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Prospects of the RadioAxion-α experiment

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The on-going experiment RadioAxion-α, based at the Gran Sasso Laboratory, aims to investigate the time modulation of the α-decay of Americium-241 deep underground as a method to explore axion dark matter. We provide the theoretical description of α-radioactivity in the presence of an oscillating axion dark matter background and present the prospects of the experiment.

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1. Introduction

We have proposed to investigate the time modulation of radioisotope decays deep underground as a method to test axion dark matter, with focus on the α-decay of Americium-241 [1]. To this end, we have constructed and installed a prototype setup (RadioAxion-α) at the Gran Sasso Laboratory.

2. Microscopic theory of α-decay

We consider a theory of α-decay of a heavy isotope, ${}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X} \to {}^{\mathrm{A}-4}_{\mathrm{Z}-2}\mathrm{X} + \alpha$, obtained by computing the tunneling probability of the α-particle within a WKB framework that employs a microscopic α–daughter-nucleus potential. In the semi-classical approximation, the half-life is given by $T_{1/2} \propto \exp(K)$ [2, 3], where, in natural units,

$$K = 2\int_{r_1}^{r_2} dr\, \sqrt{2M_\alpha [V_{\mathrm{tot}}(r) - Q_\alpha]} \tag{1}$$

is the WKB integral, $Q_\alpha = M(A,Z) - M_d - M_\alpha$ is the energy of the emitted α-particle and $r_{1,2}$ the turning points of the potential, defined by the conditions $V_{\mathrm{tot}}(r_1) = V_{\mathrm{tot}}(r_2) = Q_\alpha$.

The central potential among the α-particle and daughter nucleus is the sum of the nuclear potential, the Coulomb potential and the rotational term. In the limit of a squared potential well, the total potential reads (assuming vanishing angular momentum)

$$V_{\mathrm{tot}}(\vec{R}) = \begin{cases} -V_0 \quad \text{for } R < R_0\, A^{1/3}\,, \\ \\ \frac{Z_\alpha Z_d \alpha_{\mathrm{QED}}}{R} \quad \text{for } R > R_0\, A^{1/3}\,, \end{cases} \tag{2}$$

where $R = |\vec{R}|$ and $R_0 \approx 1.13$ fm. Such expression yields the following analytical result for the WKB integral

$$K = Z_\alpha Z_d \alpha_{\mathrm{QED}} \left(\frac{8M_\alpha}{Q_\alpha}\right)^{1/2} F\left(\frac{Q_\alpha R_0\, A^{1/3}}{Z_\alpha Z_d \alpha_{\mathrm{QED}}}\right)\,, \tag{3}$$

with

$$F(x) = \arccos\sqrt{x} - \sqrt{x}\sqrt{(1-x)} \approx \frac{\pi}{2} - 2\sqrt{x} + \dots\,. \tag{4}$$

Note that the α-decay process is exponentially sensitive to the WKB integral, so that the lifetimes span several orders of magnitudes when varying the Q_α value for different nuclei.

3. θ-dependence of α-decay

The θ-term of QCD is defined by the operator

$$\mathcal{L}_\theta = \frac{g_s^2\theta}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu}\,, \tag{5}$$

where $|\theta| \lesssim 10^{-10}$ from the non-observation of the neutron EDM [4]. The smallness of θ constitutes the so-called strong CP problem, which can be solved by promoting the θ-term to be a dynamical field, $\theta \to a(x)/f_a$, where $a(x)$ is the axion and f_a a mass scale known as the axion decay constant.

The axion field acquires a potential in the background of QCD instantons and relaxes dynamically to zero, thus explaining the absence of CP violation in strong interactions [5–8] (for a review, see e.g. [9]).

There are various ways in which the θ-dependence can manifest in nuclear physics, see Refs. [10, 11], the most prominent is through the pion mass

$$M_\pi^2(\theta) = M_\pi^2 \cos\frac{\theta}{2}\sqrt{1+\varepsilon^2\tan^2\frac{\theta}{2}}\,, \tag{6}$$

with $M_\pi = 139.57$ MeV and $\varepsilon = (m_d - m_u)/(m_d + m_u)$. A key role for the binding energy of heavy nuclei is played by the σ and ω channels, via the contact interactions [12]

$$H = G_S(\bar{N}N)(\bar{N}N) + G_V(\bar{N}\gamma_\mu N)(\bar{N}\gamma^\mu N)\,, \tag{7}$$

which control, respectively, the scalar (attractive) and vector (repulsive) part of the nucleon-nucleon interaction [13, 14]. In Ref. [15] it was found that the pion mass dependence of ω exchange leads to subleading corrections compared to the effects related to the M_π^2 sensitivity of the scalar channel. Hence, to a good approximation, we can consider only the leading θ-dependence in the scalar channel, which is described by the following fit [16] to Fig. 2 in [14]

$$\eta_S(\theta) \equiv \frac{G_S(\theta)}{G_S(\theta=0)} = 1.4 - 0.4\frac{M_\pi^2(\theta)}{M_\pi^2}\,. \tag{8}$$

Moreover, based on the relativistic mean-field simulations of [12] for two specific nuclei, Ref. [14] finds that the variation of the binding energy (BE) for a nucleus of mass number A can be written as (keeping only the variation due to $\eta_S(\theta)$)

$$\mathrm{BE}(\theta) = \mathrm{BE}(\theta=0) + (120A - 97A^{2/3})(\eta_S(\theta) - 1)\,\mathrm{MeV}\,, \tag{9}$$

where the terms proportional to A and $A^{2/3}$ represent a volume and surface contribution, in analogy to the semi-empirical mass formula [17].

Hence, substituting the expressions of the BEs above in the definition of $Q_\alpha = \mathrm{BE}(A-4, Z-2) + \mathrm{BE}(4,2) - \mathrm{BE}(A,Z)$, we find

$$Q_\alpha(\theta) = Q_\alpha(\theta=0) - 97\text{ MeV}\,(\eta_S(\theta)-1)\,\left[(A-4)^{2/3} + 4^{2/3} - A^{2/3}\right]. \tag{10}$$

It turns out that $Q_\alpha(\theta)$ provides, by far, the leading effect in order to assess the θ-dependence of α-decay.

4. Axion dark matter time modulation

Assuming an oscillating axion dark matter field from misalignment [18–20], the time dependence of the θ angle can be approximated as $\theta(t) = \theta_0\cos(m_a t)$, with

$$\theta_0 = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_a f_a}\,, \tag{11}$$

in terms of $\rho_{\rm DM} \approx 0.45\,{\rm GeV/cm}^3$. For a standard QCD axion, one has $m_a f_a = (76~{\rm MeV})^2$, corresponding to $\theta_0 = 5.5 \times 10^{-19}$. In the following, we will treat m_a and f_a as independent parameters and discuss the sensitivity of α-decay observables in the $(m_a, 1/f_a)$ plane.

Following Ref. [21] and using $\theta^2 \ll 1$, we introduce the observable

$$\begin{aligned} I(t) &\equiv \frac{T^{-1}_{1/2}(\theta(t)) - \langle T^{-1}_{1/2}\rangle}{\langle T^{-1}_{1/2}\rangle} \approx -\frac{1}{2}\frac{\mathring{T}_{1/2}(0)}{T_{1/2}(0)}\theta_0^2\cos(2m_a t) \\ &= -4.3\times 10^{-6}\cos(2m_a t)\left(\frac{\rho_{\rm DM}}{0.45\,{\rm GeV/cm}^3}\right)\times\left(\frac{10^{-16}\,{\rm eV}}{m_a}\right)^2\times\left(\frac{10^{8}\,{\rm GeV}}{f_a}\right)^2 , \qquad (12) \end{aligned}$$

where $\langle T^{-1}_{1/2}\rangle$ denotes a time average and we introduced the derivative symbol, $\mathring{f} \equiv df/d\theta^2$. Here $\mathring{T}_{1/2}(0)/T_{1/2}(0) \approx 125$ has been obtained for the transition ${}^{241}{\rm Am} \to {}^{237}{\rm Np}^\star + \alpha$ with $Q_\alpha(\theta = 0) = 5.486$ MeV.

5. Sensitivity estimate

This isotope ^{241}Am has a relatively long half-life of about 432.2 yr (approximately stable on the timescale of the measurement) and it predominantly decays by α-emission, with a γ-ray byproduct, ${}^{241}{\rm Am} \longrightarrow {}^{237}{\rm Np} + \alpha + \gamma(59.5\,{\rm keV})$. A 3” × 3” NaI crystal detects the γ-rays due to the α-decay of ^{241}Am, primarily (85% of the time) at 59.5 keV, and the X-rays from ^{237}Np atomic transitions.

The theoretical prediction in Eq. (12) can be compared with $I_{\rm exp}(t) \equiv (N(t) - \langle N\rangle)/\langle N\rangle$, where $N(t)$ is the observed number of events in a given interval of time and $\langle N\rangle$ its expected value, according to the exponential decay law. Potential sources of systematic errors include the detection of γ-rays and their time-stamping. The former is mitigated by operating the NaI detector well-below the radiation damage threshold and by the reduced background in the underground environment. The latter is handled thanks to the precision of a Rb atomic clock. Hence, we expect our uncertainties to be statistically dominated in the current setup.

With a rate of about 4 kHz events, we expect to reach a 2σ error of $2/\sqrt{4000/s \times \pi \times 10^7 s} \approx 6 \times 10^{-6}$ on $I_{\rm exp}$ after one year of data taking. Given the 160 ns time resolution of our setup and referring to the oscillation period as Δt, we consider two realistic benchmarks corresponding to distinct experimental phases: *i*) Phase 1: $1\,\mu{\rm s} < \Delta t < 10$ days and $I_{\rm exp} = 2 \times 10^{-5}$ at 2σ with one month of data taking and *ii*) Phase 2: $1\,\mu{\rm s} < \Delta t < 1\,{\rm yr}$ and $I_{\rm exp} = 4 \times 10^{-6}$ at 2σ with three years of data taking.

We show the region of the parameter space we aim to test in the two phases of the experiment in Fig. 1. See [22] for a summary of the relevant constraints on this plane.

6. Conclusions

Our investigation into the time modulation of radioisotope decays deep underground at the Gran Sasso Laboratory has successfully established the RadioAxion-α experiment. This setup, centered on the α-decay of ^{241}Am, will allow us to cover a wide range of oscillation periods from microseconds to a year. Based on realistic projected sensitivities, we will provide with just few years of data competitive constraints on the axion decay constant, spanning 13 orders of magnitude

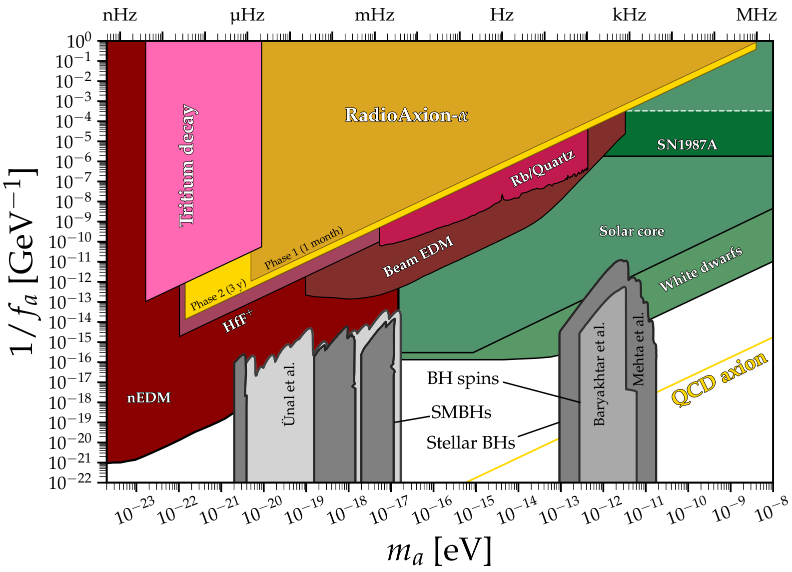

Figure 1: Constraints on the axion dark matter coupling to gluons. The projected sensitivities of RadioAxion-α are displayed for two experimental phases (yellow-shaded areas). Limits from laboratory experiments (red-shaded areas), astrophysics (green) and black holes (gray) are shown as well for comparison. Figure adapted from [22].

in axion mass, from from 10^{-9} eV to 10^{-22} eV. We anticipate a better sensitivity compared to existing experiments based on radioactivity, such as Tritium decay, and moderately weaker than radio-frequency atomic transitions, which are both sensitive to $\theta^2(t)$. On the other hand, EDM-like searches still remain the most effective ones, since they depend linearly from $\theta(t)$.

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