Axions as a probe of solar metals

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If axions or axion-like particles exist and are detected, they will not only extend the standard model of particle physics but will also open a new way to probe their sources. Axion helioscopes aim to detect axions which are produced in the core of the sun. Their spectrum contains information about the solar interior and could in principle help to solve the conflict between high and low metallicity solar models. Using the planned International Axion Observatory (IAXO) as an example, we show that helioscopes could measure the strength of characteristic emission peaks caused by the presence of heavier elements with good precision. In order to determine unambiguously the elemental abundances from this information, an improved modelling of the states of atoms inside the solar plasma is required.

I. INTRODUCTION

A. The solar abundance problem

The sun has been the object of intensive studies and by now a detailed picture of processes inside the sun has emerged [1, 2]. Especially the important parameters pressure, temperature, density, hydrogen mass fraction and radiative opacities are well described by the so-called standard solar models [2], which have proved very reliable even though they were questioned at the time when the solar neutrino problem had not yet been solved [3]. However, details of the chemical composition of the sun remain under discussion with conflicting measurements being made, resulting in the solar metallicity\textsuperscript{1} or solar composition problem [4–8].

The abundance of heavy elements inside the sun (metallicity) is quantified by $Z/X$, where $Z$ is the mass fraction of elements heavier than helium and $X$ the mass fraction of hydrogen. Abundances of metals can be estimated in several ways (see [7] for a detailed overview). Helioseismic measurements [2, 9–11] consistently prefer high-$Z$ models ($Z/X = 0.0245$ [2]) while modern photospheric measurements\textsuperscript{2} reach a significantly lower $Z$ ($Z/X = 0.0178$ [7]). This discrepancy was even larger [13] before the photospheric model AGSS09 was published [7], which revised $Z$ upwards\textsuperscript{3}. Photospheric models also predict the base of the solar convective envelope and the surface helium mass fraction which disagree with helioseismic data at 5 and 11 $\sigma$, respectively [8].

This constitutes an important problem in solar modelling and so far no satisfactory solution has been found, even though alternative solar models have been considered and the required opacity calculations have been updated [5, 7, 18, 19].

B. Solar axions

Axions are light, weakly interacting pseudoscalar particles originally proposed to solve the strong CP problem [20–23]. Axions as well as their relatives, axion-like particles\textsuperscript{4}(cf. e.g. [24, 25] for reviews), have since become attractive dark matter candidates [26–29] and may also be able to explain astrophysical observations such as the anomalous cooling of stellar objects and the gamma-ray transparency of the universe (cf. [30] for a comprehensive overview). For simplicity we will henceforth just talk about axions, but axion-like particles are meant to be included.

If axions exist, they would be emitted in large numbers by the sun and could be detected on earth with an axion helioscope [31]. Such an experiment consists of a strong magnetic field of strength $B$ and length $L$. If it is aimed towards the sun, axions can convert to X-ray photons by coupling to the magnetic field. The conversion probability of a light axion ($m_a \lesssim 10 \text{ meV}$) to a photon is [31]

$$P_{a\rightarrow\gamma} = \frac{g_{a\gamma}^2 B^2 L^2}{4},$$

where $g_{a\gamma}$ quantifies the strength of the coupling to photons. The X-rays can be focused and detected with an energy dependent efficiency $Q(\omega)$. The detected spectral

\textsuperscript{1}According to astrophysical convention “metals” here refers to all elements heavier than helium.

\textsuperscript{2}All results since the major revision of [12] by Asplund et al. [13].

\textsuperscript{3}The most recent solar abundances of heavy elements from spectroscopic observations can be found in [14–16]. They do not change the general picture [17].

\textsuperscript{4}Usually, the term axion-like particles refers particles similar to the QCD axion in that they are light (pseudo-)scalars and have very weak couplings to Standard Model particles, but they do not solve the strong CP problem. For our purposes only the two-photon and electron couplings are relevant. Their mass can be different from that of the QCD axion and can therefore be treated as a free parameter.
flux of photons $d\Phi_\gamma/d\omega$ can therefore be related to the solar axion flux $d\Phi_a/d\omega$ via

$$d\Phi_\gamma/d\omega = Q(\omega)P_{a\rightarrow\gamma}\frac{d\Phi_a}{d\omega}. \quad (2)$$

The proposed helioscope IAXO [32–34] will be able to improve the sensitivity in parameter space by more than one order of magnitude in comparison to the CAST experiment. This will enable new applications beyond a discovery of axions, for example the possibilities to measure the mass of axions as well as to measure both the axion-photon and the axion-electron coupling [35, 36]. Beyond that, as we will argue in this letter, it can also serve as a new tool to measure astrophysical parameters.

In particular, we show that in a viable range of axion parameter space we can measure the strength of characteristic peaks in the emission spectrum of axions. These peaks are due to the atomic transitions of metals and are therefore directly linked to the abundance of these elements in the interior of the sun. However, their strength also depends on the plasma properties such as the occupation numbers of the relevant excited states. Comparing four different models, we find sizeable differences, preventing an unambiguous determination of metal abundances. Nevertheless, measurements of the peak strength would still give us valuable information. If modelling of the atomic states can be sufficiently improved, we could determine the elemental abundances to a level relevant for the solar abundance problem. Or, coming from the other direction, the peaks themselves can tell us about the atomic states in the environment of the sun’s interior.

II. ABUNDANCE MEASUREMENTS WITH AXIONS

A. Metals and the solar axion flux

Particles produced in the core of the sun and leaving without further interactions can provide information on metal abundances without the need to consider stellar envelope effects. Indeed, neutrinos mostly from the CNO cycle have already been proposed as such a probe [6, 42]. However, since they are produced in nuclear processes, they can only provide information on elements involved in such processes therefore giving only limited sensitivity to heavier elements.

Axions are also produced in the core of the sun. Importantly, metals inside the sun lead to characteristic peaks in the part of the solar axion flux arising from a coupling to electrons. The peaks are due to bound-bound transitions of electrons and therefore not dependent on nuclear processes.

We note a factor of 2 discrepancy in the Compton contribution. The plotted result in [43] being larger than the one given in the equation Eq. (2.19), which gives the correct result. We are indebted to Javier Redondo for clarifying this. Our computation also features a slightly higher contribution from free-free transition at low energies (most likely due to some difference in the approximation of the Debye screening scale). Since both contributions are continuous and the Compton contribution is by far the smallest one, this small discrepancy does not significantly impact our results.

5In a similar way, the discovery of axions in a haloscope [31] experiment could allow to determine detailed properties of the local dark matter such as the velocity distribution inside the galaxy [37–41].
immediately clear that iron will be the best candidate for detection. Depending on the size of the two photon coupling, the Primakoff production of axions provides an additional continuous background. To get an impression of the effect that this would have on different peaks, it is plotted in Fig. 1 for an exemplary value of the two photon coupling, $g_{a\gamma} = 10^{-11}$ GeV$^{-1}$.

### B. Measuring the peak strength

To test whether IAXO would be sensitive enough for measuring solar metal abundances, we employ a simple simulation of the signal. As this is a post-discovery measurement, we take the experimental parameters from the IAXO+ setup [30], as briefly summarized in Tab. I. A relatively long observation time of five years and a high energy resolution of 10 eV is assumed. We also choose the energy resolution so that it is smaller than the width of any of the peaks, which means that high resolution X-ray detectors like metallic magnetic calorimeters would be required [50]. For simplicity, the axion is assumed to be massless or very light ($m_a \lesssim 10$ meV) and hence Eq. (1) can be applied\textsuperscript{7}. Putting everything together and using Eq. (2), a IAXO signal can be generated for arbitrary coupling constants.

Looking at peaks from one element at a time, the energy region of interest is smaller than $\sim 1$ keV (100 bins). The expected number of events can be split up into two contributions, one from the metal that we want to detect $\mu_{\text{peak}}$ and one from all other (continuous) processes, which effectively constitute the background $\mu_{\text{back}}$. We can now ask to what level of precision we can measure $\mu_{\text{peak}}$. As our benchmark scenario, we use the peak strength obtained from OP data and the solar model AGSS09.

It is necessary to calculate the expected relative error on a fine grid in parameter space. To do this in an efficient manner, we use an Asimov data set instead of a Monte Carlo approach (cf. [51]). After calculating the relative error of an abundance measurement for every position in the coupling plane, contours can be plotted, indicating at which coupling strengths a given precision is reached. To make sure that both Wilks’ theorem and the Asimov approximation are applicable, we have checked some exemplary values of $g_{a\gamma}$ and $g_{ae}$ with a Monte Carlo simulation with 10000 repetitions. We find good agreement between the two methods.

Fig. 2 shows the 20\% accuracy contours for the most relevant elements. The best results are obtained for iron. In a sizeable part of parameter space that is not excluded by CAST or LUX, the abundance can be measured to at least 20\% accuracy. It even reaches into the region preferred by stellar cooling observations. The same method can be applied to all other elements responsible for significant peaks in the axion flux spectrum. Elements like oxygen with a low Primakoff background perform better in comparison to others, when the background is Primakoff dominated. Parameter space covered by the DFSZ I and II models is shaded in blue. Above this region, the DFSZ models violate perturbativity [52–54]. Each point in parameter space has a corresponding model-dependent mass, which we neglect for simplicity. Hints from stellar cooling are taken from [54] with the 1, 2 and 3σ contours and the best fit value shown in yellow. Larger couplings outside the 3σ contour are disfavored by astrophysical observations. Experimental limits from CAST [55, 56] (we naively combine the two limits by taking the stronger of the combined electron and photon coupling limit of [55] and the pure photon coupling limit of [56]) are shown as dashed blue line. Finally, the results of LUX [57] are depicted by the dashed-dotted blue line.

\textsuperscript{7}The effect of higher masses can be compensated by introducing a buffer gas at the cost of some amount of absorption.

| Magnetic field | $B$ [T] |
|----------------|---------|
| Effective area | $A$ [m$^2$] |
| Length | $L$ [m] |
| Efficiency | $Q$ |
| Observation time | $t$ [years] |

TABLE I. Parameters of the employed IAXO+ setup following Tab. 5 of [30]. $Q$ is the combined efficiency of the detector and the optics, which, for simplicity, we take to be energy independent. The background is effectively negligible.

**FIG. 2.** Contours of 20\% relative error in the measurement of the peak strength for several elements using solar axions. Iron is by far the easiest element to detect. Depending on the strength of the Primakoff background at the position of the peak, some elements like oxygen perform better in comparison to others, when the background is Primakoff dominated. Parameter space covered by the DFSZ I and II models is shaded in blue. Above this region, the DFSZ models violate perturbativity [52–54]. Each point in parameter space has a corresponding model-dependent mass, which we neglect for simplicity. Hints from stellar cooling are taken from [54] with the 1, 2 and 3σ contours and the best fit value shown in yellow. Larger couplings outside the 3σ contour are disfavored by astrophysical observations. Experimental limits from CAST [55, 56] (we naively combine the two limits by taking the stronger of the combined electron and photon coupling limit of [55] and the pure photon coupling limit of [56]) are shown as dashed blue line. Finally, the results of LUX [57] are depicted by the dashed-dotted blue line.
FIG. 3. Characteristic axion emission line from iron obtained from the Opacity Project [44, 45], OPAS [46, 47], ATOMIC [48, 58], and LEDCOP [49, 58] data. For clarity, we have removed the continuous background.

(Primakoff) or the axion-electron coupling. In the Primakoff dominated region, we have, $g_{\gamma g_{\gamma}} \sim \sqrt{g_{\gamma}}$ and consequently $g_{ae} \sim \text{const}$. If the axion-electron coupling is the largest contribution to the continuous part of the spectrum, we have, $g_{\gamma g_{\gamma}} g_{ae}^2 \sim \sqrt{g_{\gamma}} g_{ae}^2$ and therefore $g_{ae} \sim g_{\gamma}^{-1}$. The contours of constant relative errors exhibit this expected asymptotic behaviour.

C. From peak strengths to abundances - Systematic uncertainties

Naively, the peak strength is directly related to the metal abundance $n_{\text{metal}}$ via,

$$\mu_{\text{peak}} = g_{\gamma g_{\gamma}} g_{ae}^2 C_{\text{metal}} n_{\text{metal}}. \quad (3)$$

We can therefore hope to use the measurements of the peak strength to determine the elemental abundances.

Unfortunately, Eq. (3) suffers from a number of uncertainties. The first ones are the axion couplings. However, since a requirement for the detection of peaks is that the contribution from electron processes is detectable, it is possible to measure $g_{\gamma g_{\gamma}} g_{ae}$ with the methods described in [35].

The second and indeed most problematic one is the solar modelling itself, reflected in the constant $C_{\text{metal}}$. The first ingredient is that the metal composition inside the sun may vary as a function of the radius. However, this is most likely not a huge effect as typically more than 90% of the axion emission originates from radii smaller than 0.3 times the solar radius (indeed for iron it is less than 0.2). Within this radius, metal fractions in solar models do not vary dramatically. A significantly bigger uncertainty arises from the different modelling of the atomic states as reflected in the opacity data. To estimate this, we compare the results obtained with four different opacity sets\(^8\). These are the OP [44, 45] data used above, the data from OPAS [46, 47]\(^9\) and finally ATOMIC [48] and LEDCOP\(^10\)[49] which are elemental opacities that can be combined with the TOPS code and are available online at [58]. For the example of iron, we show the resulting axion emission (without the continuum contribution) in Fig. 3. We can see that not only the detailed structure is quite different but also the overall emission differs significantly between the data sets. We find similar differences for the other elements that, unfortunately, also depend strongly on the element in question. An overview of the relative peak strength is given in Tab. II. At present, this uncertainty limits the ability to infer the metal abundances.

### III. CONCLUSIONS

If axions are detected in the near future, they can provide a novel probe of the interior of our sun. We have shown that, in suitable regions of the axion parameter space, a helioscope like IAXO, equipped with sufficiently good energy resolving detectors, would allow a measurement of the strength of characteristic emission peaks in the axion spectrum. These peaks are due to the presence of heavier elements, most notably iron, neon and oxygen that are relevant to the solar abundance problem [5, 7]. As the peak strength is related to the elemental abundance, such a measurement could be an extremely powerful tool in resolving the solar abundance problem. Crucially, to realise this potential, an improved precision in the modelling of the atomic emission lines inside the plasma is mandatory. Turned around, such a measurement could also be used to test this modelling, e.g. by measuring different emission lines of the same element.

Going beyond that, a measurement of the total metallicity of the sun would require the independent measurement of the carbon and nitrogen abundances. This is because carbon and nitrogen contribute significantly to the differences

|     | Fe  | S   | Si  | Mg  | Ne  | O   |
|-----|-----|-----|-----|-----|-----|-----|
| OPAS/OP | 1.68 | 1.75 | 2.92 | 2.46 | 3.37 | 4.70 |
| ATOMIC/OP | 0.39 | 0.83 | 1.55 | 1.20 | 0.52 | *   |
| LEDCOP/OP | 1.07 | 1.05 | 1.51 | 1.52 | 0.90 | *   |

\(\star\)We are indebted to Javier Redondo for this suggestion.

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\(\star\)The publicly available opacity tables generated with ATOMIC and LEDCOP are not regarded as spectroscopically resolved by their authors. Nevertheless, we decided to include them to demonstrate the uncertainties of opacity calculations.
total metallicity (~22%) but do not cause large peaks in the axion spectrum. Fortunately, carbon and nitrogen abundances could in future be inferred from the solar neutrino flux, as neutrinos from the CNO cycle come within reach of detectors [42]. In this way axion and neutrino experiments could complement each other with neutrinos indicating the light metal abundances and IAXO detecting heavier elements.

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