Atomki Anomalisi: Bulgular ve Güncel Durum

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YEFIST2025

Outline

Introduction

Figure: The ATOMKI set up.[1]

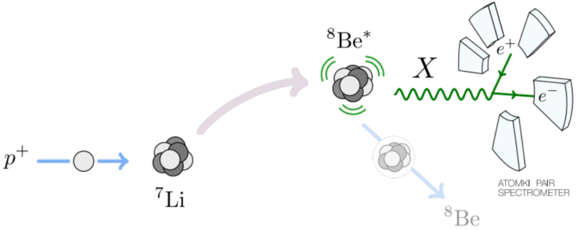
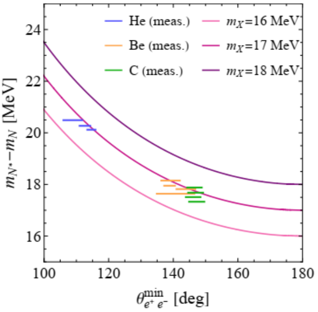
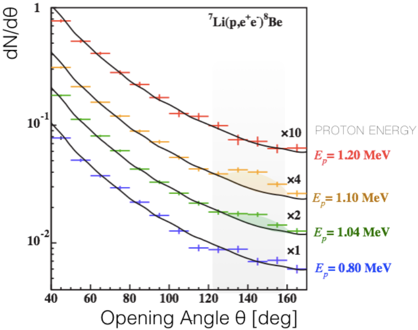


Figure: An illustration of the experiment. Retrieved from [2]





Contours are obtained by the relation $\theta^{min}_{e^+e^-} \approx 2arcsin(m_X/(m_{N^*} - m_N))$ where $N^* \rightarrow NX$ [3].

Bumps in the angular correlation of e^+e^- pairs at different proton energies. This figure is from ref-[4], which is adapted from ref-[5].

Why to believe this is a genuine anomaly?

- Observed standard deviation is always greater than 6σ,
- The set-up was improved from five arms to six. Nevertheless, the anomaly was observed anyway.
- They have used different position-sensitive detectors, but the anomaly didn't disappear.
- The anomaly was also observed with different proton beam energies.
- The bumps show up at different angles with ^{8}Be and ^{4}He. Nevertheless, it is consistent with the theoretical expectation of 17 MeV particles.
- No anomaly was observed with calibration atoms.

Framework

$$\phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \quad \phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix} \tag{1}$$

where $v^2 = v_1^2 + v_2^2 = (246\ GeV)^2$.

$$\begin{aligned} V(\phi_1, \phi_2) &= m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 - (m_{12}^2 \phi_1^\dagger \phi_2 + h.c.) + \frac{\lambda_1}{2}(\phi_1^\dagger \phi_1)^2 \\ &+ \frac{\lambda_2}{2}(\phi_2^\dagger \phi_2)^2 + \lambda_3(\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_4(\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) \\ &+ \left[\frac{\lambda_5}{2}(\phi_1^\dagger \phi_2)^2 + \lambda_6(\phi_1^\dagger \phi_1)\phi_1^\dagger \phi_2 + \lambda_7(\phi_2^\dagger \phi_2)(\phi_1^\dagger \phi_2) + h.c.\right] \end{aligned} \tag{2}$$

Table: Z_2 Parities charges in each 2HDM type

Model	ϕ_1	ϕ_2	U	D	E	Q,L
Type I	-	+	+	+	+	+
Type II	-	+	+	-	-	+
Lepton-specific	-	+	+	+	-	+
Flipped	-	+	+	-	+	+

The Type-I model: $\phi_1 \to -\phi_1, \quad \phi_2 \to \phi_2$
$m_{12} = \lambda_6 = \lambda_7 = 0$

$$V(\phi_s, \phi_1, \phi_2) = m_\phi^2 + \phi_s^\dagger \phi_s + \frac{\lambda_s}{2}(\phi_s^\dagger \phi_s)^2 + (\mu \phi_1^\dagger \phi_2 \phi_s + h.c.) + \mu_1 \phi_1^\dagger \phi_1 \phi_s^\dagger \phi_s + \mu_2 \phi_2^\dagger \phi_2 \phi_s^\dagger \phi_s \quad (3)$$

$$\mathcal{L}_{scalar} = (D_\mu \phi_1)^\dagger (D_\mu \phi_1) + (D_\mu \phi_2)^\dagger (D_\mu \phi_2) + (D_\mu \phi_s)^\dagger (D_\mu \phi_s) \quad (4)$$

where the covariant derivative is,

$$\mathcal{D}_\mu = \partial_\mu - igt^a W_\mu^a - ig' Y B_\mu - ig_D q_D X_\mu \quad (5)$$

- covariant derivative acting on the doublets:

$$\mathcal{D}_\mu \phi_i = \begin{pmatrix} \partial_\mu - \frac{ig}{2} W_\mu^3 - ig' Y_i B_\mu - ig_D q_{Di} X_\mu & \frac{-ig}{2}(W_\mu^1 - iW_\mu^2) \\ \frac{-ig}{2}(W_\mu^1 + iW_\mu^2) & \partial_\mu + \frac{ig}{2} W_\mu^3 - ig' Y_i B_\mu - ig_D q_{Di} X_\mu \end{pmatrix} \begin{pmatrix} 0 \\ v_i \end{pmatrix} \quad (6)$$

- covariant derivative acting on to singlet:

$$\mathcal{D}_\mu \phi_s = (\partial_\mu - ig_D h_s X_\mu) v_s \quad (7)$$

$$\mathcal{L}_{gauge} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{2}sin\epsilon X_{\mu\nu}B^{\mu\nu} \tag{8}$$

Transformation to remove the mixing term:

$$\begin{pmatrix} \tilde{B}_\mu \\ W_{3\mu} \\ \tilde{X}_\mu \end{pmatrix} = \begin{pmatrix} 1 & 0 & \sin\epsilon \\ 0 & 1 & 0 \\ 0 & 0 & \cos\epsilon \end{pmatrix} \begin{pmatrix} B_\mu \\ W_{3\mu} \\ X_\mu \end{pmatrix} \equiv V_1 \begin{pmatrix} B_\mu \\ W_{3\mu} \\ X_\mu \end{pmatrix} \tag{9}$$

The Winberg transformation:

$$\begin{pmatrix} A_\mu \\ \tilde{W}_{3\mu} \\ \tilde{X}_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W & 0 \\ -\sin\theta_W & \cos\theta_W & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \tilde{B}_\mu \\ W_{3\mu} \\ \tilde{X}_\mu \end{pmatrix} \equiv V_2 \begin{pmatrix} \tilde{B}_\mu \\ W_{3\mu} \\ \tilde{X}_\mu \end{pmatrix} \tag{10}$$

Last transformation will diagonalize the mass matrix

$$\begin{pmatrix} A_\mu \\ Z_\mu \\ A'_\mu \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\tau & \sin\tau \\ 0 & -\sin\tau & \cos\tau \end{pmatrix} \begin{pmatrix} A_\mu \\ \tilde{W}_{3\mu} \\ \tilde{X}_\mu \end{pmatrix} \equiv V_3 \begin{pmatrix} A_\mu \\ \tilde{W}_{3\mu} \\ \tilde{X}_\mu \end{pmatrix} \tag{11}$$

for this angle

$$\tan 2\tau = \frac{a - 2m_{ZSM}\, v\, g_D\, b}{(m_{ZSM}^2(b^2-1) + \sec^2\epsilon[m_s^2 + g_D^2(v^2(\cos^2\beta\, h_1^2 + \sin^2\beta\, h_2^2) + v_s h_s)] - ab\sin\epsilon}$$

$$a = 2m_{ZSM} v g_D(\cos^2\beta\, h_1 + \sin^2\beta\, h_2) \qquad b = \tan\epsilon\sin\theta_W \tag{12}$$

Mass terms come from this part of the Lagrangian:

$$\frac{1}{2}m_s^2 X_\mu X^\mu + (D_\mu \phi_s)^\dagger (D^\mu \phi_s) + \sum_{i=1}^{2} (D_\mu \phi_i)^\dagger (D^\mu \phi_i) \rightarrow \mathcal{L}_{mass} \tag{13}$$

Arranging the field terms will now give a mass matrix as follows:

$$\mathcal{L}_{mass} = \frac{1}{2} \begin{pmatrix} A_\mu & Z_\mu & A'_\mu \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 \\ 0 & M_Z^2 & 0 \\ 0 & 0 & M_{A'}^2 \end{pmatrix} \begin{pmatrix} A_\mu \\ Z_\mu \\ A'_\mu \end{pmatrix} \tag{14}$$

Masses of Z and A'

$$
\begin{aligned}
M_Z^2 =& m_s^2 \sin^2\tau \sec^2\epsilon + g_D^2 \sin^2\tau \sec^2\epsilon (v^2 (cos^2 \beta h_1^2 + sin^2 \beta h_2^2) + v_s^2 h_s^2) \\
& - 2 m_{ZSM} v g_D \sin\tau \sec\epsilon (\cos^2\beta h_1 + \sin^2\beta h_2)(\cos\tau + \sin\theta_W \sin\tau \tan\epsilon) \\
& + m_{ZSM}^2 (\cos\tau + \sin\theta_W \sin\tau \tan\epsilon)^2
\end{aligned} \tag{15}
$$

$$
\begin{aligned}
M_{A'}^2 =& m_s^2 \cos^2\tau \sec^2\epsilon + g_D^2 \cos^2\tau \sec^2\epsilon (v^2 (\cos^2\beta h_1^2 + \sin^2\beta h_2^2) + v_s^2 h_s^2) \\
& + 2 m_{ZSM} v g_D \cos\tau \sec\epsilon (\cos^2\beta h_1 + \sin^2\beta h_2)(\sin\tau - \sin\theta_W \cos\tau \tan\epsilon) \\
& + m_{ZSM}^2 (\sin\tau - \sin\theta_W \cos\tau \tan\epsilon)^2
\end{aligned} \tag{16}
$$

$$\mathcal{L}_{fermion} = \sum_i \bar{\psi}_i i \not{D} \psi_i \quad (17)$$

$\psi = \psi_L + \psi_R$ where $\psi_L = \frac{1-\gamma^5}{2}$ and $\psi_R = \frac{1+\gamma^5}{2}$.

$$\begin{pmatrix} B_\mu \\ W_{3\mu} \\ X_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\cos\tau\sin\theta_W - \sin\tau\tan\epsilon & \sin\theta_W \sin\tau - \cos\tau\tan\epsilon \\ \sin\theta_W & \cos\theta_W \cos\tau & -\cos\theta_W \sin\tau \\ 0 & \sec\epsilon\sin\tau & \cos\tau\sec\epsilon \end{pmatrix} \begin{pmatrix} A_\mu \\ Z_\mu \\ A'_\mu \end{pmatrix} \quad (18)$$

$$\mathcal{L}^{interaction} = \sum_i \bar{\psi}_i \gamma^\mu (C_v^i + C_A^i \gamma_5) \psi_i Z_\mu + \bar{\psi}_i \gamma^\mu (\varepsilon_v^i + \varepsilon_A^i \gamma_5) \psi_i A'_\mu \quad (19)$$

Table: Vector and axial couplings of each fermion to A' boson.

$\varepsilon_u^V = -\frac{e(3\sin\tau - 8\sin^2\theta_W \sin\tau + 5\sin\theta_W \cos\tau \tan\epsilon)}{12\sin\theta_W \cos\theta_W} + \frac{g_D(3u+d)\cos\tau \sec\epsilon}{4}$
$\varepsilon_u^A = \frac{e(\sin\tau - \sin\theta_W \cos\tau \tan\epsilon)}{4\sin\theta_W \cos\theta_W} + \frac{g_D(u-d)\cos\tau \sec\epsilon}{4}$
$\varepsilon_d^V = \frac{e(3\sin\tau - 4\sin^2\theta_W \sin\tau + \sin\theta_W \cos\tau \tan\epsilon)}{12\sin\theta_W \cos\theta_W} + \frac{g_D(u+3d)\cos\tau \sec\epsilon}{4}$
$\varepsilon_d^A = -\frac{e(\sin\tau - \sin\theta_W \cos\tau \tan\epsilon)}{4\sin\theta_W \cos\theta_W} - \frac{g_D(u-d)\cos\tau \sec\epsilon}{4}$
$\varepsilon_e^V = \frac{e(\sin\tau - 4\sin^2\theta_W \sin\tau + 3\sin\theta_W \cos\tau \tan\epsilon)}{4\sin\theta_W \cos\theta_W} - \frac{g_D(7u+5d)\cos\tau \sec\epsilon}{4}$
$\varepsilon_e^A = -\frac{e(\sin\tau - \sin\theta_W \cos\tau \tan\epsilon)}{4\sin\theta_W \cos\theta_W} - \frac{g_D(u-d)\cos\tau \sec\epsilon}{4}$
$\varepsilon_\nu^V = -\frac{e(\sin\tau - \sin\theta_W \cos\tau \tan\epsilon)}{4\sin\theta_W \cos\theta_W} - \frac{g_D(5u+7d)\cos\tau \sec\epsilon}{4}$
$\varepsilon_\nu^A = \frac{e(\sin\tau - \sin\theta_W \cos\tau \tan\epsilon)}{4\sin\theta_W \cos\theta_W} + \frac{g_D(u-d)\cos\tau \sec\epsilon}{4}$

Experimental constraints

Best fit to X particle mass is 17.01(16) MeV and the branching ratios compared to the γ-decay [6]:

$$\frac{Br(^8\text{Be}^* \to X + {}^8\text{Be})}{Br(^8\text{Be}^* \to \gamma\ {}^8\text{Be})} \times Br(X \to e^+e^-) = 6(1) \times 10^{-6} \tag{20}$$

$$-0.09 < \varepsilon_p/\varepsilon_n < 0.11. \tag{21}$$

The ATOMKI bound on electron coupling constant:

$$|\varepsilon_e^V| \gtrsim 1.3 \times 10^{-5} \sqrt{Br(X \to e^+e^-)} \tag{22}$$

Constraints from other experiments:

NA48[7]:

$$|2\varepsilon_u + \varepsilon_d| = |\varepsilon_p| \lesssim \frac{1.2 \times 10^{-3}}{\sqrt{Br(X \to e^+e^-)}}\,. \tag{23}$$

NA64[8]:

$$\sqrt{(\varepsilon_e^V)^2 + (\varepsilon_e^A)^2} \gtrsim 3.6 \times 10^{-5} \times \sqrt{Br(X \to e^+e^-)}. \tag{24}$$

KLOE [9]:

$$\sqrt{(\varepsilon_e^V)^2 + (\varepsilon_e^A)^2} \lesssim 6.1 \times 10^{-4} / \sqrt{Br(X \to e^+e^-)}. \tag{25}$$

SLAC E158 [10]:

$$\left|\varepsilon_e^V \times \varepsilon_e^A\right| \lesssim 10^{-8}. \qquad (26)$$

TEXONO[11]:

$$\begin{aligned} \sqrt{\left|\varepsilon_e^V \varepsilon_{\nu_e}^V\right|} &< 7 \times 10^{-5}, \quad \text{for} \;\; \varepsilon_e^V \varepsilon_\nu^V > 0 \\ \sqrt{\left|\varepsilon_e^V \varepsilon_{\nu_e}^V\right|} &< 3 \times 10^{-4}, \quad \text{for} \;\; \varepsilon_e^V \varepsilon_\nu^V < 0. \end{aligned} \qquad (27)$$

Atomic Parity violation[12]:

$$\left|\varepsilon_e^A\right| \left|\frac{188}{399}\varepsilon_u^V + \frac{211}{399}\varepsilon_d^V\right| \lesssim 1.8 \times 10^{-12}\,. \qquad (28)$$

Conclusion

Various theoretical frameworks have been proposed to explain this anomaly. With the long-awaited independent experimental indication of a 17 MeV particle now available, there is renewed excitement and motivation to further investigate this anomaly.

Thank you!

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