X17: A new force, or evidence for a hard $\gamma + \gamma$ process?

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It is pointed out that the “X17 puzzle” is likely to be explained by a nuclear decay chain and a conversion of the two resulting highly energetic $\gamma$s into an electron-positron pair.

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I. INTRODUCTION

A. Inelastic $\gamma\gamma$ scattering

The laws of classical physics do not allow for direct interaction between two electromagnetic waves. In contrast, in quantum theory, such processes arise due to the contributions of virtual states. Soon after the discovery of quantum electrodynamics, as the best theory describing the quantum nature of electromagnetic interactions, it became clear that the production of electron-positron pairs from photon interactions is possible \cite{1-4}. Over the years, inelastic light-light interactions have been the subject of numerous theoretical studies and successful experimental tests \cite{5-15}.

In this paper, it is pointed out that the experimental results, known as the “X17 puzzle” might be added to this list.

B. X17 experimental result

Since 2015 the particle physics community faces an unexpected signature, which throughout this article will be called the “X17 puzzle”. This puzzle comes from an experiment which measured the angular correlations and the kinematics of electron-positron pairs, which were emitted during the relaxation of excited $^8\text{Be}$ nuclear states \cite{16}. In the angular distribution, they found an unexpected peak at a relatively large opening angle ($\theta \approx 144^\circ$). Taking the energy, the asymmetry, and the angle $\theta$ of the lepton pair on an event by event basis, the corresponding invariant energy was calculated. In this observable, a highly significant resonance at about 17 MeV was discovered. This result was unexpected because it does not seem to fit into the standard picture of nuclear and fundamental physics.

Recently, the same group announced a similar finding from an experiment with excited $^4\text{He}$ \cite{17}. This second excess, which appears at similar energy, but at significantly different angle, will not be discussed in this paper.

C. X17 in the literature

Internal formation of electron-positron pairs is a known effect in nuclear physics \cite{19-22}. In this process, an emitted high energy $\gamma$ interacts non-perturbatively with the mostly Coulomb-like background field of the nucleus such that it converts into an electron-positron pair. This reaction is similar to the Bethe-Heitler (BH) process, only that it differs in the initial state \cite{18}. This type of process was taken into account in the background analysis of the experimental studies. However, this background is strongly increased towards small angles, and it shows no peak in the resulting invariant mass spectrum. For the case of $^8\text{Be}$ a more detailed study improved the nuclear physics understanding of the observables by considering various additional effects such as the initial production...
process and interference in an effective field theory approach like the one used in [22]. It was shown that there are important additional effects that might reduce the significance of the reported observation, but it was also shown that these effects can not account for the reported experimental signature.

Given these inconsistencies with our current understanding of nuclear physics, different explanations were proposed. An incomplete list of these explanations includes new forces [24–33], new and dark matter [34–44], and axion-like particles [45, 46]. For a critical revision of these ideas, see [47]. A common feature of these models is that they invoke a new mediator particle, which couples to the nuclear states and leptonic states.

D. X17 alternative

The “new particle” hypothesis should be confirmed by complementary observables such as cross sections in as direct production experiments \((e^+ + e^- \rightarrow X)\). There are numerous such complementary experiments that are currently planned or operating [48–57]. However, it is possible that these experiments will not see any new fundamental resonance.

In this case, one has to consider alternative explanations for the X17 puzzle. In this paper, one of the intermediate nuclear states in the decay chain of the excited \(^8\)Be is studied. These nuclear states would not show up in a direct production experiment like \((e^+ + e^- \rightarrow X)\). It is shown below that such states can produce a signal pattern that is very similar to the one observed and reported in [16].

II. CASCADE THOUGH A BROAD NUCLEAR RESONANCE

It is proposed to study a modified Bethe-Heitler (MBH) process shown in figure 1. Note that the original Bethe-Heitler transition is not a perturbative process [21]. All calculations will be done in natural units, where \(\hbar = c = 1\). In these transitions, angular momentum is changed by up to \(N\) due to \(N\)-pole radiation. Further, parity is changed by powers of \((-1)^N\) in electric, and by powers of \((-1)^{N+1}\) in magnetic multipole radiation. There are two main differences between this process and the usual Bethe-Heitler process. The first one is that the incoming \(\gamma\) is provided by excited \(^8\)Be and not by external radiation. The second difference is that the second \(\gamma\) is provided by another decay of the same nucleus and not by a background field.

It will now be argued that the processes sketched in figure 1 can give experimental signatures like the ones observed in [16]. In order to show this, one needs to consider three ingredients:

- A broad intermediate state,
- orientation of the nuclear multipole coefficients due to the emission of one of the \(\gamma\)s,
- conservation of energy and momentum.

These ingredients will now shortly be explained in an on shell approximation of the process shown in figure 1 before they are applied to the specific experiment.

A. Broad intermediate state

For the MBH process to have non-vanishing probability for the conversion \(\gamma + \gamma \rightarrow e^+ + e^-\), the two \(\gamma\)s need to conspire in a very small cross section area \(A\). However, the area covered by two subsequently emitted on shell \(\gamma\)s grows as

\[
A \approx \pi t^2 \approx \frac{\pi}{\Gamma^2},
\]

where \(t\) is the time passing in the center of mass frame of the intermediate nuclear state and \(\Gamma\) is the width of this state. Thus, a large width is needed to minimize the area \(A\) and to maximize the probability of \(\gamma + \gamma \rightarrow e^+ + e^-\) conversion.

B. Angular spectrum

A complete first principle description of the excited \(^8\)Be states goes beyond the scope of this paper. Instead, it will be shown how under relatively straightforward assumptions the emission of two MeV gammas can come at a preferred relative angle \(\theta_{rel}\).

As first approximation, one can describe the angular probabilities of the electromagnetic emitted with multipole radiation. In the diagram [1], one emitted \(\gamma\) is from an electric N-pole with \(|\Delta J| = N\) and \(\Delta \pi = (-1)^N\). Another emitted \(\gamma\) is from electric \(N + 1\)-pole radiation \(|\Delta J| = N + 1\) and \(\Delta \pi = (-1)^{N+1}\). It is clear that the direction of highly energetic electric radiation in direction \(k_1\) will affect the orientation of the multipole coefficients \(a_{lm}\) of the remaining nucleus. One can choose the coordinate system such that the first emission is aligned with the electric multipole.
with the direction of the first emission $\vec{k}_1 = |\vec{k}_1| \hat{z}$. This emission will transfer a large amount of angular momentum to the remaining nucleus, which then has multipole moments $a_{10}$. However, due to the directionality of the emission, the projection of this induced angular momentum onto the $\hat{z}$ axis will be small, or even zero. This corresponds to the multipole coefficients $a_{10} \neq 0$. These multipole coefficients $a_{10}$ will now be the source for the subsequent emission. The angular distribution of this “following” emission of multipole radiation will then be [58]

$$
\frac{dP_{10}}{d\theta} \sim \sin(\theta)|a_{10}|^2 |\vec{X}_{10}(\theta)|^2,
$$

where $\vec{X}_{10}(\theta)$ is proportional to the angular momentum operator acting on a spherical harmonic function $Y_{10}$ and where $\theta_{rel}$ is the angle between the two emissions. The most likely large relative angles with $\theta > 90^\circ$ between the two emissions are

$$
\theta_{rel} \pm \delta\theta_{rel} = \begin{cases} 
(144 \pm 14)^\circ & \text{for } N = 3 \\
(152 \pm 11)^\circ & \text{for } N = 4 \\
\ldots
\end{cases} \tag{2.3}
$$

Here, $\Delta N = 3, 4$, were given, because these are the relevant quantum numbers involved in the process [3.1].

C. Kinematics

The four momenta in figure 1 are $p_1^\mu$ for $^8\text{Be}$ in the initial state, $p_2^\mu$ for the intermediate nuclear state, $p_3^\mu$ for the final nuclear state, $k_1^\mu$ for the first $\gamma$, $k_2^\mu$ for the second $\gamma$, $q_1^\mu$ for the outgoing positron, $q_2^\mu$ for the intermediate lepton, and $q_3^\mu$ the outgoing electron. The kinematics of the experiment allows for the approximations

$$
p_i^2 \gg (p_i - p_j)^2 i \neq j \gg m^2, \tag{2.4}
$$

where $m$ is the electron mass and where all particles are approximated to be on shell. For the nuclear part of the reaction, this approximation is justified if the widths of the involved states do not overlap. Within these approximations the relative angle between the leptons and between the $\gamma$s is is the same. The primary signal in [17] was found for small asymmetries $-0.5 < y < 0.5$, thus we will work in the center of mass frame of a very heavy nucleus with $y \approx 0$. The approximations (2.4) are reasonable since the nuclear masses are several GeV, which is much larger than the energies in the signal region which are of the order of 20 MeV, and the electron mass is 1/2 MeV. In these approximations, one finds that the square of the invariant mass of the electron-positron pair in figure 1 is given by

$$
m_X^2 = (q_1 + q_3)^2 = 4(\Delta M_{12})(E_{13} - \Delta M_{12}) \sin \left( \frac{\theta}{2} \right), \tag{2.5}
$$

where $\theta$ is the angle between the leptons and $\Delta M_{12} = \sqrt{p_1^2 - p_2^2}$ and $\Delta M_{23} = \sqrt{p_2^2 - p_3^2} = E_{13} - \Delta M_{12}$. This result can get corrections when one considers virtual particles in the intermediate states, which will be discussed in the next subsection.

D. Conversion of $\gamma + \gamma$ to $e^+ + e^-$

The on-shell result [25], relies strongly on the approximation that the angle between $\vec{k}_1$ and $\vec{q}_1$ vanishes $\theta_{rel} = 0$, just as the angle between $\vec{k}_2$ and $\vec{q}_2$. The validity of this approximation can be checked by evaluating the production process depicted in terms of the Feynman diagram shown in figure 2. The unpolarized squared transition amplitude for this process, without the approximations (2.4) is

$$
|M|^2 = \frac{32\pi^4}{(q_2^2 - m^2)^2} \left[ 16(q_1 \cdot q_2)(q_3 \cdot q_2) - 8(q_1 \cdot q_3)(q_2^2 - m^2) - m^2(2(q_2^2 - m^2) - 2(q_1 \cdot q_2) + (q_3 \cdot q_2)) \right]. \tag{2.6}
$$

From (2.6) one realizes that the process is enhanced at very small momentum interchange as assumed when deriving (2.5). Off-shell contributions and finite $m^2/q_0^2$ corrections will induce a non-vanishing distribution of the relative angle $\theta_{rel}$. This will, induce an additional width widening $\delta\theta_{rel}$ of a given maximal relative angle $\theta_{rel}$ between $\vec{q}_1$ and $\vec{q}_2$. It is an important consistency check that the combined angular width, arising from the initial emission $\theta_{rel}$ and the kinematical widening $\delta\theta_{rel}$, is in the ballpark of the measured width (see 5.1) of the distribution of the relative lepton angles

$$
\sqrt{(2\delta\theta_{rel})^2 + (2\delta\theta_{rel})^2} \approx \Gamma_\theta. \tag{2.7}
$$

From (2.6) one calculates differential production cross section in the CM frame

$$
\frac{d\sigma}{d\Omega_1} = \frac{1}{8(k_1^0)^2 2(2\pi)^2 |q_1|} |M|^2. \tag{2.8}
$$

This is integrated to give the total cross section $\sigma$. The two initial $\gamma$s are emitted with a time separation of $t \approx \frac{1}{\Gamma_\gamma}$. During this time the $\gamma$s span an area [24.1]. One can
The leptonic invariant energy $m$ as function of the relative angle $\theta_{\text{rel}}$. This relation for the processes (3.1) and (3.2) is shown by the blue curve and orange curve in figure 3. One notes that both curves are compatible with the data. The blue curve crosses the observed data point almost perfectly, supporting the kinematic relation (2.5). This is a highly non-trivial agreement because there is no parameter tuned in these curves.

As sanity check one can contrast the observed $\Gamma_\theta$ with the additional widening of $\delta \theta_{\text{rel}}$ derived from (2.6) and see whether (2.7) is fulfilled. The normalized squared amplitude (2.6) in terms of the relative angle $\theta_{\text{rel}}$, as measured in the center of mass frame of the lepton pair gives $\delta \theta_{\text{rel}}|_{CM} = 3.5^\circ$. Transforming this back to the laboratory frame one obtains a widening of $\delta \theta_{\text{rel}} = \pm 8^\circ$, which is sufficiently smaller than the $\Gamma_\theta = 26^\circ$ obtained from (5.1). Thus, the condition (2.7) holds.

### B. Comments

The above result deserves some comments.

- **Systematics of angular peaks:**
  
  The classical multipole formula (2.2), is a first approximation to the underlying quantum processes. It is planned to improve this by using an effective field theory description for the nuclear states in the spirit of [23] [47] [61].
• Possible peaks at small angles:
The classical multipole formula allows also for
peaks at small angles. These are likely to be invis-
ible due to the large background at small angles (see
[4]).

• A smoking gun:
Not all highly energetic γs are converted to
electron-positron pairs through the MBH process.
The conversion probability can be estimated from
[2.9]. This turns out to be about 1%. Thus, most
γs leave the nucleus without conversion. Measuring
their angular distribution would provide a smoking
gun signal for the MBH process.

• There is another experimental result with a peak
at about 17 MeV [17]. However, it has been ques-
tioned that both results originate from the same
physical process [62] because they appear at differ-
tent relative angle \( \theta_{\text{rel}} \).

IV. CONCLUSION

This paper explored a new possibility of explaining the
observed X17 anomaly reported in [16]. The study fo-
cused on a modified Bethe-Heitler transition, depicted in
figure 1. For this process, one needs to consider a broad
intermediate nuclear resonance and standard conserva-
tion of energy and momentum (2.5). The intermediate
resonance is provided by the \(^8\text{Be}^* (J^π = 4^+, T = 0)\) state
with a large width of \( \Gamma = 3.5 \) MeV at 11.35 MeV above
the ground state. One finds an almost perfect agreement
with the kinematic relation (2.5). This is the main result
of this paper, which is summarized in figure 3. There is
further a good agreement between the measured relative
angle and (2.3), but this angular estimate is subject to
larger theoretical uncertainties.

One can test the hypothesis of this paper by measuring
the angular distribution in the two γ final state. If this,
or other similar tests, give positive results, it would mean
that the “X17” is not a new fundamental force particle,
but rather a measurement of an inelastic scattering of
two high energy γs in the laboratory frame.

V. ACKNOWLEDGEMENTS

Many thanks to J. Schaffner-Bielich, H. Stoecker,
C. Greiner, A. Hoang, H. Skarke, P. Arias, and C. Diaz
for helpful remarks. This work was supported by Fondec-
cyt 1181694.

APPENDIX: DATA FIT

By using [59] one can extract information on the an-
gular distributions of the electron-positron pairs reported
in [19], as shown in figure 4.

![Angular distribution of the lepton final state](image)

**FIG. 4.** Angular distribution of the lepton final state [17].
The upper figure shows the signal in red, the interpolated
background in black, and a widened ΔN = 4 angular dis-
tribution (2.2) added to the background in blue. The lower
figure shows signal minus background and the Gaussian fit.
The error bars in the upper figure are smoothly approximated
to [17], in the lower figure they are scaled due to the change
in the signal to background ratio.

This distribution is fitted by a Gaussian
\[ N_θ = 0.49e^{-\frac{(\theta - \theta_{\text{rel}})^2}{2\sigma}} \], peaked at the angle \( \theta_{\text{rel}} = 145^o \),
with a halfwidth
\[ \Gamma_θ = 2\sqrt{2\ln(2)}\sigma = 26^o. \]  
(5.1)

With a statistical error of 18%.
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