Axions-2020

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ICCPA-2020, October 6
Some of the original results obtained jointly with
A. Korochkin, G. Rubtsov, M. Libanov,
D. Gorbunov, P. Tinyakov, I. Tkachev,
M. Fairbairn, T. Rashba

Supported in part by the Russian Science Foundation
A general U(1): axion-like particles (ALPs)

spontaneous breaking of U(1): Goldstone boson (massless)

(one scale)

spontaneous + small explicit breaking: pseudo-Goldstone boson (light)

(two scales)
The U(1): Peccei & Quinn 1977

**CP Conservation in the Presence of Pseudoparticles**

R. D. Peccei and Helen R. Quinn

Department of Physics, Stanford University, Stanford, California 94305

(Received 21 March 1977)

We give an explanation of the CP conservation of strong interactions which includes the effects of pseudoparticles. We find it is a natural result for any theory where at least one flavor of fermion acquires its mass through a Yukawa coupling to a scalar field which has a vanishing vacuum expectation value.
Roberto
PECCEI
1942 – 2020
Personal: “Peccei’s money” 1993

Nuclear Physics B412 (1994) 607–620
North-Holland

Tree amplitudes at multiparticle threshold in a model with softly broken O(2) symmetry

M.V. Libanov, V.A. Rubakov and S.V. Troitsky
Institute for Nuclear Research of the Russian Academy of Sciences, 60th October Anniversary prospect, 7a, 117 312 Moscow, Russian Federation

Received 13 July 1993
Accepted for publication 26 July 1993

The work of M.L. and S.T. is supported in part by the Weingart Foundation through a cooperative agreement with the Department of Physics at UCLA.
Axions and ALPs are popular...

- strong CP problem
- fundamental symmetries
- string theories
- dark matter
- cosmological structure formation
- topological defects
- stellar evolution
- supernovae
- gamma-ray astronomy
- UHE cosmic rays
- solar corona heating

……
ALP-photon interaction

\[ \mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} (\partial \alpha)^2 - \frac{1}{2} m^2 a^2 - \frac{1}{4} g a F_{\mu\nu} \tilde{F}^{\mu\nu} \]

- allowed by all symmetries, hence appears
- dimensionful coupling $g$ suppressed by the U(1) breaking scale
  ✓ related to the ALP mass for a particular model, e.g. the QCD axion
- photon/ALP mixing in the external magnetic field
- conversion probability depends on the mass, coupling, energy and field

\[ \frac{a}{M} F_{\mu\nu} \tilde{F}^{\mu\nu}, \quad M \sim f_A \sim \frac{\Lambda_{\text{QCD}}^2}{m} \]
ALP-fermion interaction

- coupling of a (pseudo)Goldstone boson determined by the current algebra

- dimensionless coupling suppressed by the U(1) breaking scale
  - related to the ALP mass for a particular model, e.g. the QCD axion

- zero or not, depending on particular quantum numbers

- electron-ALP coupling of particular interest

\[ \sim \frac{m_\psi}{f_A} a \bar{\psi} \gamma_5 \psi \]
ALP-photon: shining light through walls

Search for axions in a laboratory
Pair production: the Universe is opaque to gamma rays

the most intense pair production:

\[
\frac{s}{4m_e^2} \sim 2\ldots 4 \\
E_\gamma \sim 5 \times 10^{11} (\omega/eV)^{-1} \text{ eV}
\]
ALP-photon: shining light through the Universe

Search for axions with gamma-ray astronomy
ALP: “anomalous transparency of the Universe”?

- “IR/TeV crisis” – individual sources
  - Protheroe, Meyer 2000 + …

- Spectra of distant sources look differently compared to physically similar nearby ones
  - Kneiske, unpublished

- Statistics of “deabsorbed” spectra:
  - Features right at the energies for which the correction becomes important!
    - Horns, Meyer 2012
    - Rubtsov, ST 2014

State of the art – increasing statistics, better known distances:
- The anomaly is confirmed for a part of sources – both “old” and “new” ones
- Many new, weaker sources do not demonstrate any problem
- Modest overall statistical significance of the anomaly
  - Korochkin, Rubtsov, ST 2019
Anisotropy: anomalous sources point to the local filament!

Red: “anomalous” gamma-ray blazars, $E>100$ GeV

Blue: BL Lacs correlated with HiRes cosmic rays, $E>10^{19}$ eV

Black: VHE GRB (not in the statistical analysis) HESS 2020, MAGIC 2020

Shadow: weighted density of nearby galaxies 2MRS 2019

Supports the axion-photon mixing in large-scale structure filaments

Fairbairn, Rashba, ST 2009
Future tests of the anisotropy and its ALP explanation

- isotropic samples of blazars
- tests of HiRes BL Lac correlations with Telescope Array
- search for the ALP in a lab
  - ✓ ALPS-IIc in DESY (light through walls)
  - ✓ babyIAXO (solar axions/ALPs)

Test the axion-photon mixing in large-scale structure filaments

*Fairbairn, Rashba, ST 2009*
**XENON1T 2020 – a claim for a solar ALP**

- liquid xenon experiment for dark-matter search in Gran Sasso
- electronic recoil
- excess of counts at low energies (2-3 keV, range 1-30 keV)
- consistent with a signal from solar ALP interacting with electrons
- axion explanation preferred over known systematics/backgrounds
ALPs affect stellar evolution

light particles with very suppressed interactions remove energy from stellar interiors

**evolutionary timescales shorten**

light particles with stronger but suppressed interactions result in energy transfer between parts of a star

**mechanical construction of a star changes**

relevant for the electron coupling:

- **white-dwarf luminosity function**
  - average rate of WD cooling
  - *Blinnikov, Vysotsky 1990*

- **HB stars to red giants ratio**
  - time scale of helium burning
  - *Dicus et al. 1978*

- **pulsating white dwarf period change**
  - rate of individual WD cooling
  - *Isern et al. 1992*

- **tip of the red-giant branch**
  - time of helium ignition
  - *Raffelt 1990*

**constrains much stronger than from laboratory experiments**

reviews: *Raffelt 1996 (book), Giannotti et al. 2015, 2017*
XENON1T 2020 – axion explanation excluded from stars

- ALP-electron coupling too large!
- no helium-burning stars form at all...
- solar lifetime OK
- exclusion significances:

19 sigma exclusion. 10 times lower coupling already excluded at 99% CL

<table>
<thead>
<tr>
<th>Observable</th>
<th>Measured</th>
<th>Expected</th>
<th>Tension</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$ parameter</td>
<td>$1.39 \pm 0.03$</td>
<td>$\leq 0.83(g_{e13} = 9)$</td>
<td>19$\sigma$*</td>
</tr>
<tr>
<td>$M_{\chi TMB}^{\text{AMC}}$ (mag.)</td>
<td>$-4.047 \pm 0.045$</td>
<td>$\leq -4.92(g_{e13} = 9)$</td>
<td>19$\sigma$*</td>
</tr>
<tr>
<td>$g_{e13}$</td>
<td>$\leq 2.8(3\sigma)$</td>
<td>$29.7 \pm 4.8$</td>
<td>5.6$\sigma$</td>
</tr>
<tr>
<td>$f_{\text{L19-2}}^{(113)}$</td>
<td>$3.0 \pm 0.6$</td>
<td>$57 \pm 16$</td>
<td>3.4$\sigma$</td>
</tr>
<tr>
<td>$f_{\text{L19-2}}^{(192)}$</td>
<td>$3.0 \pm 0.6$</td>
<td>$95 \pm 27$</td>
<td>3.4$\sigma$</td>
</tr>
<tr>
<td>$f_{\text{PG1315+489}}$</td>
<td>$200 \pm 90$</td>
<td>$19620 \pm 5730$</td>
<td>3.4$\sigma$</td>
</tr>
<tr>
<td>$f_{\text{G117-B15A}}$</td>
<td>$4.2 \pm 0.7$</td>
<td>$113 \pm 33$</td>
<td>3.3$\sigma$</td>
</tr>
<tr>
<td>$f_{\text{RS48}}$</td>
<td>$3.3 \pm 1.1$</td>
<td>$87 \pm 25$</td>
<td>3.3$\sigma$</td>
</tr>
</tbody>
</table>
Purely laboratory axion experiment: ALPS-IIc

- light shining through the wall
- straightened HERA magnets
- locked cavities
  (resonant generation and regeneration)
- data taking soon

Axions-2020 // Sergey Troitsky
06.10.2020
Russian axion helioscope not funded

- helioscopes: detection of solar axions in a lab
- CAST in CERN – world-best limits on the photon coupling
- TASTE proposed in 2017 – x100 S/N improvement with refurbished equipment, cost 3 MEuro
- not funded in 3 years
European axion helioscope funded: babyIAXO

- similar concept and sensitivity as TASTE
- proposed in 2017, few months after TASTE
- 6.5 MEuro received from European grants
- construction started in DESY
- former TASTE groups joining babyIAXO now
Axions-2020

- tribute to late Roberto Peccei, wish more discoveries to Helen Quinn

- axions in gamma-ray astronomy: some hints and more tests to come

- XENON1T excess: axion explanation excluded from stars by 19 sigma

- new laboratory experiments are coming, but not in Russia