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An update view on the $X17$ hypothesis(*)

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Summary. — In view of the latest experimental results recently released by the ATOMKI collaboration, we critically re-examine the possible theoretical interpretation of the observed anomalies in terms of a new BSM boson X with mass ~ 17 MeV. To this end we employ a multipole expansion method and give an estimate for the range of values of the nucleon couplings to the new light state in order to match the experimental observations. Our conclusions identify the axial vector state as the most promising candidate, while other spin/parity assignments seems disfavored for a combined explanation.

1. – Introduction

In recent years the ATOMKI collaborations has reported various anomalous measurements in the IPC decays of excited ^{8}Be [1], ^{4}He [2] and, more recently, ^{12}C [3] nuclei. These anomalies appear as bumps for both the invariant mass and the angular opening of the e^+e^- pairs and have a high statistical significance, well above 5σ. The ATOMKI collaboration has proposed to interpret them as due to the on-shell emission of a new boson X from the excited nuclei, subsequently decaying to an e^+e^- pair. The best fit mass for the hypothetical new particles is estimated to be ~ 17 MeV. Although to this day no independent confirmation of these results has arrived, given the multitude of processes in which these anomalies have been observed the ATOMKI results have attracted a considerable attention from the particle physics community [4].

The ATOMKI anomalies show simple but well defined features, naturally explained by the hypothesis of resonant production of a new particle, which are:

- the excesses are resonant bumps located at the same e^+e^- invariant mass for all the ^{8}Be and ^{4}He transitions,

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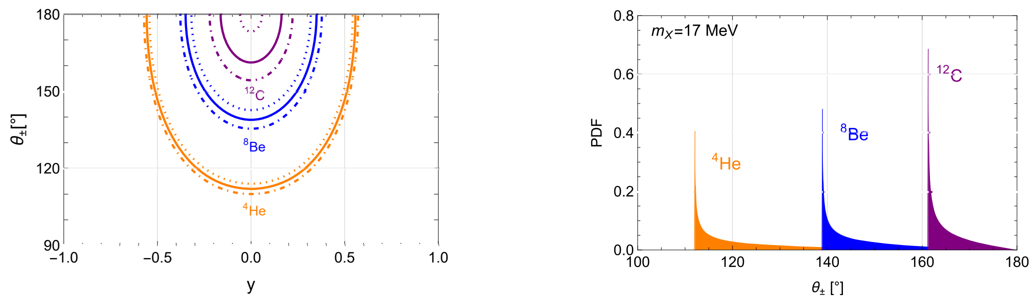

Fig. 1. – *Left panel*: Values of the e^+e^- opening angle $\theta_\pm$ as a function of the energy asymmetry y for three values of the boson mass: $m_X = 16.8$ MeV (dot-dashed line), $m_X = 17$ MeV (solid line) and $m_X = 17.2$ MeV (dotted line) for the cases of the ^{8}Be, ^{4}He and ^{12}C transitions. *Right panel*: Normalized distributions of the e^+e^- opening angles from the ^{8}Be (blue), ^{4}He (orange) and ^{12}C (purple) nuclear transitions.

- the e^+e^- opening angles of the anomalous peaks are around 140°, 115° and 155° − 160°, respectively, for the ^{8}Be, ^{4}He and ^{12}C, as predicted by the kinematic distributions and shown in the right panel of fig. 1,
- the anomalous signal in the ^{8}Be transition have been observed only inside the kinematic region given by $|y| < 0.5$, where y is the energy asymmetry of the lepton pair, *i.e.*, the ratio between the difference and the sum of their energies, as predicted by the kinematic and shown in the left panel fig. 1.

2. – Dynamics of $X17$ boson

We compute the decay widths of the excited states for real X emission in order to compare to the experimental results on this quantity reported by the ATOMKI collaboration. To perform the calculation we expand the nuclear matrix elements in terms of spherical tensor operators through a multipole expansion within some approximations that simplify the expressions. For a detailed description of the calculation see [5, 6]. We report in table I the relative angular momentum between the X boson and N in the various decay processes, based on the S^π spin-parity assignments. One sees that a pure scalar solution to the ^{8}Be anomaly is excluded, while a pseudoscalar state can explain only the ^{8}Be and ^{4}He anomaly, if the latter is dominated by the ^{4}He(21.01) excited state transition, but not the ^{12}C one. On the other side a vector or axial-vector candidate can simultaneously explain all the three anomalies, but again only one of the two ^{4}He resonant states can contribute to the signal process.

3. – Vector and axial vector scenarios

We parametrize the interaction of the X boson in terms of effective couplings as

$$\mathcal{L}_{S^\pi=1^-} = \sum_{N=p,n} \left[C_N \bar{N}\gamma^\mu N X_\mu + \frac{\kappa_N}{2m_N}\partial_\nu(\bar{N}\sigma^{\mu\nu}N)X_\mu \right] , \tag{1a}$$

$$\mathcal{L}_{S^\pi=1^+} = \sum_{N=p,n} a_N \bar{N}\gamma^\mu\gamma^5 N X_\mu , \tag{1b}$$

TABLE I. – *Orbital angular momentum of the X boson based on its possible parity-spin assignments.*

Process $N^* \to N$	X boson spin parity $S^\pi = 1^-$	$S^\pi = 1^+$	$S^\pi = 0^-$	$S^\pi = 0^+$
^{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	/	1	0	/
^{4}He(20.21) $\to$ ^{4}He	1	/	/	0
^{12}C(17.23) $\to$ ^{12}C	0, 2	1	/	1

where $\kappa_p \approx -\kappa_n \approx 2(C_p - C_n)$ as predicted by the static quark model. We now present our findings for the regions in the effective nucleon couplings parameter space for the various spin-parity assignments for the X boson. In presenting our results we assume, for simplicity, BR$(X \to e^+e^-) = 1$. We summarize the results for the spin-1 cases in fig. 2.

In the upper panels we show the results for the $S^\pi = 1^-$ assignment for the X boson. For the vector case the strongest bound comes from the non observation from the NA48 experiment of the $\pi^0 \to \gamma X$ decay in dark photon searches [7]. As it can be seen for the $\xi = 0.549$ assignment, a combined explanation of the ^{8}Be, blue region, and ^{4}He, orange region, anomalies while being compatible with the NA48 constraint is possible at 2σ but then we are in tension with the Carbon anomaly. On the other side an axial vector $S^\pi = 1^+$ state can explain both the ^{8}Be and ^{4}He ATOMKI anomalies, as shown in the lower

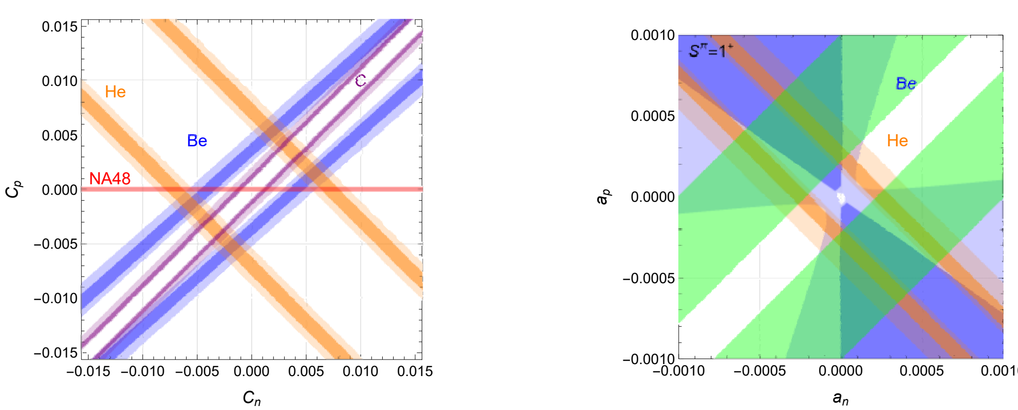

Fig. 2. – *Left panel:* Regions of the $C_{n,p}$ effective nuclear couplings of a pure vector state where the ^{8}Be (blue), ^{4}He (orange) and ^{12}C (purple) anomalous ATOMKI transition can be explained at 1σ or 2σ. Inside the red region the NA48 is satisfied. *Right panel:* Regions of the $a_{n,p}$ effective nuclear couplings of a pure axial vector state where the ^{8}Be (blue) and ^{4}He (orange) anomalous ATOMKI transition can be explained at 1σ or 2σ. In the green region the KTeV anomaly in $\pi \to e^+e^-$ decay can be satisfied, by assuming that the electron axial coupling of the X boson to electrons explains the anomalous $(g-2)_e$.

panels of fig. 2, with axial couplings to the nucleon of $\mathcal{O}(10^{-4})$. Within the green shaded area the KTeV anomaly in $\pi^0 \to e^+e^-$ decay can be explained for positive and negative values for the axial X coupling to electrons C_A^e. As regarding the possibility of also explaining the ^{12}C ATOMKI anomaly the relevant nuclear matrix element is currently unknown. Intriguingly, for the case a pure axial boson $S^\pi = 1^+$, in the parameter space where the ^{4}He and ^{8}Be anomalies can be explained, other experimental anomalies can be simultaneously satisfied, while being compatible with current constraints on the electron couplings of the X boson. This is the case of the KTeV anomaly in $\pi^0 \to e^+e^-$ decay [8], inside the green region in fig. 2, and the anomalous magnetic moment of the electron $(g-2)_e$ [9].

4. – Conclusion

We have employed a multipole expansion formalism to compute the anomalous decay rate for the decay of the excited nuclei into an e^+e^- pair via an intermediate on-shell BSM state. Our results identify an axial vector state as the most promising candidate to simultaneously explain all the three anomalous nuclear decay, while the other spin/parity assignments seems disfavored for a combined explanation.

REFERENCES

[1] Krasznahorkay A. J., Csatlós M., Csige L., Gácsi Z., Gulyás J., Hunyadi M., Ketel T. J., Krasznahorkay A., Kuti I., Nyakó B. M. *et al.*, *Phys. Rev. Lett.*, **116** (2016) 042501, arXiv:1504.01527 [nucl-ex].

[2] Krasznahorkay A. J., Csatlós M., Csige L., Gulyás J., Koszta M., Szihalmi B., Timár J., Firak D. S., Nagy Á., Sas N. J. *et al.*, arXiv:1910.10459 [nucl-ex].

[3] Krasznahorkay A. J., Krasznahorkay A., Begala M., Csatlós M., Csige L., Gulyás J., Krakó A., Timár J., Rajta I., Vajda I. *et al.*, *Phys. Rev. C*, **106** (2022) L061601, arXiv:2209.10795 [nucl-ex].

[4] Alves D. S. M., Barducci D., Cavoto G., Darmé L., Delle Rose L., Doria L., Feng J. L., Frankenthal A., Gasparian A., Goudzovski E. *et al.*, *Eur. Phys. J. C*, **83** (2023) 230.

[5] Kozaczuk J., Morrissey D. E. and Stroberg S. R., *Phys. Rev. D*, **95** (2017) 115024, arXiv:1612.01525 [hep-ph].

[6] Barducci D. and Toni C., *JHEP*, **02** (2023) 154; **07** (2023) 168(E), arXiv:2212.06453 [hep-ph].

[7] NA48/2 Collaboration (Batley J. R. *et al.*), *Phys. Lett. B*, **746** (2015) 178, arXiv:1504.00607 [hep-ex].

[8] Abouzaid E. *et al.*, *Phys. Rev. D*, **75** (2007) 012004, arXiv:hep-ex/0610072 [hep-ex].

[9] Parker R. H., Yu C., Zhong W., Estey B. and Müller H., *Science*, **360** (2018) 191, arXiv:1812.04130 [physics.atom-ph].