The nuclear physics aspects of the ATOMKI anomaly and the protophobic vector boson explanation

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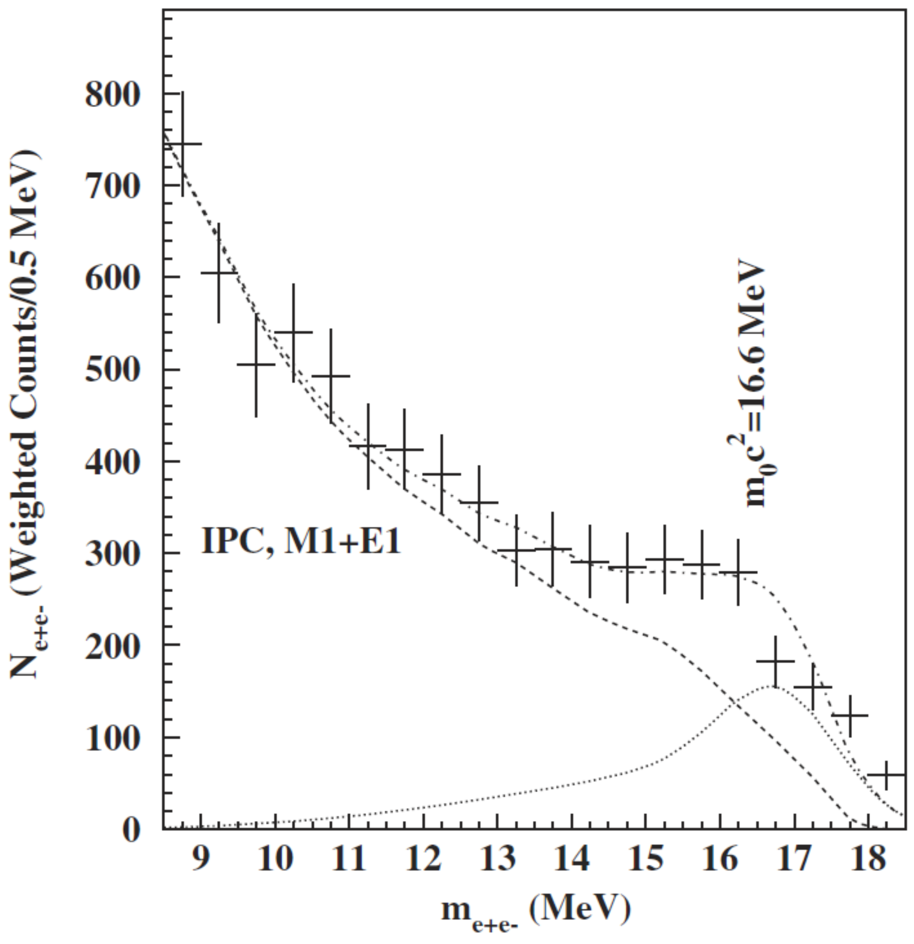
Shedding light on X17,

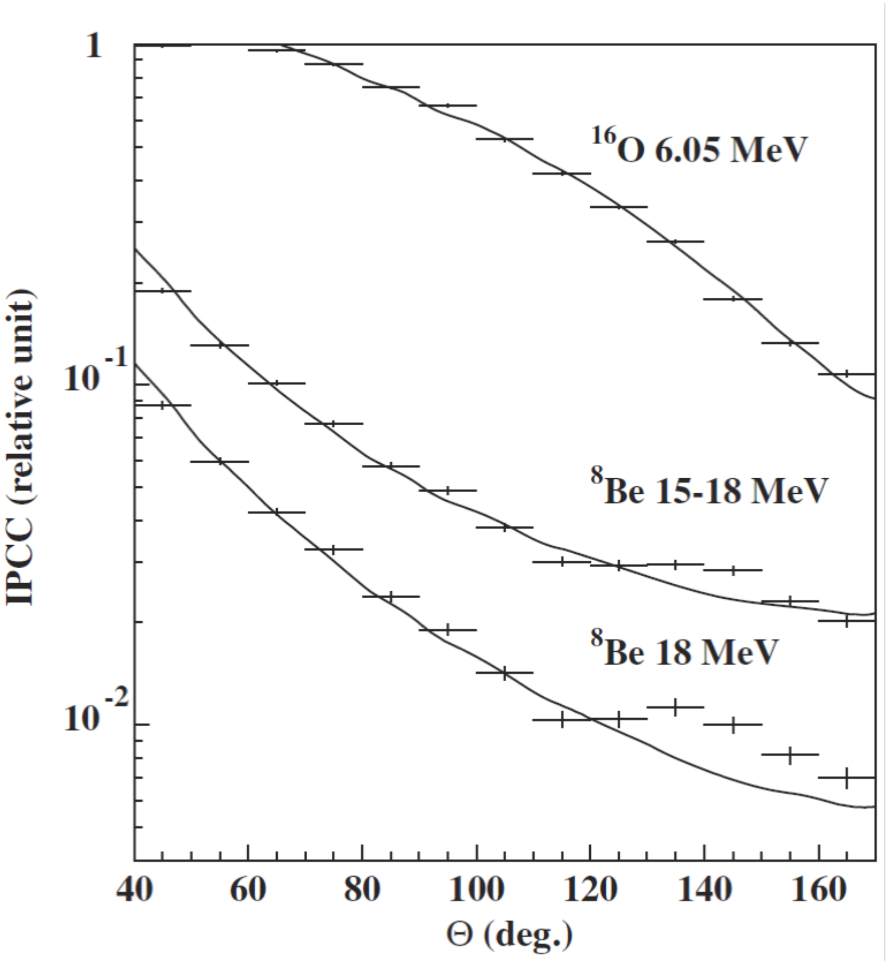
Centro Ricerche Enrico Fermi and online, Italy, Sep. 2021

Outline

- Nuclear physics behind the internal pair production in Be-8
- (Im)possible nuclear physics explanations
- Comments on the protophobic vector explanation
- Summary

The ATOMKI anomaly





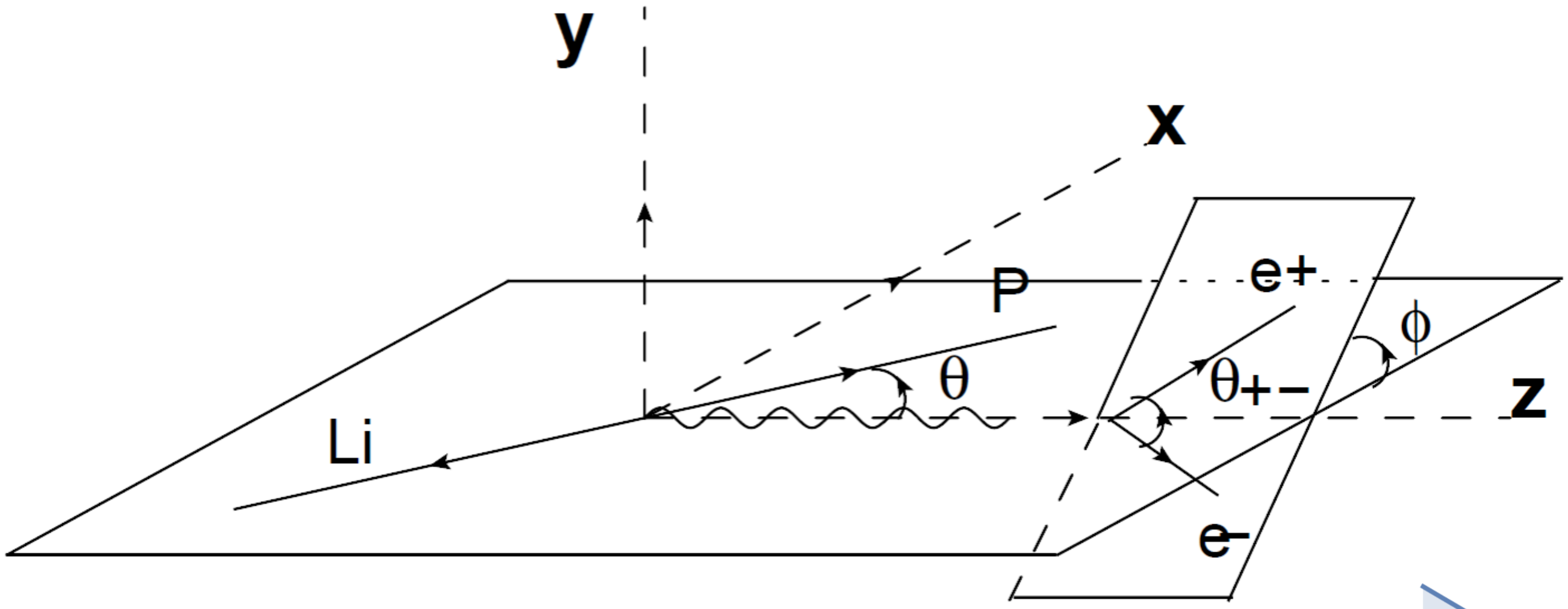
XZ and G. A. Miller
Phys.Lett.B 773 (2017) 159-165
[1703.04588]

(Im)possible nuclear physics explanations

EM multipole interferences and multipole's form factor

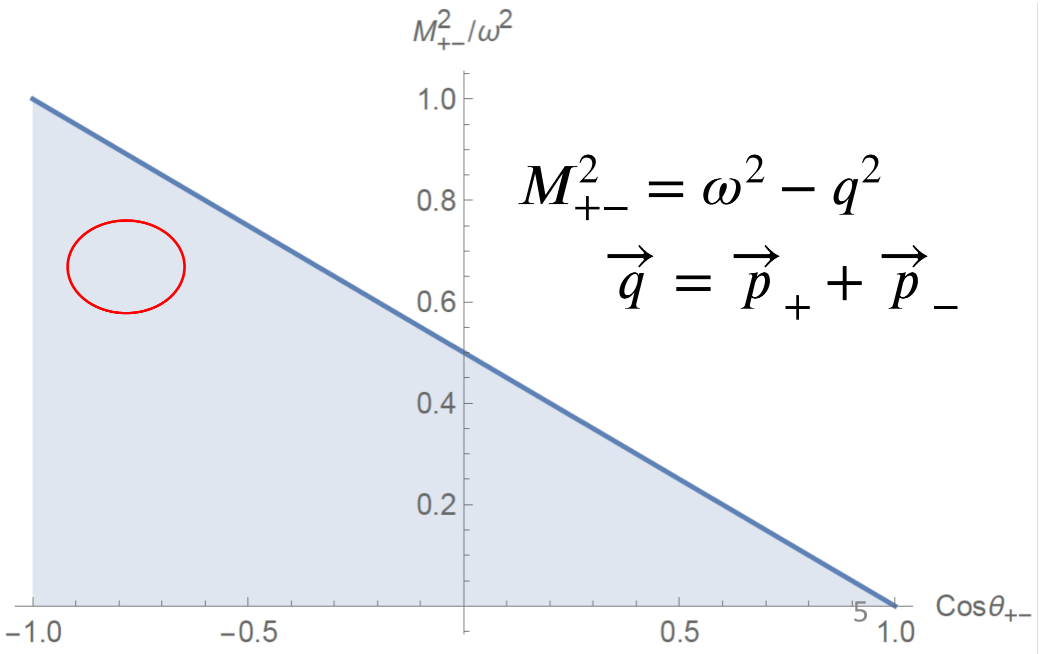
- The theoretical model used is from M. E. Rose [PR 76, **678** (1949)]
- No interference was studied.

Kinematics



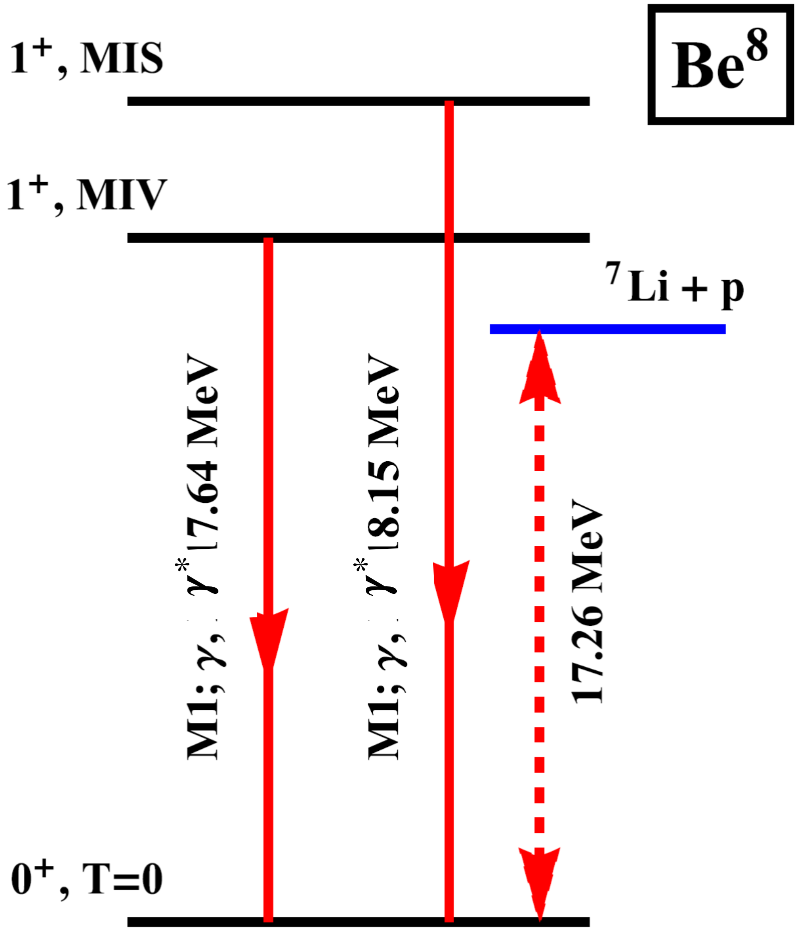
$$\frac{d\sigma}{d\cos\theta\, d\varphi\, d\cos\theta_{+-} dE_{+}}$$

$$\frac{d\sigma}{d\cos\theta\, d\varphi\, d\cos\theta_{+-} dM_{+-}}$$



$$M_{+-}^2 = \omega^2 - q^2$$

$$\vec{q} = \vec{p}_+ + \vec{p}_-$$

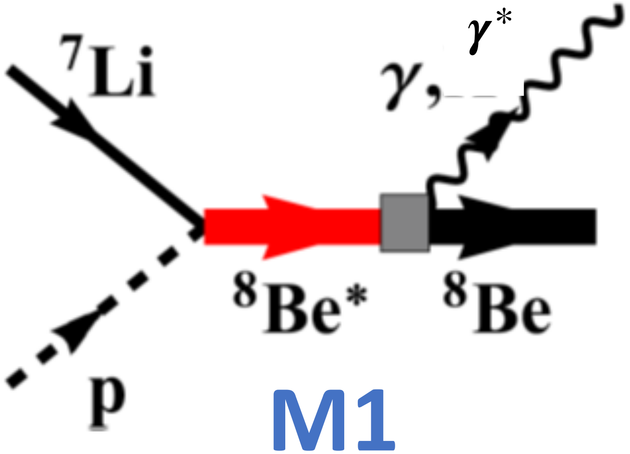


EM transitions

	λ (Operator rank)	S (Initial state total spin)	L (Initial state angular momentum)
E1	1	1	0
M1	1	1, 2	1
E2	2	1, 2	1

They interfere!

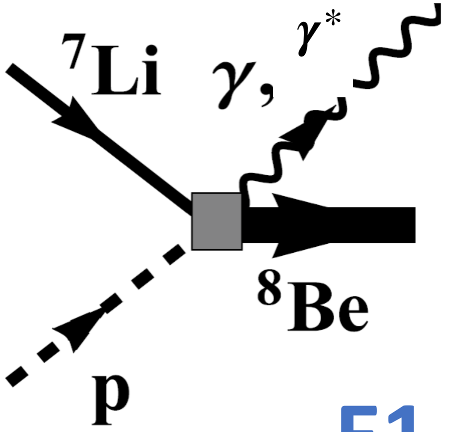
EFT-based model for $J \equiv \langle Be | \hat{J} | Li + \mathrm{p} \rangle$



M1

$$U_{M1,1} \sim -\frac{\sqrt{\Gamma_{\gamma(0)}\Gamma_{(0)}X_{(0)}}}{E - E_{(0)} + i\frac{\Gamma_{(0)}}{2}} + \frac{\sqrt{\Gamma_{\gamma(1)}\Gamma_{(1)}X_{(1)}}}{E - E_{(1)} + i\frac{\Gamma_{(1)}}{2}}$$

$$U_{M1,2} \sim \frac{\sqrt{\Gamma_{\gamma(0)}\Gamma_{(0)}(1 - X_{(0)})}}{E - E_{(0)} + i\frac{\Gamma_{(0)}}{2}} + \frac{\sqrt{\Gamma_{\gamma(1)}\Gamma_{(1)}(1 - X_{(1)})}}{E - E_{(1)} + i\frac{\Gamma_{(1)}}{2}}$$



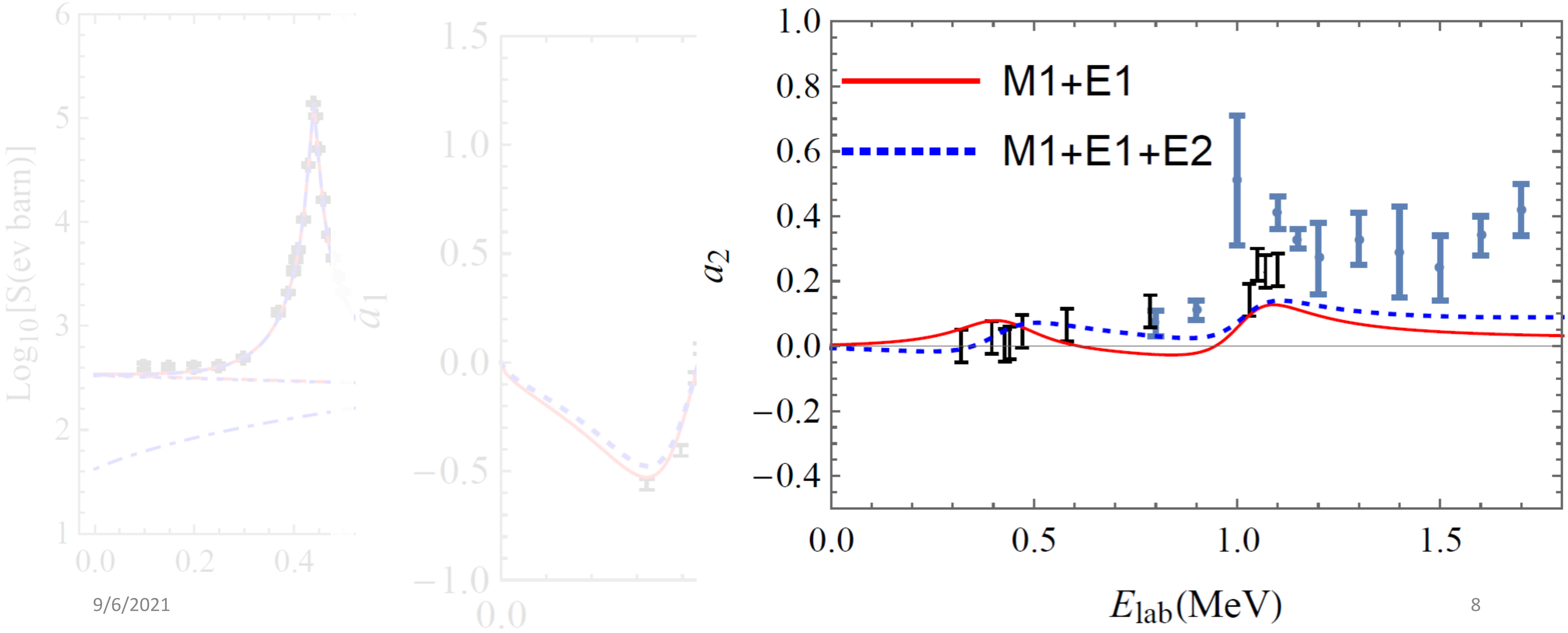
E1, E2

$$U_{E1} \sim d_{E1}\left(1 - d'_{E1}\frac{p^2}{\Lambda^2}\right); \quad U_{E2,1} \sim d_{E2,1}; \quad U_{E2,2} \sim d_{E2,2}$$

On-shell photon production

D. Zahnow et.al., *Z. Phys. A* **351**, 229 (1995); B. MainsBridge, *Nucl.Phys.* **21**, 1(1960); D.J. Schlueter, et.al., *Nucl.Phys.* **58**, 254 (1964)

$$\sum |\mathrm{M}|^2 \equiv T_0\left[1 + a_1 P_1(\cos\theta) + a_2 P_2(\cos\theta)\right]$$



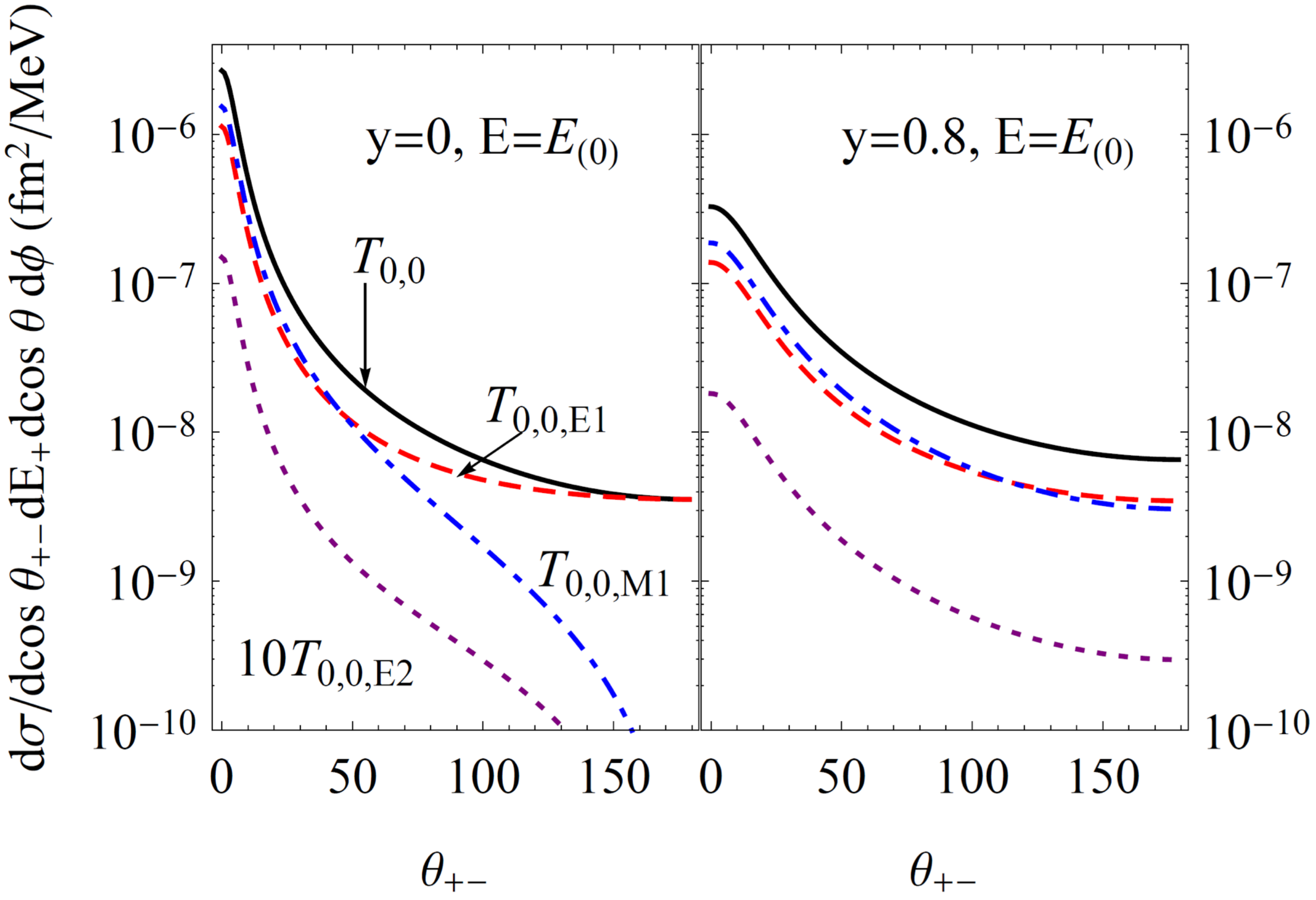
e^+e^- production

$$\frac{M_{+-}^4}{2}\sum|\mathrm{M}|^2 \equiv T_{0,0} + T_{0,2}\cos 2\varphi \; + \; T_{1,0}P_1(\cos\theta) + T_{2,0}P_2(\cos\theta)$$
$$+ T_{2,2}P_2(\cos\theta)\cos 2\varphi + T_{3,1}\sin\theta\cos\varphi + T_{4,1}\sin 2\theta\cos\varphi$$

In the large M_{+-} (Θ_{+-}), i.e., small q region:

$$T_{0,0,E1}\sim|U_{E1}|^2 M_{+-}^2\ \omega^2$$
$$T_{0,0,M1}\sim\left[\,|U_{M1,1}|^2 + |U_{M1,2}|^2\right]\left(\frac{p}{M}\right)^2 M_{+-}^2\ q^2$$
$$T_{0,0,E2}\sim\left[\,|U_{E2,1}|^2 + |U_{E2,2}|^2\right]\left(\frac{p}{M}\right)^2 M_{+-}^2\ \omega^2 q^2$$

θ and ϕ dependences comes from interferences between different multipoles



$$\frac{d\sigma}{d\cos\Theta_{+-}dE_{+}d\cos\Theta d\Phi}$$

$$y \equiv \frac{E_{+} - E_{-}}{E_{+} + E_{-}}$$

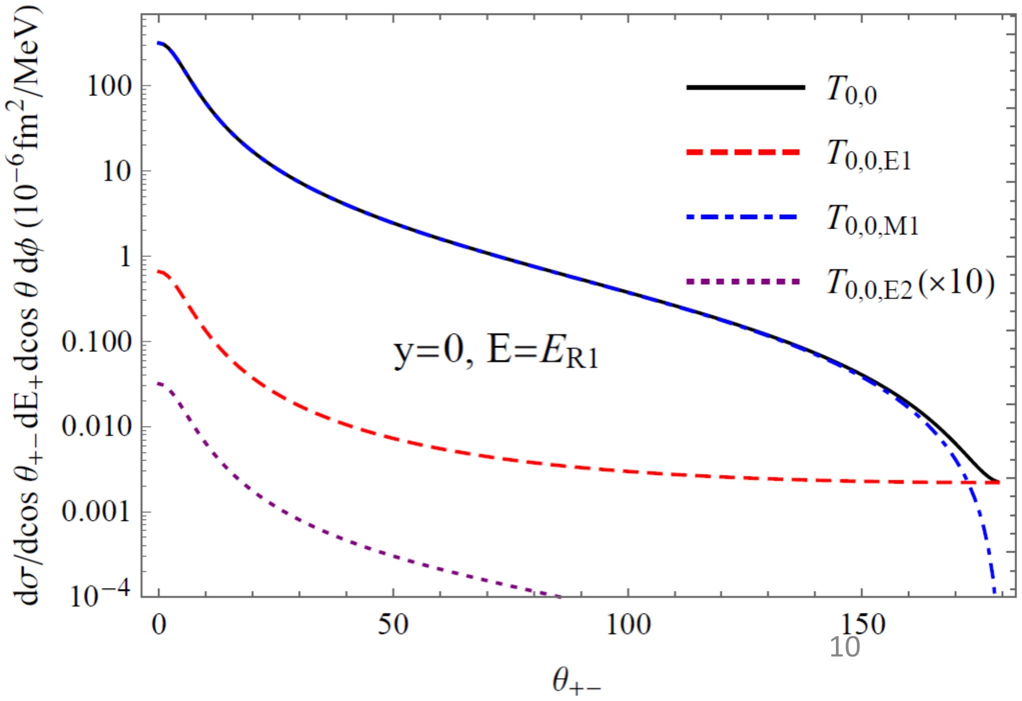


FIG. 4. The $T_{0,0}$'s contribution to the differential cross section vs. θ_{+-} and its decomposition at $y = 0, 0.8$ and $E = E_{(0)}$. $T_{0,0,E2}$ is multiplied by 10 in both plots to increase its visibility.

Anisotropy

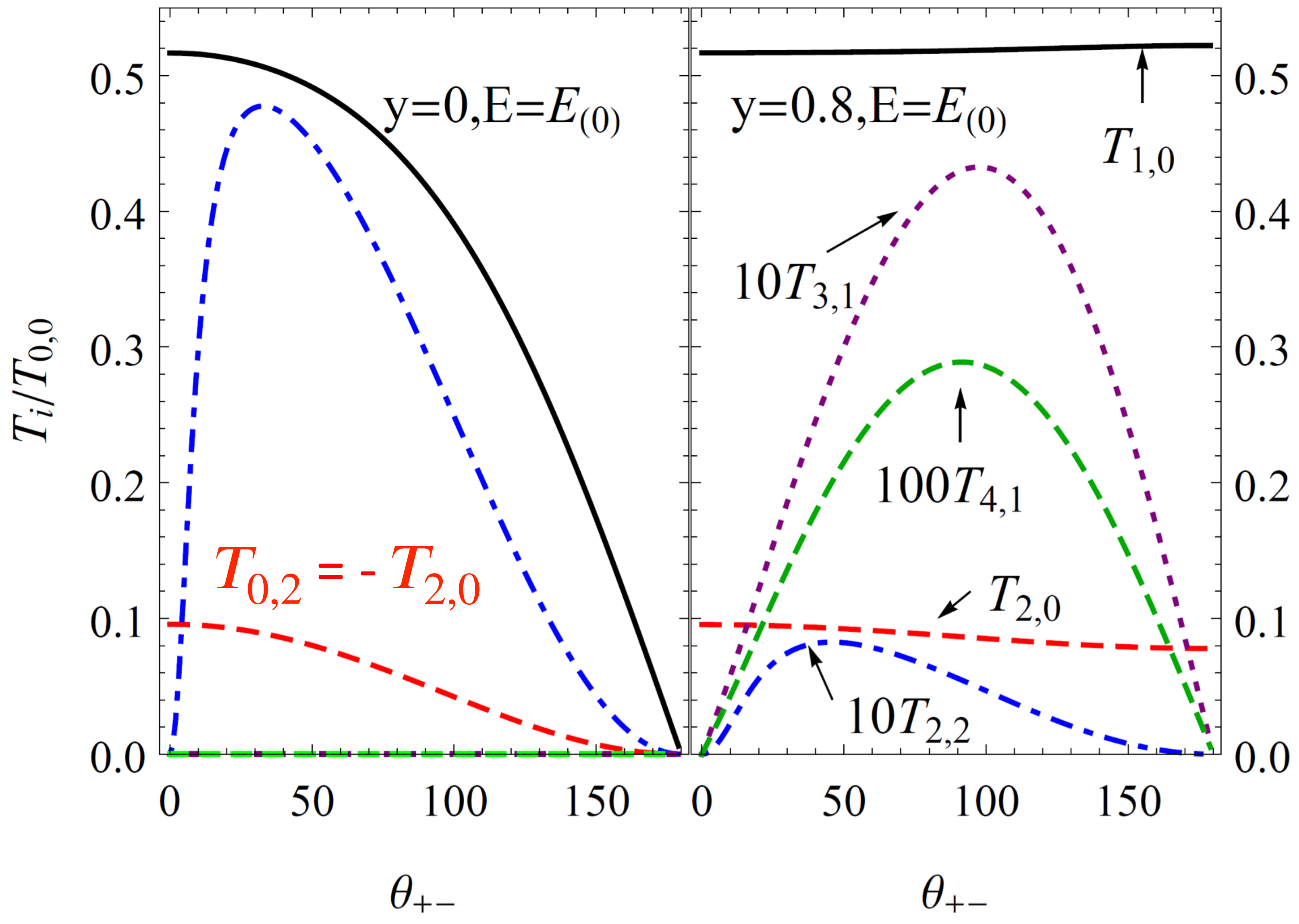


FIG. 5. The ratios between the other coefficients $T_{i,j}$ in expression (4.1) and $T_{0,0}$ at $y = 0, 0.8$ and $E = E_{(0)}$. Several components are multiplied by 10 or 100 in both plots to increase their visibility. Note $T_{3,1} = T_{4,1} = 0$ when $y = 0$.

$$T_{0,0} + T_{0,2}\cos 2\varphi$$

$$+ T_{1,0}P_1(\cos\theta) + T_{2,0}P_2(\cos\theta) + T_{2,2}P_2(\cos\theta)\cos 2\varphi + T_{3,1}\sin\theta\cos\varphi + T_{4,1}\sin 2\theta\cos\varphi$$

Relevant for data analysis?!

Anomaly due to interference?

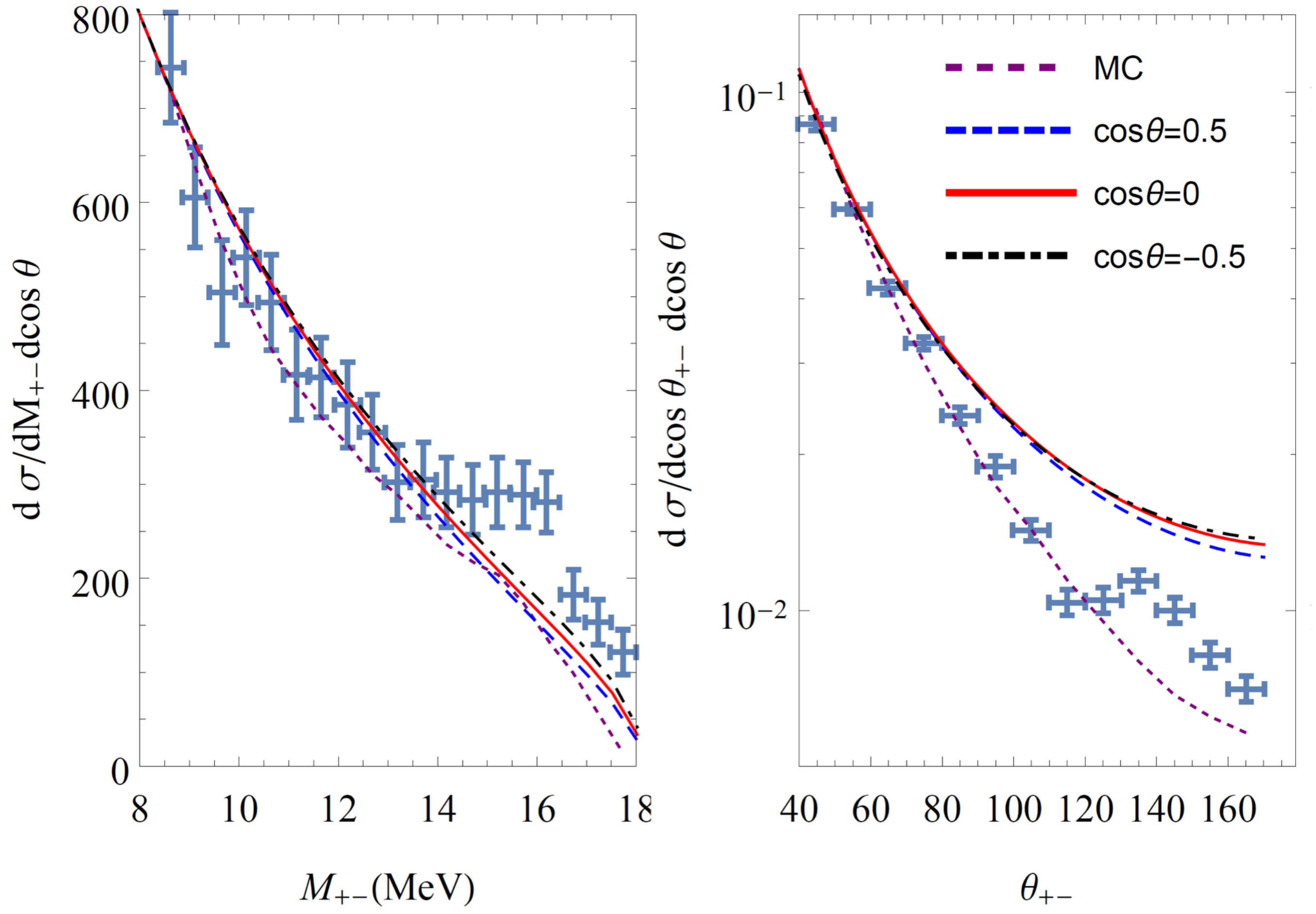


FIG. 6. The differential cross sections vs M_{+-} (left) and θ_{+-} (right) with $\cos\theta = 0$ and ± 0.5. "MC" is the experimental MC simulation [1]. In the M_{+-} distribution, the last data point [1] with M_{+-} above the so-called Q value, i.e., $E_{th} + E_{(0)} = 18.15$ MeV, is not shown here. The normalizations of our results in two plots are chosen such that the results agree with data in the lowest M_{+-} and θ_{+-} bins.

Anomaly due to M1 form factor?

$$f\left(M_{+-}^2\right) = 1 + f_1 \frac{M_{+-}^2}{(20\mathrm{MeV})^2} + f_2 \frac{M_{+-}^4}{(20\mathrm{MeV})^4} + f_3 \frac{M_{+-}^6}{(20\mathrm{Me}}$$

ff	-3.3	-5.8	18.0
ffv2	-3.3	0	0

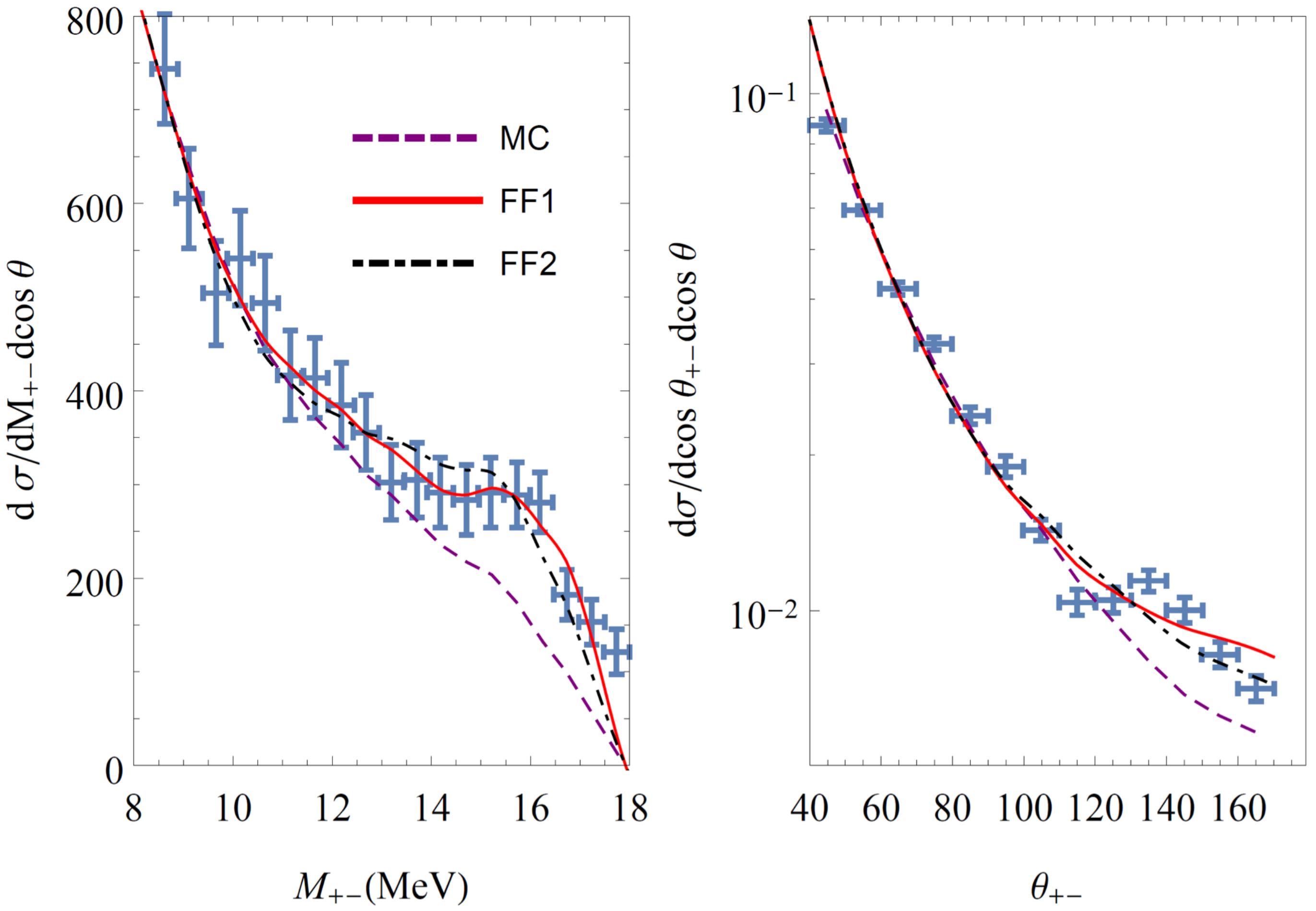


FIG. 7. The differential cross sections vs M_{+-} and θ_{+-} with $\theta = 90°$. Again "MC" is the MC simulation. The other curves are explained in the text.

However, one microscopic calculation shows a much weaker q dependence!

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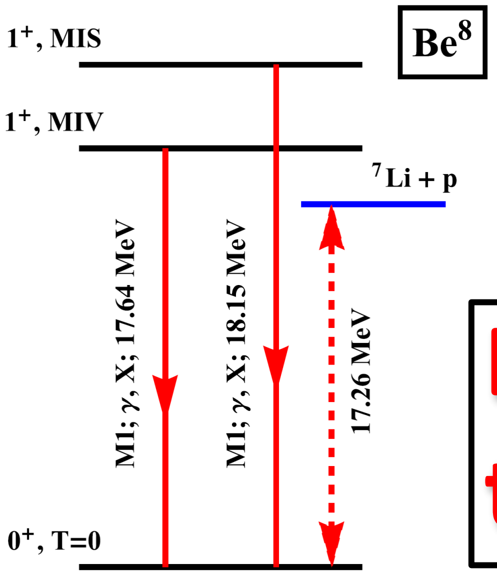
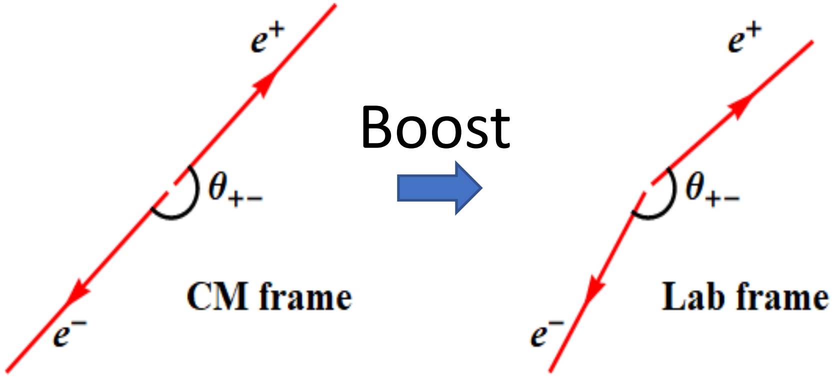
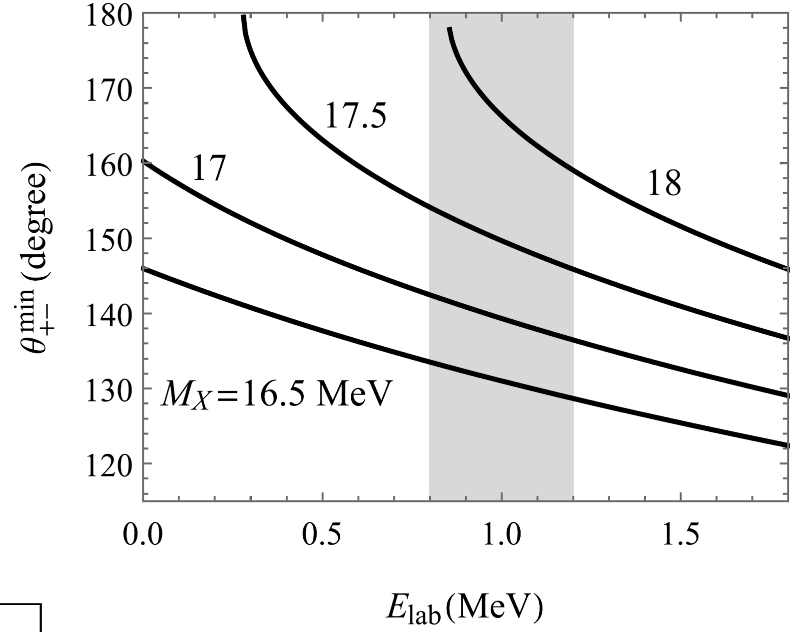
Phys.Lett.B 813 (2021) 136061 [2008.11288]

Comments on the protophobic vector boson explanation

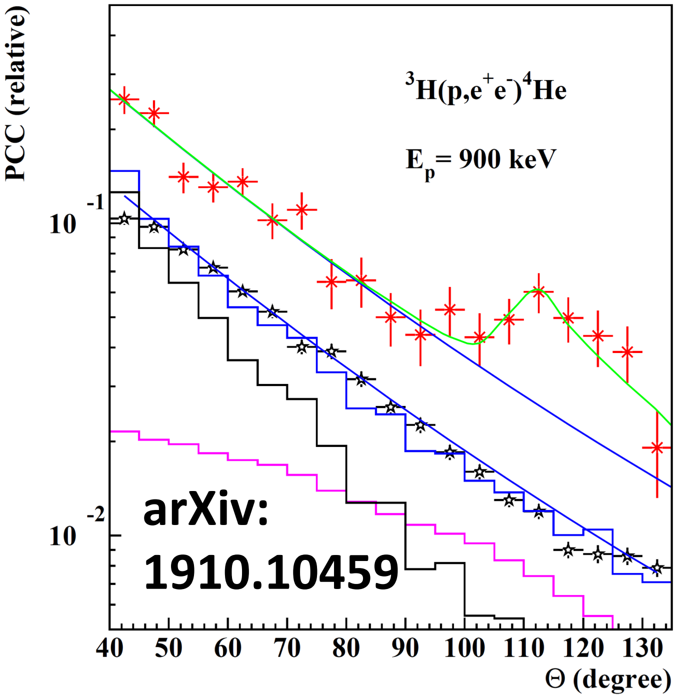
Protophobic vector boson (X) explanation



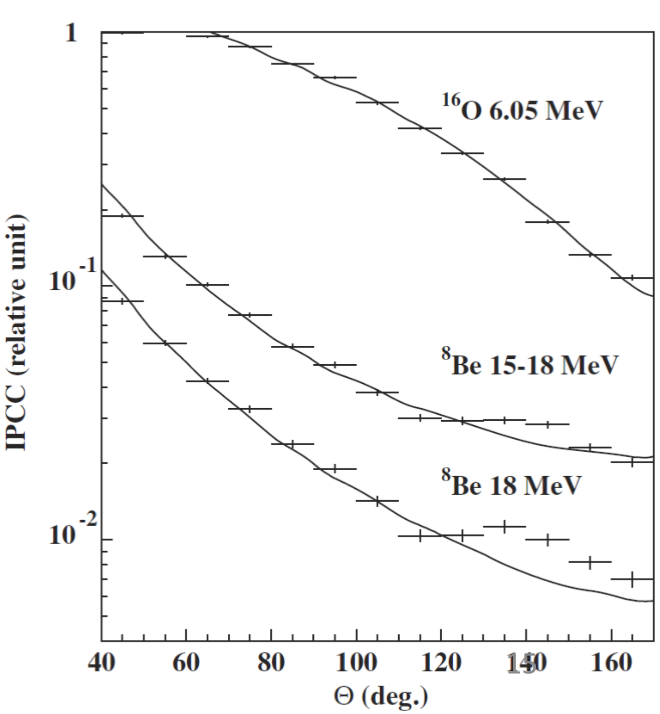




But is it true?

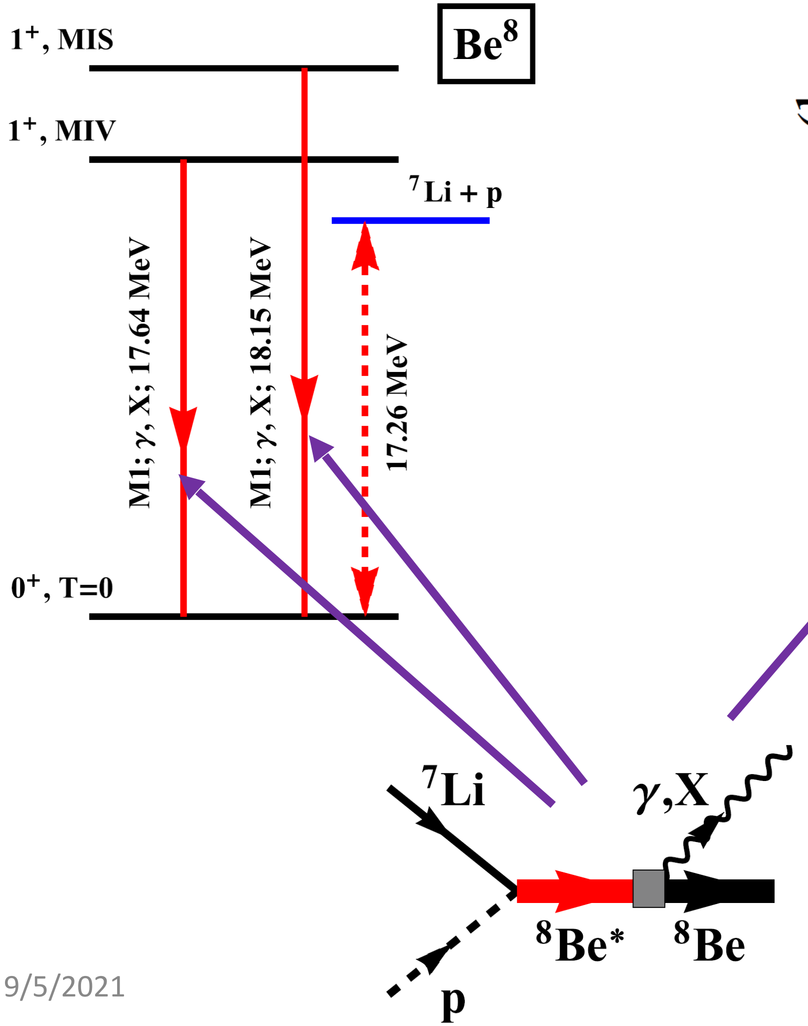


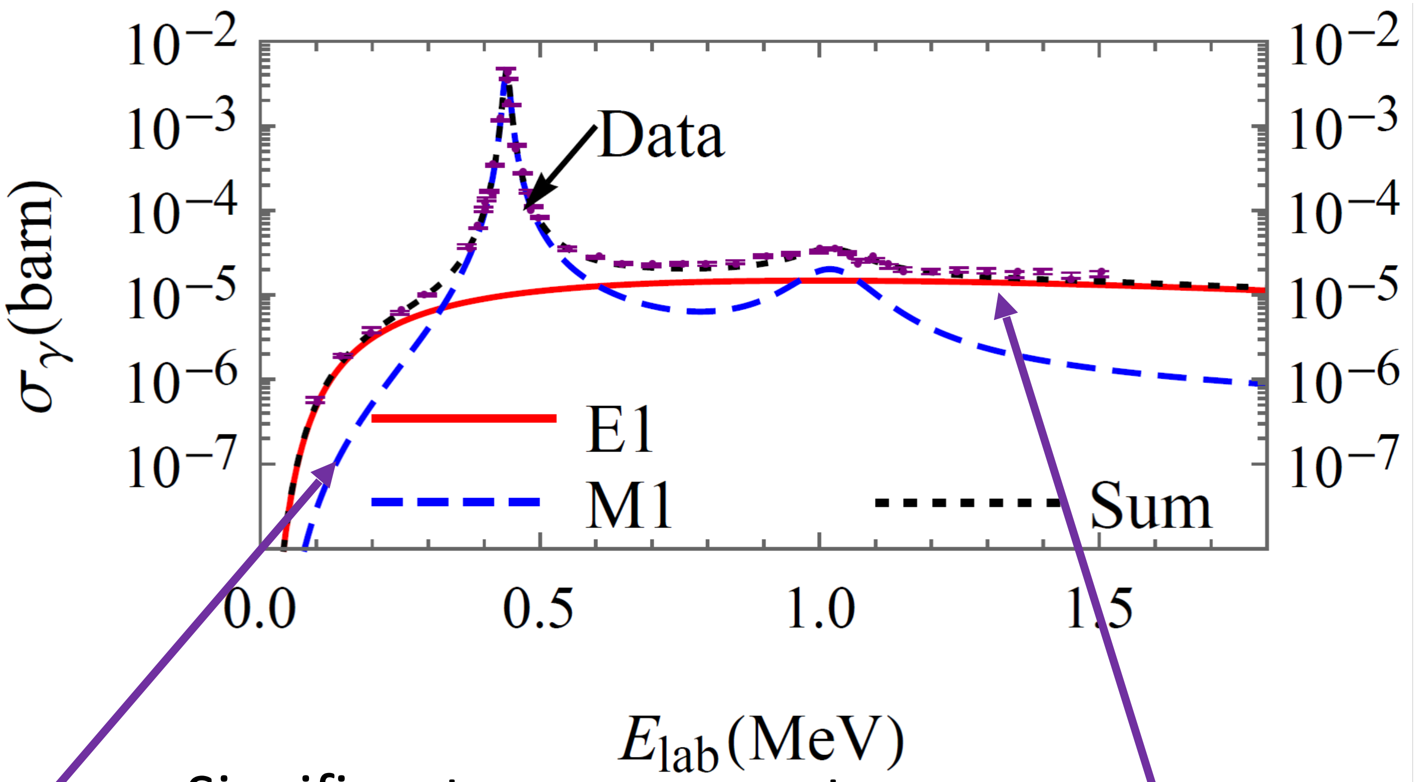
arXiv: 1910.10459



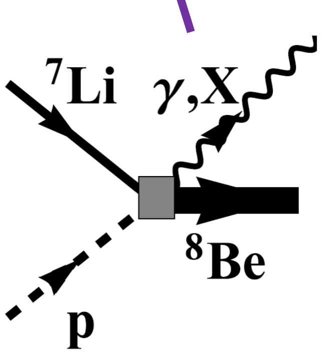
- J.L. Feng et.al., (2016, 2017): protophobic X (17 MeV) in the Be-8 transition
- J.L. Feng et.al., (2020): consistent explanation in both Be-8 and He-4 transitions
- Nontrivial part: the required X properties, including protophobia, couplings and masses, are consistent with existing constraints

Nuclear physics





- Significant non-resonant photon productions (Bremsstrahlung)
- At the 2nd res. peak, E1/ M1 ~ 1



E1: isovector

$$\mathcal{O}^{\gamma}_{\rm E1} = e_{\rm EM}\sqrt{\frac{3}{4\pi}}\sum_{i=1}^{A}\boldsymbol{r}_{(i)}\frac{\tau_{(i),3}}{2}$$

R. D. Lawson,
Theory of the nuclear shell model
(Oxford University Press,1980)

(a) *$T=0\rightarrow T=0$ E1 transitions are forbidden.* One may find many examples of this selection rule. For instance, in $^{18}_{9}F_9$ the 1·08 MeV 0^- state has a mean lifetime for gamma decay to the 1^+ ground state of 27 ± 2 picoseconds (Endt and Van der Leun 1974a). From Table 5.2 it follows that

$$\frac{w_{\rm expt}(0^-\rightarrow1^+)}{w_{\rm W}(0^-\rightarrow1^+)}=4\cdot3\times10^{-5}$$

where $w_{\rm expt}$ and $w_{\rm W}$ are the experimental and Weisskopf estimates for the transition probability/unit time. For nuclei with $A<45$ the data on these isospin-forbidden transitions have been collected (Endt and Van der Leun 1974, 1974a), and it is found that on the average they are inhibited by about a factor of 10^4 from the Weisskopf estimate.

(b) *$\Delta T=0$ E1 transitions in $T_z=0$ nuclei are forbidden.* This selection rule implies that the same transition in neighbouring nuclei may differ markedly. An example would be provided by comparing the transition from the first excited 1^- state in $^{14}_{6}C_8$ (at 6·09 MeV) to the ground state and the analogous decay in $^{14}_{7}N_7$; i.e. 8·06 MeV $T=1$, $1^-\rightarrow$ 2·31 MeV $T=1$, 0^+. For the latter the transition is isospin-forbidden whereas there is no selection rule to inhibit the former. Unfortunately data such as these are difficult to obtain and only crude limits have so far been set on these lifetimes (Ajzenberg-Selove 1970).

(c) *Corresponding transitions in nuclei with the same $|T_z|$ have the same value of $B(E1;I_i\rightarrow I_f)$.* This follows because when $T_z\rightarrow -T_z$ the isospin Clebsch at most changes sign. This rule says, for example, that $B(E1)$ for the $\frac{1}{2}^-\rightarrow\frac{1}{2}^+$ decay in $^{19}_{9}F_{10}$ and $^{19}_{10}Ne_9$ should be the same. For the former, the mean lifetime of the 110 keV $\frac{1}{2}^-$ level for decay to the $\frac{1}{2}^+$ ground state is 849×10^{-12} s and for the latter the $\frac{1}{2}^-$, which lies at 280 keV, has a mean life of 61×10^{-12} s (Endt and Van der Leun 1974a). Thus from Table 5.1 it

M1 transitions between $T=0$ states in self-conjugate nuclei should be much slower (approximately $(0{\cdot}38/4{\cdot}2)^2$) than transitions in the same nucleus with $\Delta T=1$ or those in neighbouring $T\neq 0$ nuclei.

An example of this rule is provided by the decay of the 3·95 MeV $I=1^+$ $T=0$ state om $^{14}_{7}N_7$. The decay to the $I=1^+$ $T=0$ ground state has a radiative width of $5{\cdot}8\times10^{-4}$ eV and that to the $I=0^+$ $T=1$ 2·31 MeV level has $\Gamma_\gamma=0{\cdot}14$ eV (Ajzenberg-Selove 1970) where Γ_γ is defined by equation (5.21). Thus

$$R_1=\frac{\Gamma_\gamma\{3{\cdot}95(1^+,0)\rightarrow \text{g.s.}(1^+,0)\}}{\Gamma_\gamma\{3{\cdot}95(1^+,0)\rightarrow 2{\cdot}31(0^+,1)\}}=4{\cdot}1\times10^{-3}.$$

Naively one would have anticipated that R_1 would be approximately the ratio of the cube of the transition energies

$$R_1=\left(\frac{3{\cdot}95}{3{\cdot}95-2{\cdot}31}\right)^3=14.$$

M1: mostly isovector

$$\mathcal{O}^{\gamma}_{\mathrm{M1}} \overset{\text{here}}{\approx} \sqrt{\frac{3}{4\pi}}\frac{e_{\mathrm{EM}}}{2M_N}\sum_i\left[\left(\lambda^{(1)}+\frac{1}{4}\right)\boldsymbol{\sigma}_{(i)}+\frac{1}{2}\boldsymbol{J}_{(i)}\right]\tau_{(i),3}$$

R. D. Lawson,
Theory of the nuclear shell model
(Oxford University Press,1980)

Problem with X

$$J_\gamma^\mu = \overline{N}\left(\Gamma_s^\mu + \Gamma_v^\mu \tau_3\right) N$$

$$J_X^\mu = \overline{N}\left(\varepsilon_s \Gamma_s^\mu - \varepsilon_v \Gamma_v^\mu \tau_3\right) N$$

$$\mathcal{O}_{\mathrm{E1}}^\gamma = e_{\mathrm{EM}} \sqrt{\frac{3}{4\pi}} \sum_{i=1}^{A} \boldsymbol{r}_{(i)} \frac{\tau_{(i),3}}{2}$$

$$\mathcal{O}_{\mathrm{M1}}^\gamma \overset{\text{here}}{\approx} \sqrt{\frac{3}{4\pi}} \frac{e_{\mathrm{EM}}}{2M_N} \sum_i \left[\left(\lambda^{(1)} + \frac{1}{4}\right)\boldsymbol{\sigma}_{(i)} + \frac{1}{2}\boldsymbol{J}_{(i)}\right] \tau_{(i),3}$$

Non-res piece dominate over the res. piece

Since $\varepsilon_s \approx \varepsilon_v$

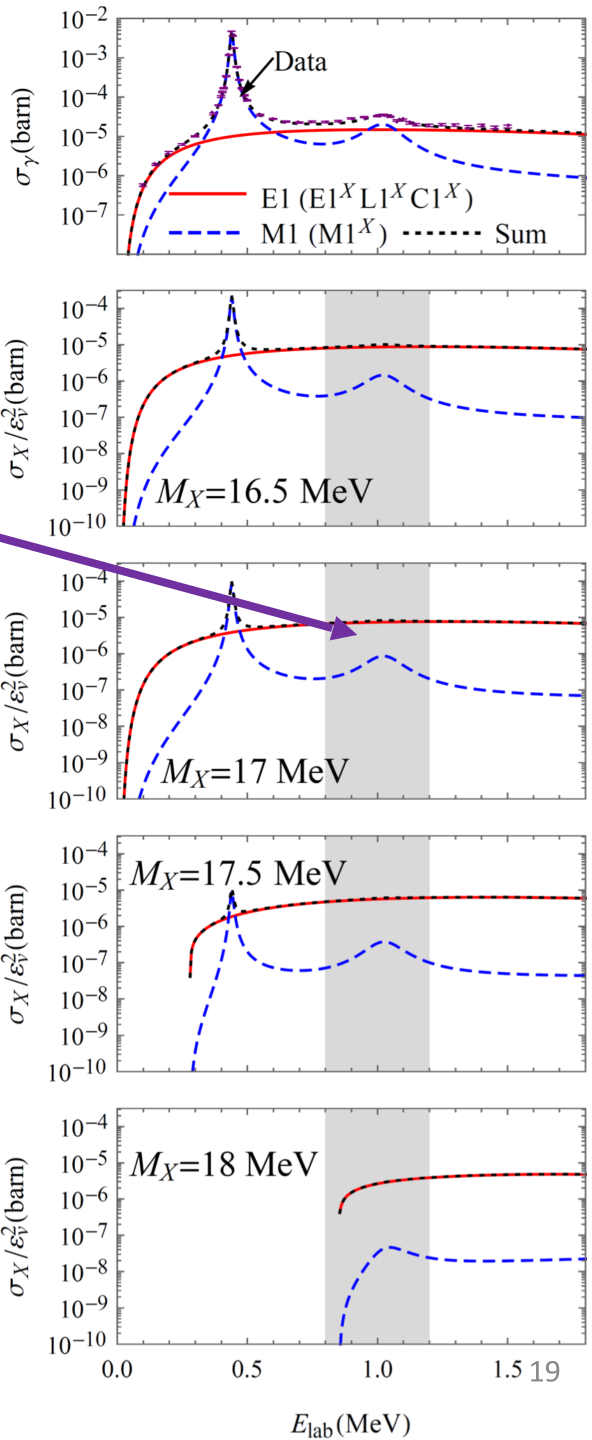
$$\mathcal{O}_{\mathrm{E1}}^X = -\varepsilon_v \mathcal{O}_{\mathrm{E1}}^\gamma$$

$$\mathcal{O}_{\mathrm{M1}}^X \approx -\varepsilon_v \mathcal{O}_{\mathrm{M1}}^\gamma$$

No X was observed in the energies 1-width away from the peak!

→ **disprove X**

$$\left.\frac{\sigma_{X,ELC1^X}}{\sigma_{X,M1^X}}\right|_{MIS} = \frac{2\omega^2 + M_X^2}{2(\omega^2 - M_X^2)} \left.\frac{\sigma_{\gamma,E1}}{\sigma_{\gamma,M1}}\right|_{MIS} \overset{M_X=17}{\approx} 8.6$$



To evade the conflict,

$$\left|\frac{\varepsilon_s}{\varepsilon_v}\right| > 12\,.$$

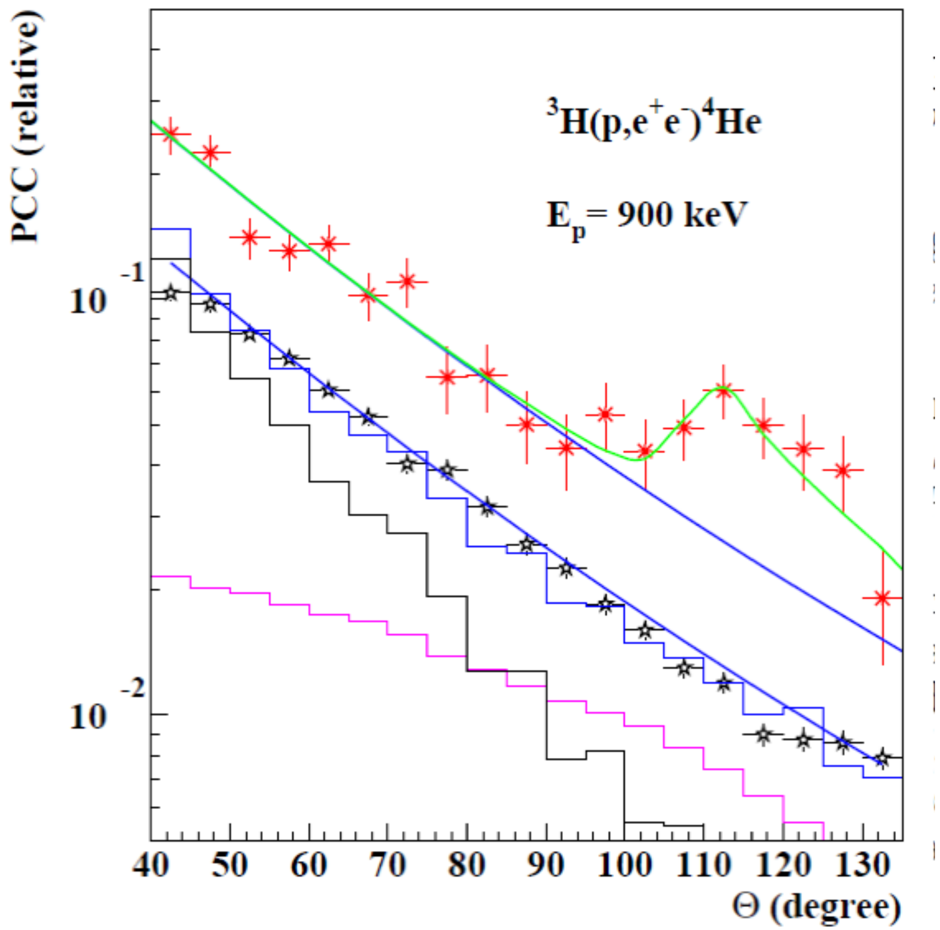
There are other multipoles, but they only increase the Bremsstrahlung component.

Summary

- A model for different EM transitions and interferences is available
- Interferences give nontrivial angular dependences
- Interferences and multipole form factor could NOT explain the anomaly
- For (protophobic vector): significant non-resonant (Bremsstrahlung) productions besides the resonant production
- This was not observed → disprove the protophobic-X explanation
- The non-resonant productions could be relevant for He-4 system

Now similar anomaly seen in He-5

New evidence supporting the existence of the hypothetic X17 particle



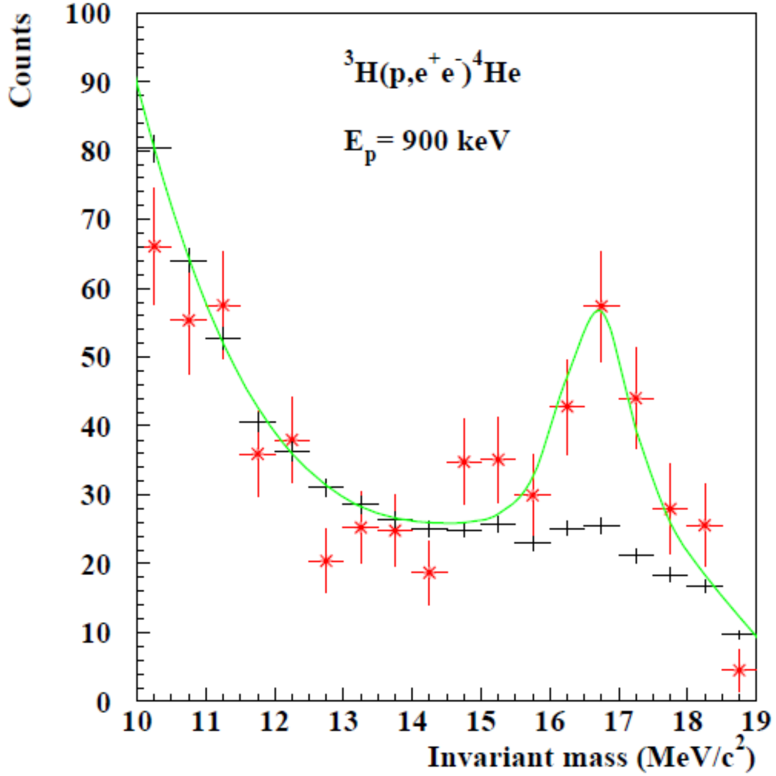


FIG. 3. *Invariant mass distribution derived for the 20.49 MeV transition in* ^{4}He.