The ATOMKI anomaly after MEG-II: A theoretical overview

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Summary. — Recent results from the Atomki collaboration have reported anomalous features in nuclear transitions involving Beryllium, Helium, and Carbon, which may point to physics beyond the Standard Model. However, in light of MEG-II null result, we revisit theoretical interpretations involving a new boson X with mass around 17 MeV. In particular, we study the phenomenology of a spin 2 mediator and reassess the viability of a purely CP-even scalar, which was previously disfavored due to its inability to account for the Beryllium signal.

1. – The discovery of X17

This proceeding summarizes results from our recent work [1], co-authored with D. Barducci, D. Germani, M. Nardecchia, C. Toni.

The X17 anomaly was first reported in 2015 by the ATOMKI experiment in Hungary [2]. The goal of the experiment was to study rare nuclear transitions by bombarding a target material A with a low-energy proton beam, thereby producing an excited nuclear state N^*. Typically, such excited nuclei decay via the emission of a real photon (gamma decay). However, in rare cases, the photon is virtual and can internally convert into an electron–positron pair. This process is known as internal pair creation (IPC). The reaction under investigation can be schematically written as $p + A \to N^* \to N + e^+e^-$.

IPC is a Standard Model (SM) process, with a predicted branching ratio typically of order 10^{-6}, depending on the specific properties of the nucleus involved. What the SM does not account for, however, is the resonance-like feature observed in the invariant mass spectrum of the e^+e^- pairs: a pronounced peak around 17 MeV, as shown in fig. 1. The same resonant behaviour observed in Beryllium was later reported in transitions involving Helium [3] and Carbon [4] nuclei. These observations suggest the possible existence of a new, intermediate resonance—interpreted as a hypothetical particle—produced in the decay from the excited nuclear state to the ground state. The proposed decay chain is: $N^* \to N + X \to N + e^+e^-$. The mass m_X is measured to be $m_X = 16.85\,\text{MeV}$ [5]. Lacking imagination, the name chosen was X17.

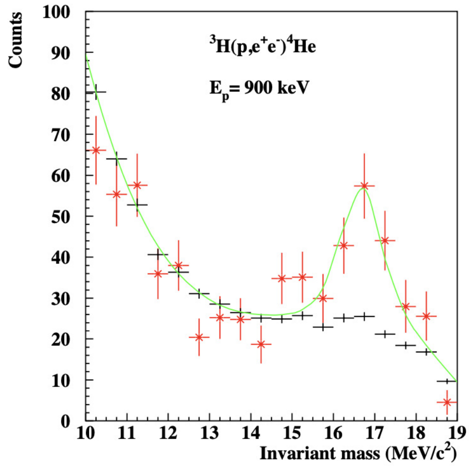

Figure 1.: Histogram of e^+e^- invariant mass. Notice the resonant peak around 17 MeV. Courtesy of [**?**].

The ATOMKI collaboration summarizes the observed excess in terms of a dimensionless ratio [2, 3, 4]:

$$R_N = \frac{\Gamma(N^* \to N + X)}{\Gamma(N^* \to N + \gamma)} \times \mathrm{BR}(X \to e^+e^-) \tag{1}$$

where N denotes the nucleus exhibiting this resonant pattern in decay. According to SM, $R_N = 0$ [6], hence why new light physics appears to be necessary to account for $R_N \neq 0$.

At the time, the theoretical community appeared to be torn between two equally valid approaches, reflecting two two fundamental questions about X17: what is its intrinsic nature, and where else should we look for to find new experimental signatures of its existence. The first question led to efforts in model building, aiming to embed the X17 boson within a consistent framework of physics beyond the Standard Model [7, 8, 9, 10]. The second question led other theoreticians to determine the quantum numbers of this X17, and the observable phenomenology that those numbers entail [11, 12].

While we do believe that both are equally important, we think the second question should be answered first. Identifying the viable quantum numbers can immediately exclude broad classes of UV completions that predict incompatible phenomenology, particularly in parameter regions already ruled out by existing experimental constraints.

2. – Phenomenological analysis of X17

With this in mind, we now outline the methodology adopted in our analysis. The starting point is the assignment of quantum numbers to the X17 boson, specifically its spin and parity. In all cases, we assume parity conservation, as parity-violating models would typically induce effects in highly sensitive observables—such as atomic parity violation—which have shown no evidence for new physics, thereby placing stringent constraints on any parity-violating couplings of X17.

Next, we ensure that angular momentum conservation is satisfied in the nuclear transitions observed by ATOMKI. For example, assigning a half-integer spin to X17 would immediately violate angular momentum conservation, as nuclei have integer spin. Once a viable spin-parity assignment is established, we construct the most general effective Lagrangian consistent with Lorentz invariance and the assumed quantum numbers. This allows us to identify the relevant interaction terms and define a set of free parameters, typically corresponding to coupling strengths, which we aim to constrain.

We then compute all relevant observables that could be influenced by the presence of X17. These include the ATOMKI signal strengths R_N, but also bounds from other experiments that have not observed any X17-like signature and are therefore sensitive to its absence. This includes, for example, searches for light bosons in meson decays, precision electroweak measurements, and beam dump experiments.

Finally, we combine all constraints on the free parameters and present the results in the form of exclusion plots.

2˙1. *Spin 0*. – Let us start with spin 0 assignment. We need to check that the transition $N^* \to N + X$ is not excluded by angular momentum conservation. To do so, we look at table I, which reports angular momentum assignments of X17, needed to account for the nuclear transition. One observes immediately that 0^+ is excluded by Beryillium, and 0^-

Process	$S^\pi = 0^+$	$S^\pi = 0^-$	$S^\pi = 1^+$	$S^\pi = 1^-$
^{8}Be(18.15) $\to$ ^{8}Be	/	1	0, 2	1
^{8}Be(17.64) $\to$ ^{8}Be	/	1	0, 2	1
^{4}He(21.01) $\to$ ^{4}He	/	0	1	/
^{4}He(20.21) $\to$ ^{4}He	0	/	/	1
^{12}C(17.23) $\to$ ^{12}C	1	/	1	0,2

Table I.: Relative angular momentum between the X boson and N in the various decays, based on its possible parity-spin assignments.

is excluded by Carbon. X17 cannot be of spin 0.

2˙2. *Spin 1*. – We now turn to the case of a spin 1 boson. For several years, spin 1 has been the most widely studied and favored assignment for X17. However, increasing theoretical and experimental scrutiny has revealed significant tensions in this scenario.

In particular, ref. [11] identified a 2σ tension within the 1^- (vector boson) hypothesis when comparing all ATOMKI observables to bounds from the NA48 experiment. The tension arises in the $C_p - C_n$ plane, where C_p and C_n denote the couplings of X17 to protons and neutrons, respectively. Since X17 must couple to quarks to be produced in nuclear processes, it necessarily couples to nucleons.

Subsequently, an independent calculation of the nuclear matrix element relevant for Carbon transitions, presented in ref. [12], showed that the 1^+ (axial-vector) model also exhibits a 2σ tension when confronted with existing data. This result casts further doubt on the viability of any spin 1 interpretation of the X17 signal.

2˙3. *Spin 2.* – This is where our work [1] comes into play. Given the increasing tension with the spin 1 hypothesis, spin 2 emerges as the next logical possibility to explore. Angular momentum conservation is satisfied for integer spin bosons, and the observed nuclear transitions are compatible with the emission of a spin 2 particle.

We begin by constructing the Lagrangian. However, a complication arises: the presence of many off shell terms introduces a proliferation of parameters. As shown in ref. [14], it is therefore convenient to restrict the analysis to on-shell processes involving X17. This reduces the number of free parameters and allows for a more tractable phenomenological description.

A massive spin 2 particle can only arise in an effective field theory (EFT), as no dimension 4 interaction operators exist for such a state. This is expected: the X17 resonance is presumed to be a composite object or bound state, and its ultraviolet (UV) completion lies beyond the reach of our effective description. In analogy with chiral perturbation theory (χPT), we introduce a cutoff scale $\Lambda \approx 4\pi m_X \approx 200\,\mathrm{MeV}$.

At the same time, we imagine that the energy scale of the new sector that is extending SM and produces $X17$ at low energy $M_{\mathrm{BM}} \gg \Lambda$, and will be the scale of the Wilson coefficients of the theory. As a result, we select operators at dimension 5, and identify the couplings as C_p, C_n, C_e for the vector tensor 2^+ and $\tilde{C}_p, \tilde{C}_n, \tilde{C}_e$ for the axial vector tensor 2^-. No neutrino coupling and no photon coupling are considered. For 2^- case, the first operator involving 2 photons has dimension 7, and for the 2^+ case, a dimension 5 photon operator would not change the picture, given the very large exclusion we will encounter. To avoid exclusion of the 2^+ model, we would need $C_\gamma \gg C_e$, which would collide with the ATOMKI observation in the channel of electron-positron.

In addition to the R_N values, calculated in the spin 2 model, the SINDRUM experiment can be considered [15], which bounds the decay $\pi^+ \to e^+\nu_e X$

$$\mathrm{BR}(\pi^+ \to e^+\nu_e X) \times \mathrm{BR}(X \to e^+e^-) < 6 \times 10^{-10} \tag{2}$$

In our model, this decay is generated by bremsstrahlung diagrams in the pion decay, and are evaluated using χPT.

The exclusion plot is shown in fig. 2. Observe how both parities for the spin 2 framework are completely excluded by the SINDRUM bound.

So, to sum up, spin 0 is excluded due to angular momentum and parity conservation, spin 1 is built on shaky ground and is excluded by JINR experiment, and spin 2 is excluded directly by the SINDRUM constraint. Is this the end of the story?

3. – MEG-II null result: CP-even scalar

In 2024, the MEG-II Collaboration performed a dedicated search for an anomalous signal in the Beryllium nuclear transition, employing a setup closely resembling that used by the ATOMKI experiment [17]. Their analysis found no statistically significant excess over the expected background, leading to the exclusion of an anomaly at the 1.5σ level.

While this result does not constitute a definitive exclusion, it is, importantly, still statistically compatible with the original ATOMKI observation. In light of this, two possible approaches can be taken to incorporate the MEG-II data into our analysis. The first consists of a direct combination of the ATOMKI and MEG-II results. In our treatment, we model the MEG-II null result using a truncated Gaussian likelihood (to account for the fact that the signal rate cannot be negative), and combine it with

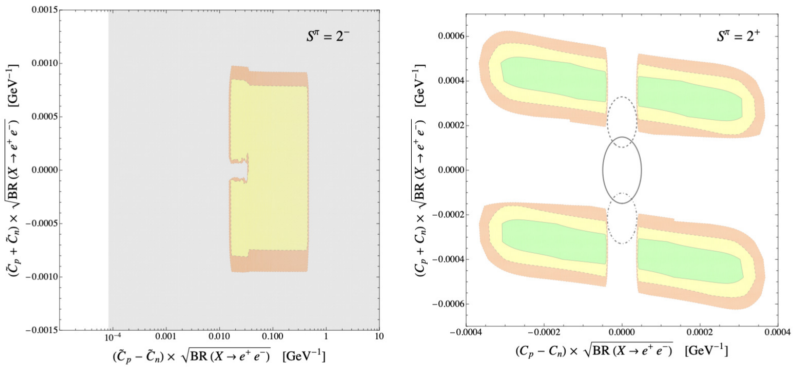

Figure 2.: *Left panel:* Green, yellow, orange areas correspond to the $1\sigma, 2\sigma, 3\sigma$ compatibility regions, defined by the requirement $\chi^2_{\text{profiled}} < 2.28, 5.99, 11.62$, for an axial tensor boson. The gray region is excluded by SINDRUM search. *Right panel:* Green, yellow, orange areas correspond to the $1\sigma, 2\sigma, 3\sigma$ compatibility regions, defined by the requirement $\chi^2_{\text{profiled}} < 2.28, 5.99, 11.62$, for a tensor boson. The regions outside the solid, dashed and dot-dashed gray lines are excluded by the SINDRUM search at 90% CL respectively for $C_e = 0$, $C_e = -0.001\ \text{GeV}^{-1}$ and $C_e = 0.001\ \text{GeV}^{-1}$.

the ATOMKI measurement of the Beryllium anomaly. This has actually been done throughout [1] and the plots in fig. 2 are evaluated including this combination.

The other possibility is to exclude only Beryllium signal, according to MEG-II findings. We see from table I that the exclusion of Beryllium opens up again the possibility of a 0^+ model. After repeating the same analysis we employed for the spin 2 case (even adding the SINDRUM constraint), by considering only renormalizable couplings to protons, neutrons and electrons (z_p, z_n, z_e), we arrive at the exclusion plots shown in fig. 3. This time, SINDRUM bound is less constraining, because of a suppression of m_e^2/m_μ^2 in

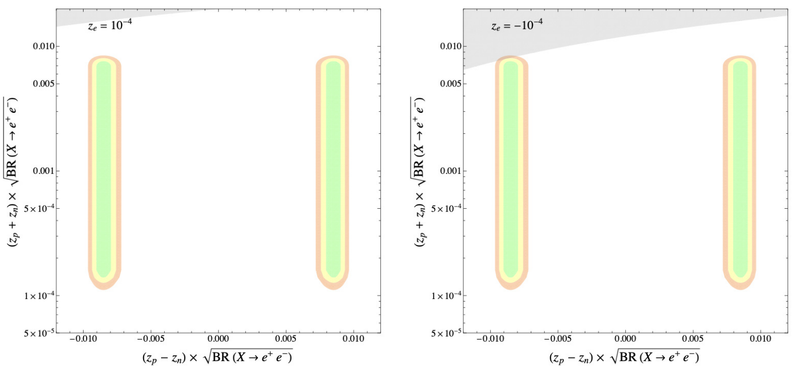

Figure 3.: Green, yellow, orange areas correspond to the $1\sigma, 2\sigma, 3\sigma$ compatibility regions, defined by the requirement $\chi^2_{\text{profiled}} < 2.28, 5.99, 11.62$, for a scalar boson. The gray region is excluded by SINDRUM search fixing $z_e = 10^{-4}$ (left panel) and $z_e = -10^{-4}$ (right panel).

the branching ratio, absent in the $\mathcal{O}(p^2)$ spin 2 case, but present in the $\mathcal{O}(p^2)$ 0^+ case. This has required us to include NLO $\mathcal{O}(p^4)$ in the chiral Lagrangian evaluation.

So, the parity even scalar hypothesis enters as a viable option for $X17$, as long as the Beryllium signal is excluded.

4. – Conclusions

We have recapped the phenomenology of the resonance interpretation of the ATOMKI anomalies, $X17$, in light of new theoretical reevaluations (excluding the axial vector hypothesis [12]) and experimental results (MEG-II [17]).

As a result, no spin and parity quantum number assignments to $X17$ produce a phenomenologically viable model, even using the most conservative hypotheses. Spin 0 is excluded by angular momentum conservation, while spin 1 and spin 2 are both excluded by phenomenology (and spin 1 is also excluded by $\gamma\gamma$ channel searches).

Instead, excluding Beryllium signal from ATOMKI, according to MEG-II findings, we found that the parity even scalar model is a viable candidate. This scenario, though, raises concerns regarding the consistency of the other ATOMKI signals observed in Helium and Carbon, which were measured with the same experimental apparatus, and thus does not currently appear to be a fully realistic solution.

Further data from MEG-II is necessary to refute or confirm this interpretation. Moreover, new measurements of $X17$ are coming from PADME Collaboration in the next future, as the direct e^+e^- production channel offers promising prospects to shed new light on this anomaly.

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