{DM}}^{\text{proj}}(R_{\text{ext}})$, the projected dark matter masses per luminosity distance $M_{\text{DM}}^{\text{proj}}/D_s^2$ are given in columns (3) and (8), columns (4), (5), (9), and (10) show the weighting factors $\omega_{\text{DM}}$ calculated based on the total counts in the fitting band 2–6 keV and the weighting factors $\omega_{\text{DM}}$ calculated based on the predicted dark matter flux. These factors are used to stack the ARFs and RMFs of each cluster in the sample.

Figure 1. The 3–4 keV band of the binned stacked Suzaku XIS FI (left panel) and XIS BI (right panel) spectra of the full sample. The figures show the energy band where the unidentified 3.5 keV line is detected by Bu14a. Gaussian lines with maximum values of the flux normalizations of K XVIII and Ar XVII DR are already included in the models. The 3.5 keV line is not significantly detected in either of these samples. The red and blue model lines in the top panels show the total model before and after a Gaussian line is added. The red and blue model lines in the bottom panels show the total model before and after a Gaussian line is added.

The change in the $\chi^2$ corresponds to a 2σ detection for an additional degree of freedom in the stacked FI observations of the full sample. The stacked XIS FI spectrum of the full sample, and the best-fit models before and after the Gaussian line is added, are shown in Figure 1 left panel.

For the BI observations of the full sample, the fit with line-free apec model and additional Gaussians for known cluster is given in Table 3 for each cluster in the full Suzaku sample.

Initially, we examine the 3–4 keV band of the stacked FI observations of the full sample. After the addition of the Gaussian model at 3.54 keV, the new best-fit $\chi^2$ becomes 1028.1 for 1068 dof. The change in the $\chi^2$ is 4.1 after the addition of a dof. The best-fit flux of the line is $1.0^{+0.5}_{-0.3} \times 10^{-6}$ phs cm$^{-2}$ s$^{-1}$. The change in the $\chi^2$ corresponds to a 2σ detection for an additional degree of freedom in the stacked FI observations of the full sample. The stacked XIS FI spectrum of the full sample, and the best-fit models before and after the Gaussian line is added, are shown in Figure 1 left panel.
atomic lines give a good-fit with $\chi^2 = 1111.5$ (1078 dof). The line is not detected at a statistically significant level in this spectrum. An additional Gaussian line at 3.54 keV improves the fit by $\Delta\chi^2 = 1.5$ for an extra dof (the $\chi^2$ becomes 1109.9 for 1077 dof). The best-fit flux of the line is $9.1^{+1.3}_{-1.1} \times 10^{-7}$ ph/s/cm$^2$/keV. The stacked XIS FI spectrum of the full sample and the best-fit models before and after the Gaussian line is added at 3.54 keV are shown in Figure 1, right panel.

To test the decaying dark matter origin of the signal, we further investigate if the mixing angles indicated by these fluxes are consistent with the previous detections in the literature. The measured flux from a mass of dark matter within the FOV can be converted into the decay rate, assuming dark matter particles decaying monochromatically with $E_r = m_r/2$. The mixing angle for this decay is

$$\sin^2(2\theta) = \frac{F_{DM}}{12.76 \text{ cm}^{-2} \text{ s}^{-1}} \left( \frac{10^{14} M_\odot}{M_{DM}^{\text{POV}}} \right) \left( \frac{D_L}{100 \text{ Mpc}} \right)^2 \frac{1}{1 + \frac{D_L}{100 \text{ Mpc}}} \left( \frac{1 \text{ keV}}{m_r} \right)^4,$$

where $F_{DM}$ is the observed flux due to dark matter decay (Pal & Wolfenstein 1982) and is related to the surface density or flux of decaying dark matter particles within the FOV;

$$F_{DM} = \frac{M_{DM}^{\text{POV}} \Gamma}{4\pi D_L^2 m_r} (1 + z) \text{ photons cm}^{-2} \text{ s}^{-1},$$

where $\Gamma$ and $m_r$ are the decay rate and dark matter particle mass, respectively.

Using $\omega_{dm}$ and the projected dark matter masses given in Table 3, we find that the weighted projected dark matter mass-distance squared of the full Suzaku sample is $1.17 \times 10^{10}$ $M_\odot$ Mpc$^{-2}$. Using Equation (2), one can calculate the mixing angle to be $\sin^2(2\theta) = 2.7^{+1.4}_{-1.1} \times 10^{-11}$ for the full Suzaku FI sample, for a particle mass of $m_r = 7.08$ keV. The associated 90% upper limit to the mixing angle is $\sin^2(2\theta) < 6.1 \times 10^{-11}$ in this sample. To compare the consistency between XIS FI spectrum and the previously detected line flux in XMM-Newton observations (Bu14a), we scale the flux based on the signal from the larger cluster sample, under the dark matter decay scenario. Figure 2 shows the zoomed-in 3.3–3.8 keV band of the stacked XIS full FI sample spectrum. The solid line marks the best-fit flux of the 3.54 keV line, scaled from the Bu14a full sample flux, with the 90% uncertainties marked by dashed lines. As the figure clearly shows, the XIS FI observations are consistent with the XMM-Newton observations at a 90% level.

The Suzaku BI observations of the full sample give a mixing angle measurement of $\sin^2(2\theta) = 2.5^{+0.4}_{-0.3} \times 10^{-11}$ for the same weighted mass-per-distance squared. These are given in Table 4. The Suzaku full FI/BI sample measurements are consistent with each other. The mixing angles measured from the full XMM-Newton MOS/PN samples ($\sin^2(2\theta) = 6.8^{+1.2}_{-1.0} \times 10^{-11}$) are consistent at a 1σ confidence level, and the MOS observations of bright clusters (Coma+Ophiuchus+Centaurus; $\sin^2(2\theta) = 1.8^{+0.4}_{-0.3} \times 10^{-10}$) are consistent at a $\sim 2.7\sigma$ confidence level (see Bu14a). The core excited observations of the Perseus cluster ($2.3^{+0.7}_{-0.6} \times 10^{-10}$; see Bu14a) measurement are in tension with the present Suzaku sample result at a level of $\sim 2.5\sigma$.

Comparison of mixing angles measured from Suzaku samples with the previous detections and limits are shown in Figure 3.

3.2. Cool-core Clusters

We now divide the full sample into two independent subsamples, in order to investigate whether the line flux correlates with the presence of cool gas in the intra-cluster plasma. The clusters are divided into cool-core clusters (CC) and non-cool-core clusters (NCC), based on previous identifications in the literature. If, indeed, the flux of the 3.5 keV line is stronger in the stacked cool-core cluster sample (i.e., if a correlation is observed between gas temperature and the flux), this would be a strong indication that the 3.5 keV line is astrophysical in origin. The classification of each cluster is given in Table 1. For some of the clusters in the full sample (e.g., A2495, A2249, A272, RXC J2218.8-0258, MS 2216.0-0401, and A566) the X-ray studies with high angular resolution observatories, e.g., Chandra and XMM-Newton, are not available in the literature. Due to the relatively large point-spread-function ($\sim 2^\prime$ half-power diameter) of the Suzaku mirrors, we cannot distinguish if these clusters have cool intra-cluster gas in their center. Hence, we exclude these clusters from both subsamples.

We have performed the stacking process following the same approach outlined in Section 2 for the CC clusters. A total of 3.1 Ms of good stacked FI and 1.5 Ms BI observations are obtained in this subsample. The weighted mean redshift of this subsample is 0.13. The stacked FI/BI observations of this subsample contain 52% and 51% of the total source counts of the full FI and BI observations.

We fit the stacked Suzaku FI spectra of the CC cluster as described in Section 3. The best-fit temperatures, normalizations, and fluxes of SXV, SXVI, CaXIX, and CaXX are given in Table 2. Cl Lyα at 2.96 keV is not detected significantly in this spectrum, therefore, we exclude the Cl Lyβ line at 3.51 keV from our fits. Overall, we obtain a good fit to the stacked CC spectrum with $\chi^2 = 1130.0$ (1068 dof). Adding an extra Gaussian model to the MOS spectrum at 3.54 keV does not improve the fit significantly ($\Delta\chi^2 = 1.68$) for an additional dof, and results in a non-detection. The 90% upper limit on the flux of this line at 3.54 keV is $1.4 \times 10^{-6}$
Table 4  
Measured Flux of the 3.5 keV Line in the Stacked Suzaku Clusters

| Sample          | Inst. | Energy (keV) | Flux \( (10^{-6} \text{ phs cm}^{-2} \text{ s}^{-1}) \) | \( \chi^2 \) (dof) | \( \Delta \chi^2 \) (dof) | \( \frac{M_{\text{flux}}}{D^2} \) (10^{10} M_{\odot} \text{ Mpc}^{-2}) | \( \sin^2(2\theta) \) (10^{-11}) |
|-----------------|-------|-------------|----------------------------------|------------------|------------------|---------------------------------|------------------|
| Full Sample     | FI    | 3.54        | \( 1.0^{+0.5}_{-0.5} C_{+1.9} \)    | 1028.1 (1068)    | 4.11 (1)         | 1.17                            | \( 2.7^{+14}_{-14} \) (C_{+5.9}) |
|                 | BI    | 3.54        | \( 0.9^{+0.2}_{-0.2} C_{+2.5} \)    | 1109.9 (1077)    | 1.46 (1)         | 1.17                            | \( 2.5^{+15}_{-15} \) (C_{+5.9}) |
| Cool-core Clusters | FI | 3.54 | <1.4 | | 1131.7 (1069) | 1.68 (1) | 1.06 | <5.1 |
|                 | BI    | 3.54        | <2.1 | | 11430.0 (1072) | 0.15 (1) | 1.06 | <6.1 |
| Non-cool Core Clusters | FI | 3.54 | \( 2.0^{+0.7}_{-0.7} C_{+1.9} \) | 10347.0 (1075) | 6.56 (1) | 1.19 | \( 5.3^{+16}_{-16} \) (C_{+5.9}) |
|                 | BI    | 3.54        | <5.4 | | 11599.9 (1072) | 0.51 (1) | 1.19 | <14.1 |

Note. Columns (2) and (3) are the rest energy and flux of the unidentified line in the units of photons cm\(^{-2}\) s\(^{-1}\) at the 68% (90%) confidence level. Columns (4) and (5) show the \( \chi^2 \) after the line is added to the total model, and change in the \( \chi^2 \) when an additional Gaussian component is added to the fit; column (6) is the weighted ratio of mass-to-distance squared of the samples; and column (7) shows the mixing angle limits measured in each sample. Reported constraining limits are at 90% confidence. Energies are held fixed during the model fitting.

Figure 3. Comparison of sterile neutrino mixing angle upper limits, obtained from the stacked galaxy clusters observed with Suzaku. The results in the literature are also shown. The error bars and upper limits from this work and Bu14a results are at 90% confidence levels. The upper limits from the stacked spheroidal galaxies (Malyshev et al. 2014, 2\( \sigma \)) and stacked galaxies (Anderson et al. 2015, 90\%), along with the detections in the Galactic Center (Boyarsky et al. 2015, 90\%), the Draco dwarf spheroidal (Ruchayskiy et al. 2015, 1\( \sigma \)), and M31 (Bo14a, 1\( \sigma \)) are shown. Anomalously high Perseus flux reported in Bu14a is clearly seen in the figure. We note that the particle mass is not compared here.

photons cm\(^{-2}\) s\(^{-1}\) from this spectrum. The upper limit on the flux can be translated to a mixing angle of \( 5.1 \times 10^{-11} \) for a given projected dark matter mass-per-distance squared for the sample \( (1.06 \times 10^{10} M_{\odot} \text{ Mpc}^{-2}) \). The mixing angle indicated by the stacked FI observations of CC clusters is consistent with the full Suzaku sample and the previous XMM-Newton detections.

We note that the discrepancy observed in plasma temperatures between FI and BI observations of the cool-core clusters might be due to the difference in the response of the FI and BI sensors, or the power-law normalizations for CXB that were left free during the fits. We note that spectra of individual clusters are rescaled to their emitter frame before being stacked. Therefore, the stacked spectra do not contain any physical meaning after the blue-shifting and stacking processes. The main goal of this work is to model the continuum accurately to make the analysis sensitive to faint line detections. Therefore, the observed difference is not worrying in the context of this work. The crucial point is that the line ratios observed in FI and BI observations within each sample are consistent. The line ratios are used to determine the plasma temperature and fluxes of faint lines in the 2.5–4.1 keV band.

The overall fit to the stacked BI observations to CC clusters is acceptable, with \( \chi^2 \) of 1142.85 for 1068 dof. Adding an extra Gaussian line at 3.54 keV does not improve the fit significantly, and results in a non-detection. The 90% upper limit to the flux is \( 2.1 \times 10^{-6} \) photons cm\(^{-2}\) s\(^{-1}\) from this spectrum; the upper limit on the mixing angle \( (<6.1 \times 10^{-11} M_{\odot} \text{ Mpc}^{-2}) \) from this flux limit is consistent with the full-sample and FI detections.

### 3.3. Non-cool Core Clusters

We now examine the FI and BI observations of the NCC clusters. A total of 2.2 Ms good FI and 1.1 Ms good BI observations are obtained for this sample. The NCC cluster sample contains 46% of the total FI source counts, and 45% of the total BI source counts, for the full sample. The redshift has a weighted mean value at 0.11, and the projected dark matter mass-per-distance squared is \( 1.19 \times 10^{10} M_{\odot} \text{ Mpc}^{-2} \) of the NCC subsample.

To be able to conservatively estimate the fluxes of the K\text{XVIII}, Cl\text{XVII}, and Ar\text{XVII} lines, we use the Ca\text{XIX} and Ca\text{XX} lines for this sample. Probing the 3–4 keV band, FI observations do not reveal significant residuals around 3.54 keV. Indeed, the first fitting attempt (without a Gaussian model at 3.54 keV) is an overall good fit with \( \chi^2 \) of 1041.3 for 1076 dof. Addition of a Gaussian model improves the fit by \( \Delta \chi^2 \) of 6.56 for an extra dof. The best-fit flux of the line becomes \( 2.0^{+1.0}_{-1.0} (-1.2) \times 10^{-7} \) photons cm\(^{-2}\) s\(^{-1}\). The mixing angle corresponding to this flux is \( 5.3^{+18}_{-18} (-3.1) \times 10^{-11} \), which is consistent with the full sample. The 90% upper limit of its flux is \( 3.9 \times 10^{-6} \) photons cm\(^{-2}\) s\(^{-1}\) in the FI observations of the non-cool clusters, with a mixing angle of \( 1.0 \times 10^{-10} \).
4. SUMMARY

Stacking X-ray spectra of galaxy clusters at different redshifts provides a sensitive tool to detect weak emission features. This method, tested on the XMM-Newton observations of 73 clusters (Bu14a), resulted in the detection of a very weak unidentified spectral line at \(\sim 3.5\) keV. In this work, we take a similar approach and stack Suzaku FI (XIS0, XIS3) and BI (XIS1) observations of 47 nearby (0.01 < \(z\) < 0.45) galaxy clusters to look for the unidentified emission line. Our Suzaku sample consists of 5.4 Ms of FI and 2.1 Ms of BI observations. The total source counts collected in this study are less than those of the stacked XMM-Newton observations, by a factor of 1.8. The redshift span is slightly larger in the Suzaku full sample than the full XMM-Newton sample, leading to more effective smearing of the instrumental features. The redshift range of the full Suzaku sample corresponds to an energy difference of up to 1.44 keV at 3.5 keV, which is sufficient to smear out and eliminate the background or response features.

The stacked FI data for the full sample prefers an additional emission line at \(E = 3.54\) keV (the energy fixed at the best-fit value for the Suzaku line detection in Perseus Franse et al. 2016), but only at \(2\sigma\) confidence level, with a flux of \(1.0^{+0.5}_{-0.5} \times 10^{-6}\) phs cm\(^{-2}\) s\(^{-1}\). The statistics of the data set are insufficient to constrain the properties of this faint line. The line is not significantly detected in the BI observations; however, an additional Gaussian model improves the fit by \(\Delta \chi^2 = 1.5\) and has a flux of \(9.1^{+2.2}_{-1.8} \times 10^{-6}\) phs cm\(^{-2}\) s\(^{-1}\). The fluxes observed in FI and BI observations are in agreement with each other.

In an attempt to investigate a possible correlation of the flux of the unidentified line with cooler gas in the ICM, we divide the full sample into two subsamples: CC and NCC clusters. If a correlation is observed, it would be an indication that the unidentified line is astrophysical in origin. Atomic lines are more prominent in cool-core clusters, where a significant amount of cooler gas with higher metal abundances resides in the core. However, we do not detect any significant spectral feature at 3.5 keV in the separate CC and NCC clusters. The FI observations of the NCC sample show a weak \(2.5\sigma\) residual at 3.54 keV, with a flux of \(5.3^{+2.6}_{-1.8} \times 10^{-6}\) phs cm\(^{-2}\) s\(^{-1}\) at 3.54 keV. The upper limits derived from these samples are consistent with previous detections. We note that both CC and NCC subsamples contain fewer source counts compared to all of the XMM-Newton samples studied in Bu14a, so the sensitivity of the presented Suzaku analysis is weaker. We also note that, due to smaller FOV and lower effective area of the Suzaku XIS detectors (compared to the XMM-Newton EPIC detectors), this analysis might be less sensitive to a weak signal from dark matter decay. The value of this analysis is in that it is independent and performed with a different instrument.

The upper limits provided by this work (full sample; sin\(^2\)(2\(\theta\)) = 6.1 \times 10^{-11}) are in agreement with the detections in the combined M31, Galactic center observations (sin\(^2\)(2\(\theta\)) = 5.7 \times 10^{-11}; see Boyarsky et al., 2015), and results from deep MOS (sin\(^2\)(2\(\theta\)) < 5.8 \times 10^{-11}) and PN (sin\(^2\)(2\(\theta\)) = 1.8–8 \times 10^{-11}) observations of the Draco galaxy (Ruchayskiy et al. 2015). However, the line flux in the core of the Perseus cluster is in tension with the presented stacked Suzaku and XMM-Newton clusters and other detections (Bu14a, Franse et al. 2016). Studying the origin of the 3.5 keV line with CCD resolution observations of galaxy clusters and other astronomical objects appears to have reached its limit; the problem requires higher-resolution spectroscopy, such as that expected from Hitomi (Astro-H).

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REFERENCES

Abazajian, K. N. 2014, PhRvL, 112, 161303
Anderson, M. E., Churazov, E., & Bregman, J. N. 2015, MNRAS, 452, 3905
Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco, CA: ASP), 17
Boyarsky, A., Franse, J., Iakubovskyi, D., & Ruchayskiy, O. 2015, PhRvL, 115, 161301
Boyarsky, A., Ruchayskiy, O., Iakubovskyi, D., & Franse, J. 2014, PhRvL, 113, 251301
Bulbul, E., Markovich, M., Foster, A., et al. 2014a, ApJ, 789, 13
Bulbul, E., Markovich, M., Foster, A., et al. 2014b, arXiv:1409.4143
Bulbul, E., Randall, S. W., Bayliss, M., et al. 2016, ApJ, 818, 131
Carlson, E., Jeltema, T., & Profumo, S. 2015, ICAP, 2, 009
Foster, A. R., Ji, L., Smith, R. K., & Brickhouse, N. S. 2012, ApJ, 756, 128
Frasne, J., Bulbul, E., Foster, A., et al. 2016, arXiv:1604.01759
Gu, L., Kastra, J., Raassen, A. J. J., et al. 2015, A&A, 584, L11
Horüchi, S., Bozek, B., Abazajian, K. N., et al. 2016, MNRAS, 456, 4346
Iakubovskyi, D., Bulbul, E., Foster, A. R., Savchenko, D., & Sodova, V. 2015, arXiv:1508.05186
Jeltema, T., & Profumo, S. 2015, MNRAS, 450, 2143
Malyshhev, D., Neronov, A., & Eckert, D. 2014, PhRvD, 90, 103506
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493
Pal, P. B., & Wolfenstein, L. 1982, PhRvD, 25, 766
Protassov, R., van Dyk, D. A., Connors, A., Kashyap, V. L., & Siemiginowska, A. 2002, ApJ, 571, 545
Ruchayskiy, O., Boyarsky, A., Iakubovskyi, D., et al. 2016, MNRAS, 460, 1390
Smith, R. K., Brickhouse, N. S., Liedahl, D. A., & Raymond, J. C. 2001, ApJL, 556, L91
Tamura, T., Izuka, R., Maeda, Y., Mitsuda, K., & Yamasaki, N. Y. 2015, PASI, 67, 23
Urban, O., Werner, N., Allen, S. W., et al. 2015, MNRAS, 451, 2447
Vikhlinin, A., Burenin, R. A., Ebeling, H., et al. 2009, ApJ, 692, 1033