Search of axions from a nuclear power reactor with a high-purity germanium detector

H.M. Chang,1,2 H.T. Wong,1‡ M.H. Chou,1 M. Deniz,1,3 H.X. Huang,1,4 F.S. Lee,1 H.B. Li,1 J. Li,5,6 H.Y. Liao,1,2 S.T. Lin,1,2 V. Singh,1 S.C. Wu,1 and B. Xin4
(TEXONO Collaboration)

1 Institute of Physics, Academia Sinica, Taipei 115, Taiwan.
2 Department of Physics, National Taiwan University, Taipei 106, Taiwan.
3 Department of Physics, Middle East Technical University, Ankara 06531, Turkey.
4 Department of Nuclear Physics, Institute of Atomic Energy, Beijing 102413, China.
5 Institute of High Energy Physics, Chinese Academy of Science, Beijing 100039, China.
6 Department of Engineering Physics, Tsing Hua University, Beijing 100084, China.
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A search of axions produced in nuclear transitions was performed at the Kuo-Sheng Nuclear Power Station with a high-purity germanium detector of mass 1.06 kg at a distance of 28 m from the 2.9 GW reactor core. The expected experimental signatures were mono-energetic lines produced by their Primakoff or Compton conversions at the detector. Based on 459.0/96.3 days of Reactor ON/OFF data, no evidence of axion emissions were observed and constraints on the couplings \( g_{a\gamma\gamma} \) and \( g_{aee} \) versus axion mass \( m_a \) within the framework of invisible axion models were placed. The KSVZ and DFSZ models can be excluded for \( 10^3 \text{ eV} \lesssim m_a \lesssim 10^6 \text{ eV} \). Model-independent constraints on \( g_{a\gamma\gamma} g_{aNN}^4 < 7.7 \times 10^{-9} \text{ GeV}^{-2} \) for \( m_a \lesssim 10^3 \text{ eV} \) and \( g_{aee} g_{aNN}^4 < 1.3 \times 10^{-10} \) for \( m_a \lesssim 10^6 \text{ eV} \) at 90% confidence level were derived. This experimental approach provides a unique probe for axion mass at the keV–MeV range not accessible to the other techniques.

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I. INTRODUCTION

The axions \((a)\) were proposed in the 1970’s as a solution to the strong CP problem – the near-perfect cancellations between the QCD vacuum angle and the quark mass matrix, as constrained by experimental bounds on the neutron electric dipole moments. The interactions of the axions with matter (photons, electrons and nucleons) can be described by the effective Lagrangian \([1,2]\)

\[
\mathcal{L}_{\text{int}} = g_{a\gamma\gamma} \phi_a \vec{E} \cdot \vec{B} + ig_{aee} \phi_a \vec{E} \cdot \vec{B} + i \phi_a \psi_N \gamma_5 (g_{aNN}^0 + g_{aNN}^1 \tau_3) \psi_N ,
\]

where \(\phi_a\), \((\vec{E}, \vec{B})\), \(\psi_e\) and \(\psi_N = \begin{pmatrix} p \\ n \end{pmatrix}\) represent respectively the axion, electromagnetic, electron and nucleon fields. The couplings of the axions to the photons and electrons are parametrized by \(g_{a\gamma\gamma}\) and \(g_{aee}\), while \(g_{aNN}^0\) and \(g_{aNN}^1\) are their isoscalar and isovector couplings to the nucleons.

A generic feature of the axion models is that all the coupling constants as well as the axion mass \((m_a)\) are inversely proportional to the symmetry breaking scale \((f_a)\). The original “Peccei-Quinn-Weinberg-Wilczek” (PQWW) model \([3]\) took \(f_a\) to be the electroweak scale, implying \(m_a\) of the order of \(\sim 100 \text{ keV}\). This has been tested and excluded after extensive efforts. Current research programs \([4]\) focus on larger \(f_a\) in the “invisible axion models”, the two popular variants of which are the DFSZ (or GUT) \([5]\) and KSVZ (or hadronic) models \([6]\).

The axion couplings with matter within the framework of these models were evaluated and discussed in details in Refs. \([7,8]\).

The light-mass axion is a well-motivated dark matter candidate. Cosmological and astrophysical arguments \([1,9]\) constrain the axion mass to be \(10^{-6} \text{ eV} < m_a < 10^{-2} \text{ eV}\), but the bounds are model-dependent and with large uncertainties. Experiments have been performed to look for dark matter axions as well as those produced in the sun, power reactors and radioactive nuclear transitions.

All previous reactor experiments \([10,11]\) focused on the searches of the PQWW axions via their decays, and contributed much to exclude their existence. In this article, we present results on a new search over a broad axion mass range, using an alternative detection strategy through its interactions with matter. This detection scheme was successfully used in a previous experiment using radioactive isotope as axion source \([2]\).

II. REACTOR AS AXION SOURCE

The axions are pseudoscalar particles and have quantum numbers like those of magnetic photons. It can be emitted through magnetic transitions in radioactive gamma-decays \([12]\). Nuclear power reactors are powerful radioactive sources and are therefore potential axion sources as well. Axions can be emitted in competition with the photons as a result of neutron captures

\[
n + (Z, A) \rightarrow (Z, A + 1) + \gamma/a
\]
or nuclear de-exci-tations

\[(Z, A)^* \rightarrow (Z, A) + \gamma/a\ .\]  

(3)

There are six prominent channels of magnetic gamma-transitions at typical nuclear reactors, as listed in Table I. Thermal neutron captures on the \(^{10}\text{B}\) in the control rods and on proton in the cooling water produce \(a^+\) Li\(^*\) and \(d+\gamma\), respectively. Their photon fluxes (\(\Phi_\gamma\)), in units of fission\(^{-1}\) and GCI, were evaluated by full neutron transport simulations \([12]\). The other sources of \(^{91}\text{Y}\^*, \(^{97}\text{Nb}\^*, \(^{135}\text{Xe}\^*,\) and \(^{137}\text{Ba}\^*\) are all fission daughters. Their corresponding \(\Phi_\gamma\) were derived from standard tables on fission yields \([14]\) and cross-checked by previous calculations \([10]\). For comparisons, the \(\nu_e\) and \(\nu_e\) yields \([13]\) at reactors are about 7.2 and \(\sim 10^{-5}\) fission\(^{-1}\), respectively.

The axion flux (\(\phi_a\)) at a distance \(L\) from a reactor core of fission rate \(R_f\) can be described by

\[\phi_a(L) = \frac{R_f \cdot \Phi_\gamma}{4\pi L^2} \cdot \frac{\Gamma_\gamma}{\Gamma_a} \cdot P_{dk} \cdot P_{int} ,\]  

(4)

where \((\Gamma_a/\Gamma_\gamma)\) is the branching ratio of axion emissions in the transitions. It depends on the axion-nucleon couplings and the nuclear structures of the transitions. The probabilities of the axions surviving the flight from reactor core to detector without decays or interactions are given, respectively, by

\[P_{dk} = \exp[-\frac{L \cdot m_a}{p_a \cdot \tau_a}] \quad (5)\]

and

\[P_{int} = \exp[-L \cdot \rho_L \cdot \sigma_{int}],\]  

(6)

where \(m_a, \tau_a, p_a, E_a\) are the axion mass, lifetime, momentum and total energy, \(\sigma_{int}\) is the axion interaction cross section with matter at effective target number density \(\rho_L\).

In particular, the axions can decay in flight via the emissions of \(2\gamma\) (\(\Gamma_\gamma: a \rightarrow \gamma\gamma\)) or \(e^+e^-\) pairs (\(\Gamma_{ee}: a \rightarrow e^+e^-\)). Their decay rates are related to the \(g_{a\gamma\gamma}\) and \(g_{aee}\) couplings by \([12]\):

\[\frac{1}{\Gamma_\gamma} = \frac{64\pi}{g_{a\gamma\gamma} m_a^3} \]  

and

\[\frac{1}{\Gamma_{ee}} = \frac{8\pi}{g_{aee} \sqrt{m_a^2 - 4m_e^2}},\]  

(7)

(8)

The axion lifetime is then given by

\[\tau_a = \frac{1}{\Gamma_\gamma + \Gamma_{ee}}.\]  

(9)

### III. AXION DETECTION AND EXPERIMENTAL SETUP

Data were taken with a high-purity germanium detector (HPGe) of mass 1.06 kg at the Kuo-Sheng (KS) Reactor Laboratory. The HPGe target and the associated anti-Compton (AC) detectors as well as passive shieldings are depicted in Figure I. The principal AC detector was a well-shaped NaI(Tl) crystal scintillator of mass 19.7 kg. Descriptions of the experimental hardware and analysis procedures were presented in details in Refs. \([15]\) & \([16]\). The primary scientific goal was the search of neutrino magnetic moments. A physics threshold of 12 keV and a background level of 1 day\(^{-1}\) kg\(^{-1}\) keV\(^{-1}\) comparable to those of underground dark matter experiments were achieved. The source-detector distance of KS was \(L=28\) m while \(\rho_L\) was modeled to be 27.75 m of water and 0.25 m of lead.

FIG. 1: Schematic layout of the HPGe with its anti-Compton detectors as well as inner shieldings and radon purge system.

The search strategies for reactor axions with these unique HPGe data were inspired by a previous experiment \([2]\) where a 15 kCi \(\gamma\)-source of \(^{65}\text{Zn}\) was used as a potential axion source instead. Two interaction mechanisms of axions with matter were studied: Primakoff
and Compton conversions as shown schematically in Figures 2a&b. These processes are respectively and independently sensitive to $g_{a\gamma\gamma}$ and $g_{aee}$. Their cross-sections were both given in Ref. [2] – (a) Primakoff conversion on the nuclei:

$$\sigma_P = g_{a\gamma\gamma}^2 \frac{Z^2 \alpha_{em}}{2} \frac{1 + \beta^2}{2\beta} \ln \left[ \frac{1 + \beta}{1 - \beta} \right] - 1 \chi , \quad (10)$$

where $\alpha_{em}$ is the electromagnetic coupling, $Z$ is the atomic number of the target, $\beta = p_a/E_a$ and $\chi$ is the atomic-screening correction factor given in Eq. 20 of Ref. [2]; (b) Compton conversion on the electrons:

$$\sigma_C = g_{aee}^2 \frac{\pi \alpha_{em}}{8 \pi m_e^2 p_a} \left[ \frac{2}{m_e^2} \left( m_a + E_a \right) y + \frac{4 m_a (m_a^4 + 2 m_a^2 m_e^2 - 4 m_e^2 E_a^2)}{y (m_e^2 + y)} + \frac{4 m_e^2 p_a^4 + m_e^4}{p_a y} \ln \frac{m_e + E_a + p_a}{m_e + E_a - p_a} \right] , \quad (11)$$

where $y = 2 m_e E_a + m_a^2$. The $m_a$ dependence of the two cross-sections at the $p_n \rightarrow d\gamma$ transition energy of $E_a = 2.23$ MeV, using the normalizations of $g_{a\gamma\gamma} = 1$ GeV$^{-1}$ and $g_{aee} = 1$, are illustrated in Figure 3.

The total energy of the axions can be fully converted by either of the two processes into measurable ionization energy in the HPGe, such that the experimental signatures are the presence of mono-energetic lines at the known $E_a$’s during the Reactor ON periods. In comparison, previous reactor-based axion experiments studied instead the axion decay channels $\Gamma_{\gamma\gamma}$ and $\Gamma_{ee}$. They were therefore not sensitive to the invisible axion regime where $m_a$ are very small and decays are kinematically blocked or suppressed.

IV. DATA ANALYSIS

The signal rates ($S_{P/C}$) for axion Primakoff/Compton Conversions in one kilogram of target mass are given by

$$S_P = \sigma_P \cdot \phi_a \cdot N \cdot \epsilon_P \quad (12)$$

and

$$S_C = \sigma_C \cdot \phi_a \cdot Z \cdot N \cdot \epsilon_C \quad , \quad (13)$$

where $\epsilon_{P/C}$ are the efficiencies of full energy deposition at the HPGe detector, $N$ is the number of atoms in the kilogram target, and $Z$ accounts for the electron target number in Compton process. The various efficiency factors were evaluated by full simulations and listed in Table III. Full energy depositions for Compton conversion at the HPGe detectors were due to interactions only in Ge, such that only $N(\text{Ge}), Z(\text{Ge})=32$ and $\epsilon_C(\text{Ge})$ were involved in the derivation of $S_C$. However, photons from Primakoff conversions in both Ge and NaI could contribute to $S_P$ as full-energy peaks at the HPGe, such that there are terms involving, respectively, $[N(\text{Ge}), \epsilon_P(\text{Ge})]$ and $[N(\text{NaI}), \epsilon_P(\text{NaI})]$.

Evidence of reactor axions would manifest as peaks at the known energies of Table III in the Reactor ON–OFF residual spectra in HPGe. Following the naming conventions of Ref. [15], Periods-I (July 2001–April 2002) and -III (Sept. 2004–Oct. 2005) with 180.1/52.7 and 278.9/43.6 days of the KS-HPGe Reactor ON/OFF data, respectively, were used for analysis. Candidate events were those uncorrelated with the anti-Compton and Cosmic-Ray vetos and having pulse shapes consistent with $\gamma$-events. Selections of these events and their efficiencies were discussed in Ref. [15]. As illustrations, the Period-III ON/OFF background spectra and the ON–OFF residual spectra for the six candidate lines are depicted in Figures 4a&b, respectively. The background $\gamma$-lines were identified [15] and indicated that ambient radioactivity dominated.

The count rates and their errors of the various transitions shown in Table III were derived by best-fits of the residual spectra to Gaussian lines at fixed $E_a$’s and resolutions. No excess were observed in all channels and upper limits of the signal rates ($S_a$) at 90% confidence level(CL) were derived. The most sensitive channel in
TABLE II: Summary of the detector efficiencies for Primakoff and Compton conversions on axions of energy $E_a$, the measured Reactor ON–OFF event rates at the signal regions and the 90% CL upper limits ($S_u$).

| Channel   | $E_a$ (keV) | $\epsilon_P(Ge)$ | $\epsilon_P(NaI)$ | $\epsilon_C(Ge)$ | Period I (day$^{-1}$kg$^{-1}$) | Period III (day$^{-1}$kg$^{-1}$) | Combined (day$^{-1}$kg$^{-1}$) | $S_u$ (day$^{-1}$kg$^{-1}$) |
|-----------|-------------|-------------------|-------------------|------------------|-------------------------------|--------------------------------|--------------------------------|-----------------|
| $^6$Li$^+$ | 478         | 0.36              | 0.0048            | 0.61             | -0.88±0.75                   | 0.14±0.41                     | -0.09±0.36               | < 0.49          |
| $^{135}$Xe$^*$ | 526         | 0.34              | 0.0047            | 0.58             | 0.26±0.67                    | 0.38±0.16                     | 0.37±0.15               | < 0.62          |
| $^{91}$Y$^*$ | 555         | 0.33              | 0.0044            | 0.58             | -0.47±0.67                   | -0.33±0.15                    | -0.34±0.15               | < 0.05          |
| $^{137}$Ba$^*$ | 662         | 0.30              | 0.0040            | 0.54             | -0.46±0.62                   | -0.02±0.50                    | -0.19±0.39               | < 0.46          |
| $^{97}$Nb$^*$ | 743         | 0.28              | 0.0037            | 0.53             | 0.14±0.55                    | 0.22±0.37                     | 0.19±0.31               | < 0.69          |
| pn → d$\gamma$ | 2230       | 0.16              | 0.0020            | 0.37             | -0.10±0.17                   | -0.03±0.03                    | -0.04±0.03               | < 0.02          |

FIG. 4: (a) The after-cut ON and OFF spectra and (b) the residual spectra for the six specific channels for Period-III, with the best-fit Gaussian peaks overlaid.

cays, and (b) full $E_a$ of the individual ON/OFF spectra to look for axion emissions from other possible steady-state sources, such as those from the sun [17, 18]. No signals were observed in both cases.

V. DERIVATIONS OF AXION PARAMETERS

The experimentally measured upper limits $S_u$ of Table II can be translated to bounds among the axion parameters: $m_a$, $g_{a\gamma\gamma}$, $g_{aee}$, $g_{aNN}^0$ and $g_{aNN}^1$. Two approaches were adopted: (a) specific models were used and tested, and (b) model-independent constraints among the parameters were derived.

A. Branching Ratios for Axion Emissions

The limits $S_u$ are related to reactor axion emission and detection via

$$S_P + S_C < S_u .$$

Both $S_P$ and $S_C$ depend on the reactor axion flux, and thus the branching ratios ($\Gamma_a/\Gamma_\gamma$).

Starting from the interaction Lagrangian of Eq. II the axion emission branching ratio of the pn → d$\gamma$ isovector M1 transition can be expressed as [12, 19]:

$$\left(\Gamma_a/\Gamma_\gamma\right)_{pn} = \frac{\Gamma_a}{\Gamma_\gamma}(pn \rightarrow d\gamma)$$

$$= \left(\frac{1}{2\pi\alpha_{em}}\right) \left(\frac{p_a}{p_\gamma}\right)^3 \left(\frac{g_{aNN}^1}{\mu_1}\right)^2 ,$$

while those for ML transitions in general are [2, 12]

$$\left(\frac{\Gamma_a}{\Gamma_\gamma}\right) = \left(\frac{1}{\pi\alpha_{em}}\right) \left(\frac{1}{1 + \delta^2}\right) \left(\frac{L}{L + 1}\right) \left(\frac{p_a}{p_\gamma}\right)^{2L+1}$$

$$\left[ \frac{g_{aNN}^0 + g_{aNN}^1}{(\mu_0 - \mu_1)} \right]^2 .$$

In the formulae, $L$ is the multi-polarity of the transition, $\delta$ is the known $E(L+1)/ML$ mixing ratio, $\mu_0$ and $\mu_1$...
are respectively the isoscalar and isovector magnetic moments which can be derived from the proton and neutron magnetic moments ($\mu_p$ and $\mu_n$) via:

$$
\mu_0 = \mu_p + \mu_n \simeq 0.88 \tag{17}
$$

and

$$
\mu_1 = \mu_p - \mu_n \simeq 4.71. \tag{18}
$$

The nuclear physics of the transitions are parametrized by the matrix elements $\beta$ and $\eta$ defined as

$$
\beta = \frac{<J_f || \sum_{i=1}^{A} \sigma(i) || J_i>}{<J_f || \sum_{i=1}^{A} \sigma(i) \tau_3(i) || J_i>} \tag{19}
$$

and

$$
\eta = -\frac{<J_f || \sum_{i=1}^{A} l(i) \tau_3(i) || J_i>}{<J_f || \sum_{i=1}^{A} \sigma(i) \tau_3(i) || J_i>} \tag{20}
$$

where $J_i$ and $J_f$ are the initial and final nuclear angular momentum in the transitions, while $l(i)$ and $\sigma(i)$ are the orbital angular momentum and nuclear spin operators.

### B. Invisible Axion Models

The evaluations of $(\Gamma_a/\Gamma_\gamma)$ given in Eq. 16 involve modeling of the couplings $g_{aNN}^0$ and $g_{aNN}^1$. Within the framework of the invisible axion models, these couplings are inversely proportional to the symmetry breaking scale $f_a$ which in turn is related to $m_a$ via

$$
m_a/eV = \left( \frac{1.3 \times 10^7}{f_a/\text{GeV}} \right) \sqrt{1 + \frac{z}{\sqrt{z}}} \tag{21}
$$

such that the couplings depend linearly on $m_a$.

The formulae given in Table 1 of Ref. [7] were adopted for the parametrizations of these axion-nucleon couplings:

$$
g_{aNN}^0 = C \cdot \frac{(3F - D)}{6} \left( X_u - X_d - N_f \right)
+ \frac{S}{3} \left( X_u + 2X_d - N_f \right) \tag{22}
$$

and

$$
g_{aNN}^1 = C \cdot \frac{(D + F)}{2} \left[ X_u - X_d - N_f \left( \frac{1 - z}{1 + z} \right) \right] \tag{23}
$$

where the factor common to both couplings is

$$
C = 5.2 \times 10^{-8} \left( \frac{3}{N_f} \right) [m_a/\text{eV}] \tag{24}
$$

TABLE III: The calculated numerical factors $A^{g/1}$ of Eq. 25 under the KSVZ and DFSZ invisible axion models using the formulae of Ref. [7].

| Model   | $I$   | $A^I$ | Validity |
|---------|-------|-------|----------|
| KSVZ    | 0     | $-3.5 \times 10^{-8}$ | finite $g_{a\gamma\gamma}$ |
|         | 1     | $-2.8 \times 10^{-8}$ | $g_{aee} = 0$ |
| DFSZ    | 0     | $-2.6 \times 10^{-8}$ | finite $g_{a\gamma\gamma}$ & $g_{aee}$ |
|         | 0.5   | $-2.8 \times 10^{-8}$ | $g_{aee}$ |

The terms $D \simeq 0.77$ and $F \simeq 0.48$ are the reduced matrix elements for the octet axial vector currents, $S = 0.33 \pm 0.04$ denotes the flavor singlet axial charge, $N_f = 3$ is the number of families, $z = (m_u/m_d) \simeq 0.56$ is the ratio of the up-to-down quark mass, while $X_u$ and $X_d$ represent respectively the PQ charge of the u and d quarks. The KSVZ and DFSZ models differ essentially in their choices of $(X_u, X_d)$.

Previous evaluations of axion fluxes in the stellar environment adopted the KSVZ model where $X_u = X_d = 0$. This model also specifies $g_{aee} = 0$ at tree level such that the results are only applicable to probe the axion-photon $g_{a\gamma\gamma}$-couplings. We extended the analysis to include also the DFSZ model, which allows finite $g_{a\gamma\gamma}$ and $g_{aee}$-couplings. The parameters $X_u$ and $X_d$ are positive-definite constrained by $X_u + X_d = 1$. The values of $X_u = X_d = 0.5$ were chosen for this analysis. Defining

$$
g_{aNN}^{0/1} = A^{g/1} [m_a/\text{eV}] \tag{25}
$$

the calculable numerical factors $A^{g/1}$ under both KSVZ and DFSZ models are tabulated in Table III. The isovector couplings $g_{aNN}^1$ are the same for both models with this specific choice of $(X_u, X_d)$.

Once $g_{aNN}^0$ and $g_{aNN}^1$ are fixed by the invisible axion models, the evaluations of $(\Gamma_a/\Gamma_\gamma)$ depend on the nuclear physics inputs: $\delta$, $\beta$ and $\eta$. The values adopted for these parameters are summarized in Table IV. Among the transitions, the $\text{pn} \to \gamma\gamma$ is a pure isovector M1 process. Its branching ratio $(\Gamma_a/\Gamma_\gamma)_{\text{pn}}$, as given by Eq. 15 is independent of $(\delta, \beta, \eta)$ and was used in previous reactor axion experiments [10, 11, 12]. The $7\text{Li}^+$ transition is also pre-dominantly M1. The neutron shell is closed and the transition is driven by the odd-proton, such that $(\delta, \beta, \eta) \simeq (0, 1, 0.5)$ was adopted as in Ref. [17]. There were no calculations on $(\beta, \eta)$ for the remaining four fission daughter isotopes. To make estimations, we project from the results on other heavy isotopes [2, 21], also summarized in Table IV. The matrix elements $(\beta, \eta)$ for heavy isotopes with unpaired proton and neutron are taken to be $(1, -3)$ and $(\sim -1, 1)$, respectively.

Once these $(\beta, \eta)$ assignments are made, the branching ratios $(\Gamma_a/\Gamma_\gamma)$ can be readily evaluated with Eqs. 15–25. In particular, $\beta \leq 0$ for the odd-neutron nuclei $^{135}\text{Xe}$.
TABLE IV: A summary of the nuclear physics input in the evaluations of $(\Gamma_a/\Gamma_\gamma)$. Calculated values of $(\beta, \eta)$ on the other isotopes from previous works are included for comparisons. The branching ratios $(\Gamma_a/\Gamma_\gamma)$ at $m_a=1$ eV under the KSVZ and DFSZ invisible axion models and the quality factors (QF) relative to that for the $p_n \to d\gamma$ channel are also shown.

| Channel | Unpaired Transition | $\delta$ | $\beta$ | $\eta$ | Remarks | $(\Gamma_a/\Gamma_\gamma)$ | QF/(QF)$_{pn}$ | $(\Gamma_a/\Gamma_\gamma)$ | QF/(QF)$_{pn}$ |
|---------|---------------------|---------|--------|--------|---------|----------------|----------------|----------------|----------------|
| $p_n \to d\gamma$ | – M1 | – | – | – | Refs. [10, 11, 12] | $7.4 \times 10^{-16}$ | 1.00 | $7.4 \times 10^{-16}$ | 1.00 |
| $^7\text{Li}^+$ | p M1 | 0 | 1 | 0.5 | Ref. [17] | $4.0 \times 10^{-15}$ | 0.50 | $3.0 \times 10^{-15}$ | 0.43 |
| $^9\text{Y}^*$ | p M4 | 0 | 1 | -3 | Inferred | $2.1 \times 10^{-15}$ | 0.33 | $1.5 \times 10^{-15}$ | 0.28 |
| $^{97}\text{Nb}^*$ | p M4 | 0 | 1 | -3 | { from | $2.1 \times 10^{-15}$ | 0.13 | $1.5 \times 10^{-15}$ | 0.11 |
| $^{135}\text{Xe}^*$ | n M4 | 0 | -1 | 1 | Refs. [2, 21] | $1.6 \times 10^{-16}$ | 0.02 | $7.1 \times 10^{-18}$ | 0.003 |
| $^{137}\text{Ba}^*$ | n M4 | 0 | -1 | 1 | Refs. [2, 21] | $1.6 \times 10^{-16}$ | 0.01 | $7.1 \times 10^{-18}$ | 0.003 |
| $^{60}\text{Cu}^*$ | p M1 | 0.44 | 1.81 | -6.59 | Ref. [2] | $1.0 \times 10^{-16}$ | – | $7.1 \times 10^{-16}$ | – |
| $^{57}\text{Fe}^*$ | n M1 | 0.002 | -1.19 | 0.80 | Ref. [21] | $3.4 \times 10^{-16}$ | – | $2.2 \times 10^{-17}$ | – |
| $^{55}\text{Mn}^*$ | p M1 | 0.052 | 0.79 | -3.74 | Ref. [21] | $8.5 \times 10^{-16}$ | – | $6.6 \times 10^{-16}$ | – |
| $^{23}\text{Na}^*$ | p M1 | 0.058 | 0.88 | -1.20 | Ref. [21] | $1.9 \times 10^{-15}$ | – | $1.4 \times 10^{-15}$ | – |

$^\dagger$ Evaluated at $m_a=1$ eV

and $^{137}\text{Ba}^*$, such that the $g_a^{0NN}$ and $g_a^{1NN}$ terms have opposite signs and $(\Gamma_a/\Gamma_\gamma)$ can be vanishingly small within the large nuclear physics uncertainties. These two channels were discarded in subsequent analysis. The variations of $(\Gamma_a/\Gamma_\gamma)$ with $m_a$ of the four remaining channels are depicted in Figure 5. The differences within the channels and between the KSVZ and DFSZ models are small relative to the scale in the log-log plot, and are represented by the width of the line.

![Figure 5: The variations of $(\Gamma_a/\Gamma_\gamma)$ with $m_a$ in both KSVZ and DFSZ invisible axion models as parametrized in Ref. [7]. The $^{135}\text{Xe}^*$ and $^{137}\text{Ba}^*$ channels have large uncertainties and were discarded. The width represents the variations within the four remaining channels and among the two models.](image)

The experimental sensitivities in $g_{a\gamma\gamma}$ and $g_{aee}$ can be described by a quality factor (QF) which is related to the $\gamma$-flux $\Phi_\gamma$ of Table I and the upper limit signal rates $S_u$ of Table II via:

$$\frac{1}{g_{a\gamma\gamma/aee}} \propto \text{QF} \equiv \sqrt{\frac{\Phi_\gamma \cdot (\Gamma_a/\Gamma_\gamma)}{S_u}}.$$  

Both $(\Gamma_a/\Gamma_\gamma)$ and the relative QF (with respect to that of the $p_n \to d\gamma$ channel) evaluated at $m_a=1$ eV were shown in Table IV to illustrate the relative strength of the various channels. It can be seen that the leading contribution to the sensitivities is from the $p_n \to d\gamma$ channel.

C. Model-Dependent Limits

The $(\Gamma_a/\Gamma_\gamma)$ estimates in Table IV for $p_n \to d\gamma$ and $^7\text{Li}^+$ are accurate while those for the four heavy fission isotopes are expected to have large uncertainties. In addition, the relative QF values of Table IV indicate that the $p_n \to d\gamma$ channel mostly defines the sensitivities. Accordingly, we take the conservative approach that the experimental limits on $g_{a\gamma\gamma}$ and $g_{aee}$ were derived only from this channel. The two detection channels were treated independently, via the relations

$$S_P < S_U \quad \& \quad S_C < S_U,$$

assuming, respectively, $g_{aee} = 0$ and $g_{a\gamma\gamma} = 0$. These produce less stringent bounds compared to those from the convoluted case of Eq. 14 such that the results have general validity.

The exclusion plot of $g_{a\gamma\gamma}$ versus $m_a$ is depicted in Figure 6. The model-dependence was introduced by fixing $(\Gamma_a/\Gamma_\gamma)_{pn}$ as a function of $m_a$ via Eqs. 15 & 25. The values of $(\Gamma_a/\Gamma_\gamma)_{pn}$ depend only on $g_a^{0NN}$ and are therefore the same for both KSVZ and DFSZ models, as shown in Table IV. Consequently, both models produce a common exclusion region, denoted by “KS”. On the other hand, the KSVZ model specifies $g_{aee} = 0$ at tree level, such that only the DFSZ model can be meaningfully applied to define the exclusion region, also labeled as “KS”, in the $g_{aee}$ versus $m_a$ plot of Figure 7.

In both Figures 6 & 7 the vertical bounds labeled “Kine” at 2.23 MeV are due to the kinematical constraints from the maximum $E_a$. The sensitivities are suppressed at “Decay” for the large $(m_a, g_{a\gamma\gamma}/g_{aee})$ regions,
FIG. 6: Exclusion plots of $g_{a\gamma\gamma}$ versus $m_a$ for $g_{ace}=0$. The limits from the KS experiment at 90% CL are denoted by “KS”. They are derived by fixing $(\Gamma_a/\Gamma_\gamma)_p$ with the KSVZ and DFSZ invisible axion models. Predicted regions of the PQWW, KSVZ, DFSZ and HW models on the ($m_a, g_{a\gamma\gamma}$) plane are overlaid. The boundaries defined by “Int”, “Decay” and “Kine” are constraints due to axions interactions with matter, decays in flights and kinematics, respectively. The bounds marked “Zn” are results from Ref. [2], while region labeled “R” are from previous reactor axion experiments studying $\Gamma_\gamma$ [10]. Results from the other axion experiments using different techniques [23, 24, 27, 29] are displayed as colored blocks. The astrophysical bounds [9] are denoted by the striped region.

due to $\Gamma_\gamma$ and $\Gamma_{ee}$ decays in flight. The lack of sensitivities at “Int” for large $g_{a\gamma\gamma} \gtrsim 20$ GeV$^{-1}$ and $g_{ace} \gtrsim 0.2$ are due to axion interactions in the matter between reactor core and detector. Limits marked “R” and “Zn” are respectively from previous reactor experiments studying $\Gamma_\gamma$ [10] or $\Gamma_{ee}$ [11] and the radioactive source experiment [2]. They were derived using the same modeling schemes on $(\Gamma_a/\Gamma_\gamma)$ as “KS”. The bounds from the KS reactor axion searches improve on those of Ref. [2] by two orders of magnitude, owing to enhanced axion flux, lower background and larger data sample.

The KS results define the global exclusion boundaries in $g_{a\gamma\gamma}$ for $10^3$ eV $\lesssim m_a \lesssim 10^6$ eV and in $g_{ace}$ for $10^3$ eV $\lesssim m_a \lesssim 10^6$ eV. Astrophysics arguments on stellar cooling and red giant yields [1, 8] provide more stringent bounds for $m_a \lesssim 10^5$ eV but these are model-dependent. They are represented by the striped regions in Figures 6–7, respectively. Comparisons of the KS excluded regions with the KSVZ/DFSZ predictions on the ($m_a, g_{a\gamma\gamma}/g_{ace}$) planes would rule out these models at $10^4$ eV $\lesssim m_a \lesssim 10^6$ eV. An example of other existing model predicting axion mass at the MeV range is the HW model [22], also depicted in the figures.

The experimental approach presented in this article can probe the keV–MeV axion mass range which is not accessible to the other techniques. At large $m_a \gtrsim 10^6$ eV, the sensitivities in both $g_{a\gamma\gamma}$ and $g_{ace}$ are dominated by the accelerator-based “beam dump” experiments [23]. Exclusion boundaries at small $m_a$ are defined by: (a) for $g_{a\gamma\gamma}$ – the germanium [24] and CAST [25] experiments studying solar axions, and the axion dark matter searches with microwave cavity [26]; and (b) for $g_{ace}$ – the positronium decay [27] and macroscopic force [28] experiments. At $g_{a\gamma\gamma} > 10^{-2}$ GeV$^{-1}$, the solar axion experiments are limited by axion interactions inside the Sun [3]. Part of this large-$g_{a\gamma\gamma}$ region has been rejected by the optical laser experiments [29], while the KS results contribute to probe and exclude a remaining hole at $m_a \sim 10^1$ eV. For completeness, we mention also the

FIG. 7: Exclusion plots of $g_{ace}$ versus $m_a$ for $g_{a\gamma\gamma}=0$. Similar conventions as Figure 6 are adopted. The “KS” bounds are derived by fixing $(\Gamma_a/\Gamma_\gamma)_p$ with the DFSZ model. Regions marked “R” was excluded by experiment studying $\Gamma_\gamma$ at reactors [11]. Bounds from other experiments [23, 27, 29] are shown as colored blocks.
recent PVLAS experiment which reported a finite light polarization rotation in vacuum with a transverse magnetic field \( g_{S} \). This result was interpreted as the region "P" of finite \( (m_{a},g_{a\gamma\gamma}) \) in Figure 4 well contradicted by many other experiments. This would imply that it may not be appropriate to analyze the PVLAS results using the existing axion models.

D. Model-Independent Constraints

The KS exclusion regions of Figures 6 and 7 were evaluated within the framework of the invisible axion models. Alternatively, it is also instructive to derive model-independent constraints among the axion parameters. Following the reasonings of Section V.C, only the results from the \( pn \rightarrow d\gamma \) channel were adopted, and the two couplings \( g_{a\gamma\gamma} \) and \( g_{aee} \) were treated independently.

The experimental sensitivities are defined by the signal rates \( S_{P/C} \) which are proportional to \( g_{a\gamma\gamma/aee}(\Gamma_{a}/\Gamma_{\gamma}) \) and alternatively, via Eq. 4, to \( g_{a\gamma\gamma/aee}g_{aNN} \). Limit on the Primakoff conversion rate \( S_{P} < S_{u}(pn \rightarrow d\gamma) \) gives rise to the model-independent constraint

\[
\begin{align*}
g_{a\gamma\gamma} \cdot g_{aNN} & < 5.9 \times 10^{-17} \text{ GeV}^{-2} \quad (28) \\
g_{a\gamma\gamma} \cdot g_{aNN} & < 7.7 \times 10^{-9} \text{ GeV}^{-1} \quad (29)
\end{align*}
\]

which are applicable within the ranges of \( m_{a} \lesssim 10^{6} \text{ eV} \) and \( g_{a\gamma\gamma} \lesssim 20 \text{ GeV}^{-1} \), bounded by kinematics and axion interactions in flight, respectively. Similarly, the limit on the Compton conversion rate \( S_{C} < S_{u}(pn \rightarrow d\gamma) \) leads to

\[
\begin{align*}
g_{aee} \cdot g_{aNN} & < 1.7 \times 10^{-20} \quad (30) \\
g_{aee} \cdot g_{aNN} & < 1.3 \times 10^{-10} \quad (31)
\end{align*}
\]

for \( m_{a} \lesssim 10^{6} \text{ eV} \) and \( g_{aee} \lesssim 0.2 \). The loss of sensitivities in \( g_{a\gamma\gamma} \) at \( m_{a} \sim 10^{6} \text{ eV} \) can be explained by the reduction of the Primakoff cross-section as depicted in Figure 3. These constraints on \( g_{a\gamma\gamma} \) and \( g_{aee} \) as functions of \( g_{aNN} \) and \( (\Gamma_{a}/\Gamma_{\gamma})_{pn} \) are illustrated respectively in Figures 6a & 6b. Limits from the most sensitive laboratory experiments are also displayed for comparisons.

The KS limits on \( g_{a\gamma\gamma} \) are not as sensitive as those of CAST [23] and the solar-germanium [24] experiments for \( m_{a} \lesssim 10^{6} \text{ eV} \) at all branching ratios. On the contrary, the \( g_{aee} \) sensitivities exceed those of the positronium decay [24] and macroscopic force [25] experiments. New regions are probed for \( m_{a} \gtrsim 10^{-6} \text{ eV} \) with \( (\Gamma_{a}/\Gamma_{\gamma})_{pn} > 10^{-9} \) and for \( m_{a} \lesssim 10^{-6} \text{ eV} \) with \( (\Gamma_{a}/\Gamma_{\gamma})_{pn} > 10^{-5} \).

VI. SUMMARY AND PROSPECTS

This article reports the first study of possible emissions of axions from power reactors using Primakoff and

FIG. 8. The model-independent exclusion regions of the KS experiment for (a) \( g_{a\gamma\gamma} \) and (b) \( g_{aee} \) on the \( (\Gamma_{a}/\Gamma_{\gamma})_{pn} \) and \( g_{aNN} \) axes. The \( g_{a\gamma\gamma} \) and \( g_{aee} \) limits from the leading laboratory experiments are also shown for comparisons. The ranges of validity in \( m_{a} \) are indicated.

Compton conversions as the detection mechanisms. No evidence were observed and constraints on axion parameters were placed.

The exclusion regions in the \( (m_{a},g_{a\gamma\gamma}/g_{aee}) \) parameter space were identified within the framework of the invisible axion models. The branching ratios for axion emissions associated with radioactive \( \gamma \)-decays are proportional to \( m_{a}^{2} \), such that the experiment is sensitive mostly at the large axion mass region. The KS results define the global exclusion boundaries for \( g_{a\gamma\gamma} \) and \( g_{aee} \) and excluded the KSZV and DFSZ models for \( 10^{4} \text{ eV} \lesssim m_{a} \lesssim 10^{6} \text{ eV} \).

Independent of models, the KS results are not as sensitive in constraining \( g_{a\gamma\gamma} \) compared to those from solar axi-
ion searches, but improve on the limits in $g_{\text{acc}}$ for branching ratios as small as $(\Gamma_a/\Gamma_\gamma)_\text{pn} > 10^{-9}$ for light-mass axions such as those within the cosmologically-preferred range of $10^{-6} \text{ eV} < m_a < 10^{-2} \text{ eV}$.

Our studies therefore indicate that this experimental approach can provide competitive sensitivities compared to the other techniques when (a) the axion physics is correctly described by the invisible axion models and the axion mass is at the keV–MeV range, or (b) the axion physics allows relatively large axion-nucleon couplings (and consequently the axion emission branching ratios) at small axion mass not yet covered by the current theoretical modeling.

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* Corresponding Author: htwong@phys.sinica.edu.tw

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