Tömegformula az X17 vektor bozon-térre.

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Varró S, Tömegformula az X17 vektor bozon-térre. [XVII Magyar Magfizikus Találkozó 2024, ATOMKI, Debrecen, 3-5 Sept. 2024. Szept. 5.., Csütörtök 11:20h.] [File:"Varro_S_X17_Talk_ATOMKI_Magfiz_05_Sept_2024_v_1.ppt"]

Vázlat.

Bevezetés.

A belső elektron–pozitron párkeltésnél a szögkorrelációban észlelt „ATOMKI anomália” értelmezése az X17 részecske feltételezésével(invariáns tömeg ~ 17 MeV / c^2).

A kölcsönható „töltött Dirac-részecske + kvantált elektromágneses síkhullám” rendszer *egzakt állapotai*: „Kvantált Volkov–állapotok”.

Alkalmazás protonra: az X17-re javasolt elektromágneses tömegformula *levezetésének* főbb lépései. [Alkalmazás a neutron udd kvarkjaira. Tömegformula az E38 részecskére.]

A proton [neutron] „statisztikus sugara”: ~ (2 / π) × (Compton hullámhossz); kapcsolat az X17 [E38] mért tömegével.

[Appendix. Az X17 mezon-interpretációja, plazmonok és elektromágneses sugárzás „tömeg-generálása”, a tömeges fotonok fenomenológiája, vektor bozonok mint az ötödik erő közvetítői.]

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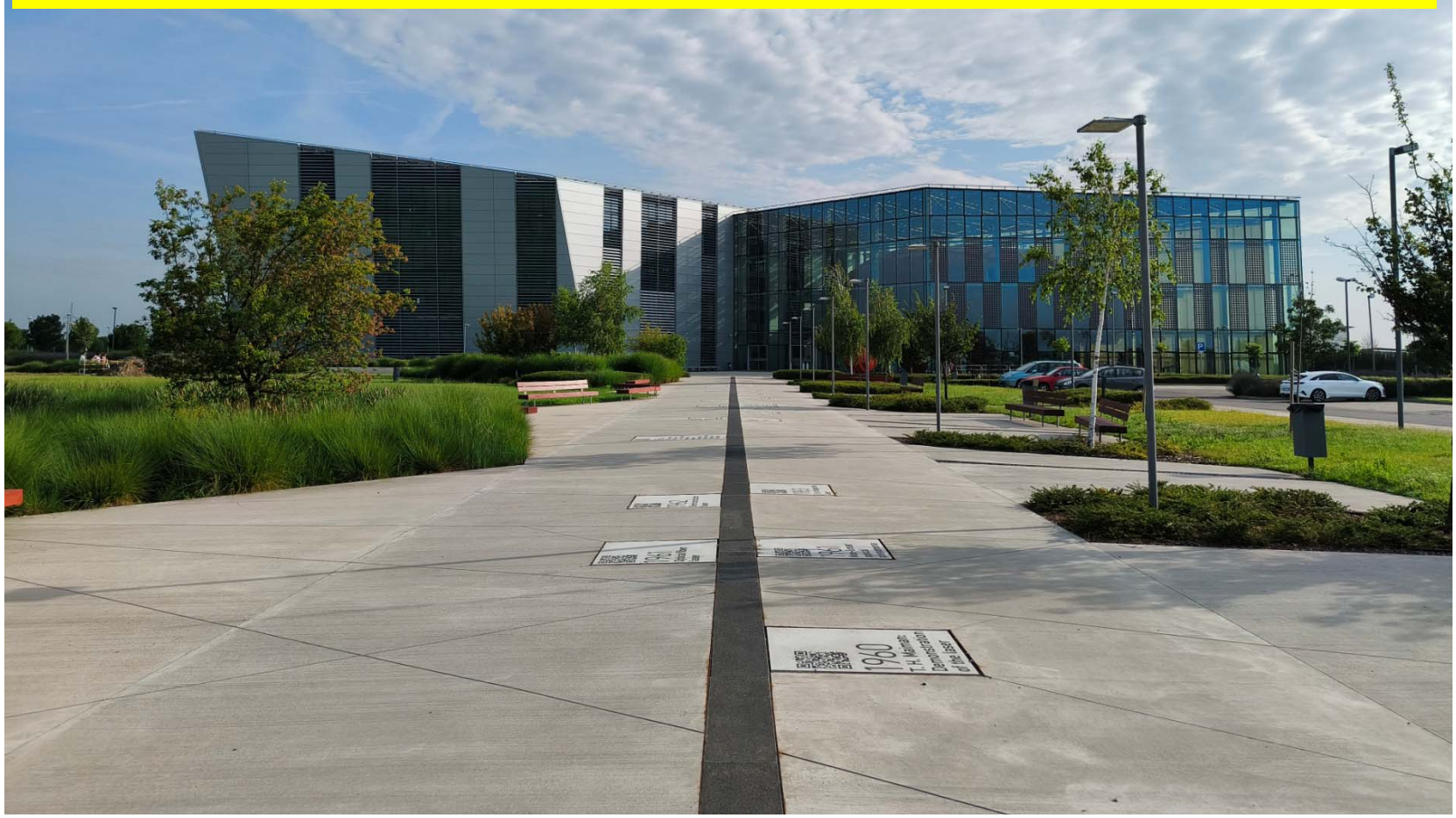
ALPS = Attosecond Light Pulse Source: Attoszekundum [10^{-18} sec]
ELI = Extreme Light Infrastructure: ALPS Szeged;
Beamlines Dolni Breznavy (Prague); NP Magurele (Bucharest).
ERIC = European Research Infrastructure Consortium 2023 November →.

ELI-ALPS Szeged, present. Photo of the site [July 2024]; ”Milestones”.



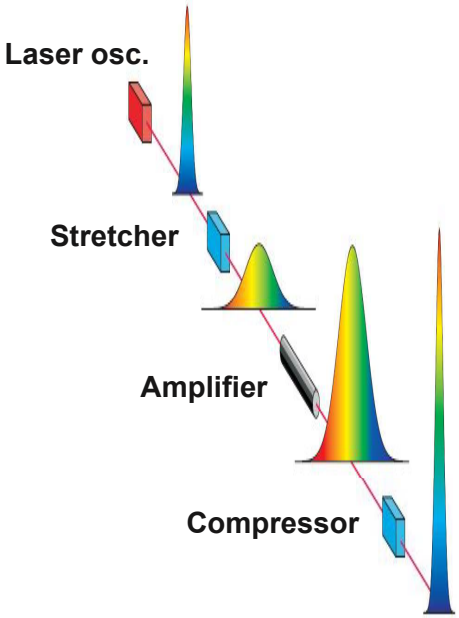
ELI-ALPS Szeged present. [14 July 2024]. Newest ”Milestone”.

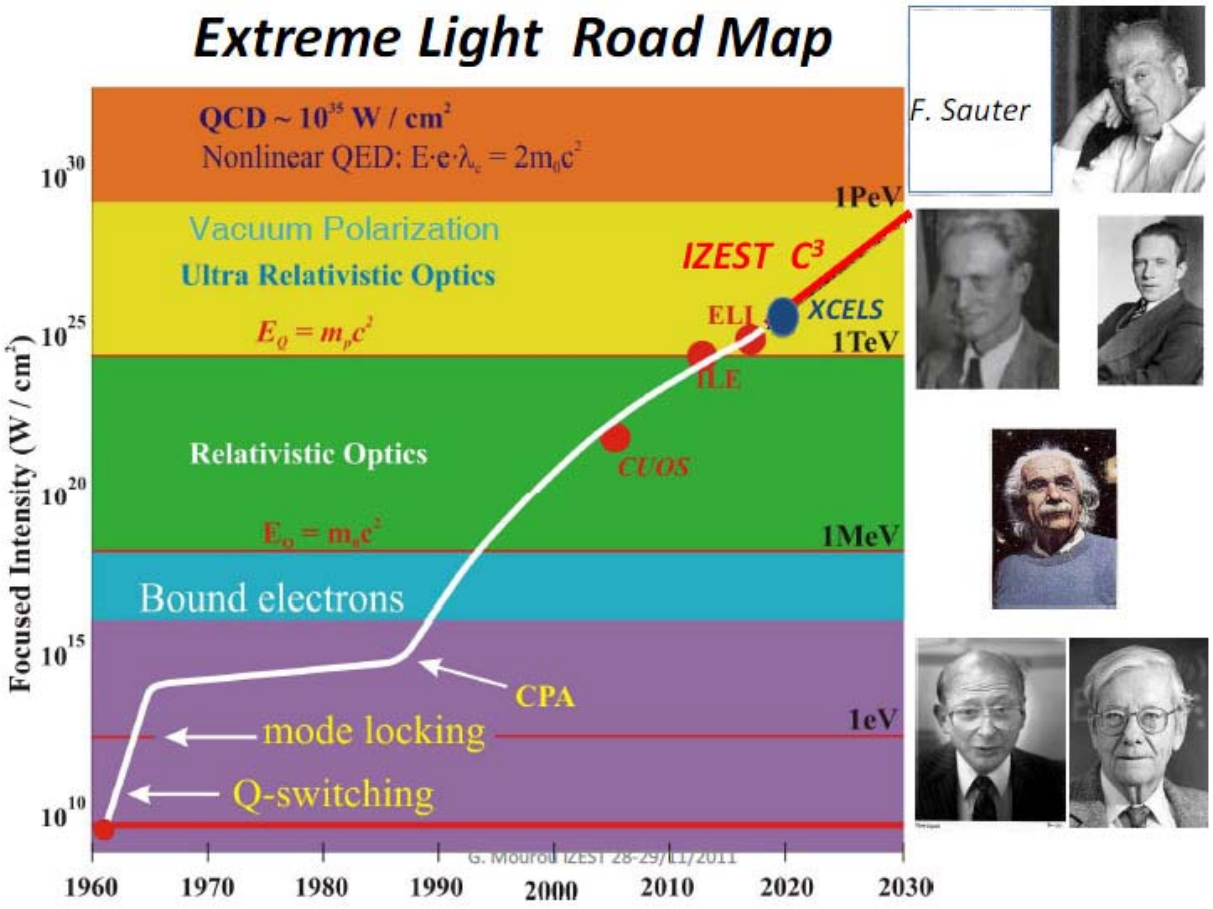
>The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics 2023 to Pierre Agostini, Ferenc Krausz and Anne L'Huillier "for experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter". <

ELI-ALPS Szeged, present. [14 July 2024]. Newest ”Milestone”. Katalin Karikó, Ferenc Krausz and Anne l’Huillier at the celebratory inauguration.

Development of very large intensity lasers based on the ‘CPA technique’. [D. Strickland and G. Mourou. The Nobel Prize in Physics 2018.]

CPA: Chirped Pulse Amplification [1985]





Right Figure taken from Gérard Mourou’s presentation at ‘IZEST’ [International Zeta-Exawatt Science and Technology.] Launching Workshop, Ecole Polytechnique, 28-29 November, 2011. Paris, France.

A belső elektron–pozitron párkeltésnél a szögkorrelációban észlelt „ATOMKI anomaly”. Az X17 invariáns tömege ~ 17 MeV / c^2.
[Az E38 invariáns tömege ~ 38 MeV / c^2.]

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Since the first publications ~2016, new and improved experimental results (2021-2023) are also pointing towards the existence of the X17.

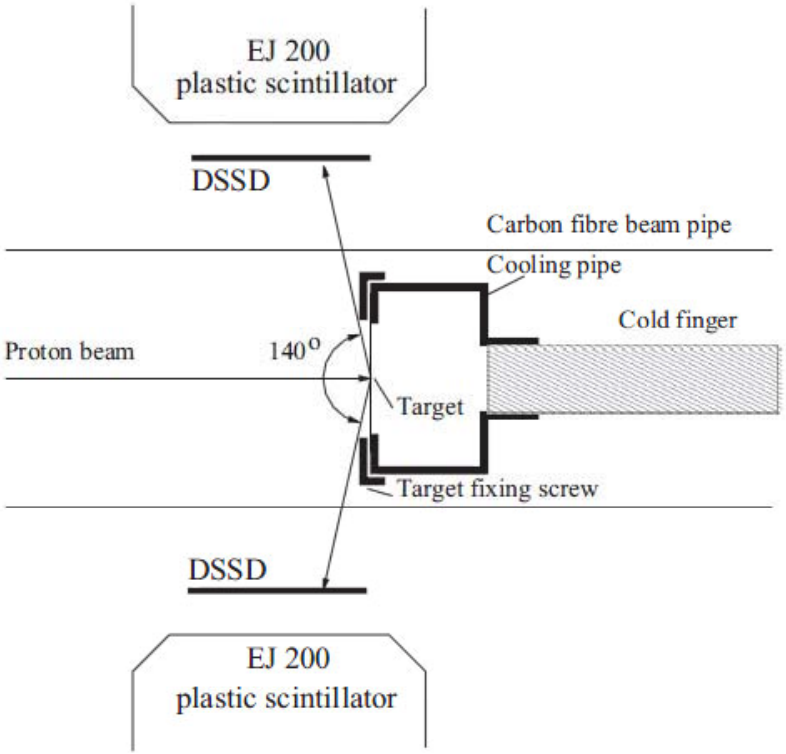


FIG. 1. Schematical drawing of the target cooling system.

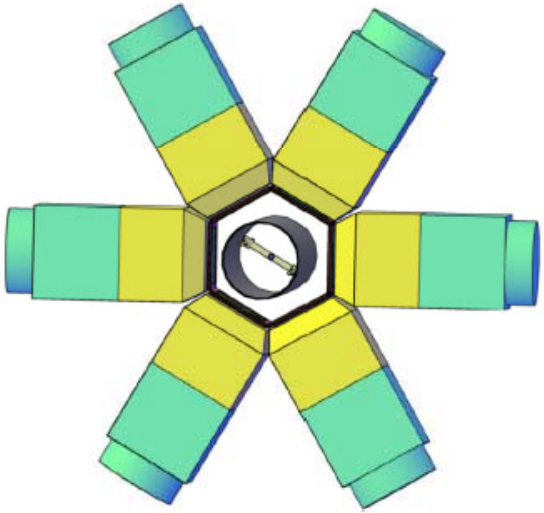


FIG. 2. CAD drawing of the e^+e^- spectrometer. The target (black/blue spot in the center of the figure) is evaporated onto 10 μm Al strip foil spanned between 3 mm thick Perspex rods to minimize the scattering and external pair creation in the vicinity of the target. The beam pipe is shown in black around which the DSSD detectors are arranged. The scintillators are shown in yellow while their light guides are in green. The PMT tubes are not shown.

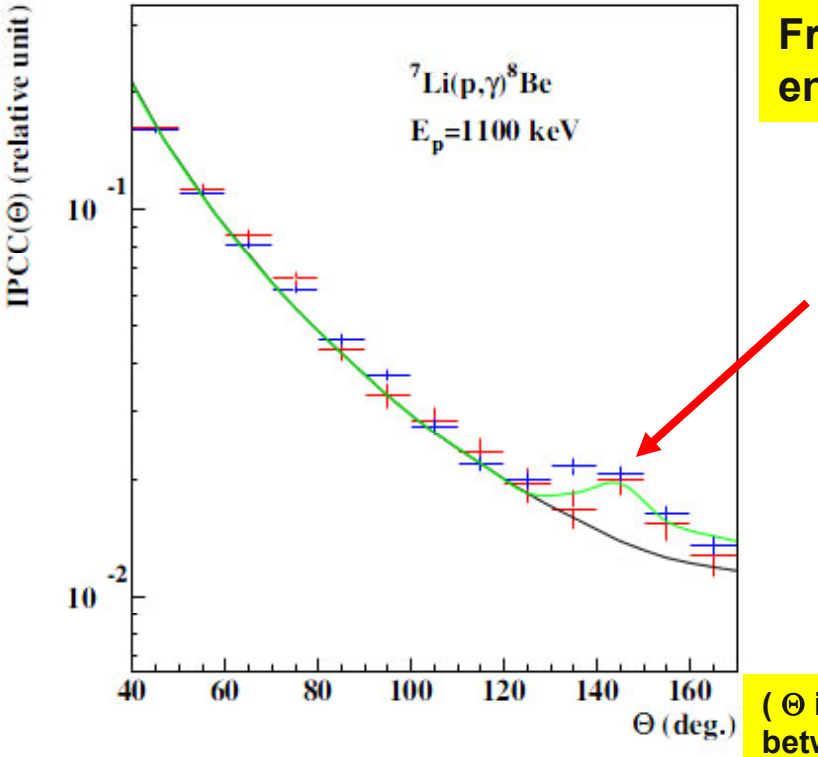
Figures copied from: [1e] Krasznahorkay A J, Csatlós M, Csige L, Gulyás J, Krasznahorkay A, Nyakó B M, Rajta I, Timár J, Vajda I and Sas N J, New anomaly observed in 4He supports the existence of the hypothetical X17 particle. Phys. Rev. C 104, 044003 (2021).

The 7Li(p,γ)8Be Experiment. Anomaly in IPCC (Internal Pair Creation Coefficient). The angular correlation anomaly corresponds to an invariant mass ~ 17 MeV / c^2.

Let us remind ourselves to the Bethe – Heitler process (1934):

$$\Phi d\theta = \frac{\theta d\theta}{\theta_0^2 + \theta^2}$$

$$\theta_0 = \frac{mc^2}{E_-}$$



From the conservation of energy and momentum:

$$E_+ + E_- = E_X$$

$$\boldsymbol{p}_+ + \boldsymbol{p}_- = \boldsymbol{p}_X$$

assuming: $(m_e << m_X)$

$$\cos\Theta = 1 - \frac{(m_X c^2)^2}{E_+ E_-}$$

(Θ is the angle between p_+ and p_-)

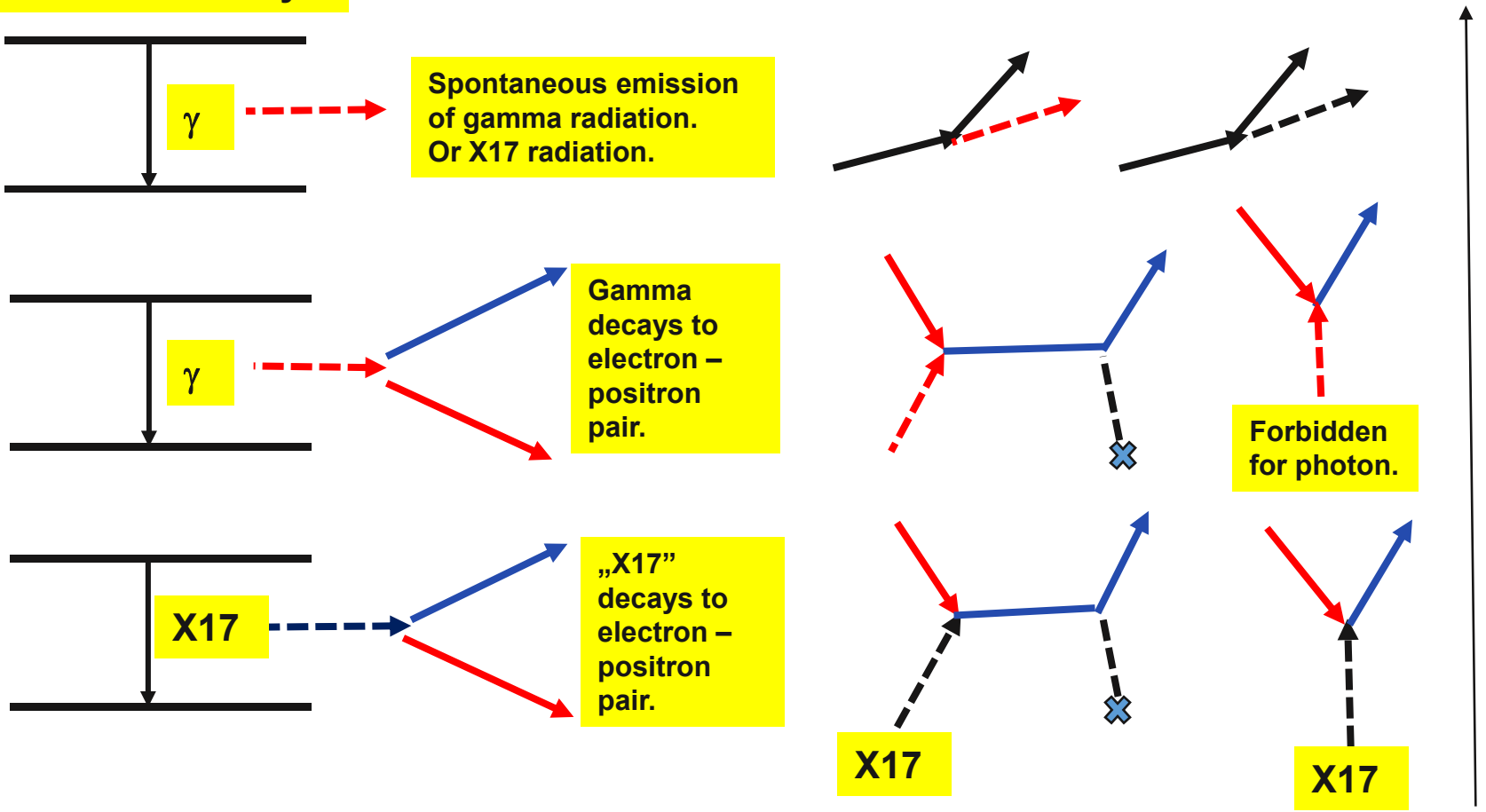
$$\approx 2$$

Figure 3. *Measured angular correlations published previously [3] (blue) and the present results (red) of the e^+e^- pairs originated from the decay of the 18.15 MeV ground state transition in ^{8}Be. The black line represents the background, while the green one is the sum of the signal and background.*

Krasznahorkay, A. J.; Csatlós, M.; Csige, L.; Firak, D. S.; Gulyás, J.; Nagy, Á.; Sas, N. J.; Timár, J.; Tornyi, T. G.; Krasznahorkay, A. On the X(17) light-particle candidate observed in nuclear transitions. *Act. Phys. Polon. B* 2019, *50*, 675-684.

E.g. the 7Li(p,γ)8Be Experiment. Anomaly in IPCC (Internal Pair Creation Coefficient). Illustrating the Bethe-Heitler process and direct decay with the gamma and the assumed X17.

Excited Be decay:



S. V., Electromagnetic mass formula for the X17 particle.

Proposal for an Electromagnetic Mass Formula for the X17 Particle.

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ELI-ERIC ALPS (Attosecond Light Pulse Sourcee) Res. Institute, ELI-HU Ltd., 6728 Szeged, Hungary;
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Abstract. Recent observations of anomalous angular correlations of electron-positron pairs in several nuclear reactions have indicated the existence of a hypothetical neutral boson of rest mass ~17 MeV/c^2, called the X17 particle. Similarly, one has interpreted an independent set of experiments on photon pair spectra around the invariant mass ~38 MeV/c^2, by assuming the existence of the so-called E38 particle. In the present paper we derive analytical mass formulae for the X17 particle and the E38 particle, on the basis of quantum electrodynamics. We shall use the exact solutions of the Dirac equation of the joint system of a charged particle and plane waves of the quantized electromagnetic radiation. When these solutions are applied to a proton, they lead to dressed radiation quanta with rest mass 17.0087 MeV/c^2, which may be identified with the X17 vector bosons. A similar consideration, applied to the udd quarks of the neutron, yields dressed quanta, whose mass equals 37.9938 MeV/c^2, corresponding to the E38 particle. These formulas, besides the Sommerfeld fine structure constant and the masses of the nucleons, do not contain any adjustable parameters. The present analysis also deliveres the value 0.846299 fm for the proton radius.

[MS: Based on the talk presented at ISMD 2023 - 52nd International Symposium on Multiparticle Dynamics, August 21-25 2023 - Gyöngyös, Hungary, https://indico.cern.ch/event/1258038/timetable/#20230825.detailed.

Varró S, Proposal for an electromagnetic mass formula for the X17 particle. *Universe* 2024, *10*, 86 (2024). [https://doi.org/10.3390/universe10020086].

This article belongs to the Special Issue "Multiparticle Dynamics", Edited by Csörgő T, Csanád M and Novák T; https://www.mdpi.com/journal/universe/special_issues/3R2XYDMCV9].

Electromagnetic mass formula for the X17 particle, derived from the exact solution of the Dirac equation of the system „proton + quantized electromagnetic plane waves".

$$m_X c^2 = \sqrt{\frac{e^2}{\pi\hbar c}}(m_p c^2)\sqrt{4 f(y_1)} = 17.0087 \;\; MeV$$

where

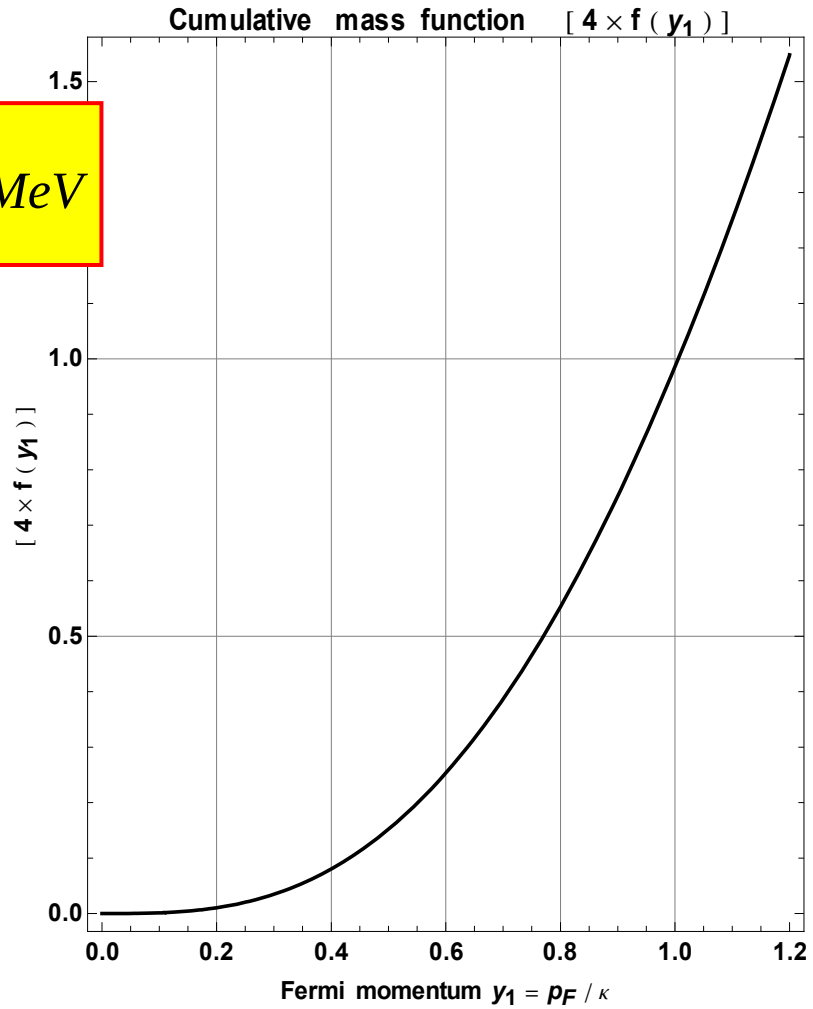
$$f(y) = \sqrt{1+y^2}\,\log(\sqrt{1+y^2}+y) - y$$

$$y_1 = p_F / \kappa = 0.487446$$

The Fermi momentum, y_1 = 0.487446, have been determined from the normalization condition (see below).

Purely analytical formula:

$$m_X c^2 = \frac{2}{3\pi}\sqrt{\frac{e^2}{\hbar c}}(m_p c^2) = 17.0087 \;\; MeV$$



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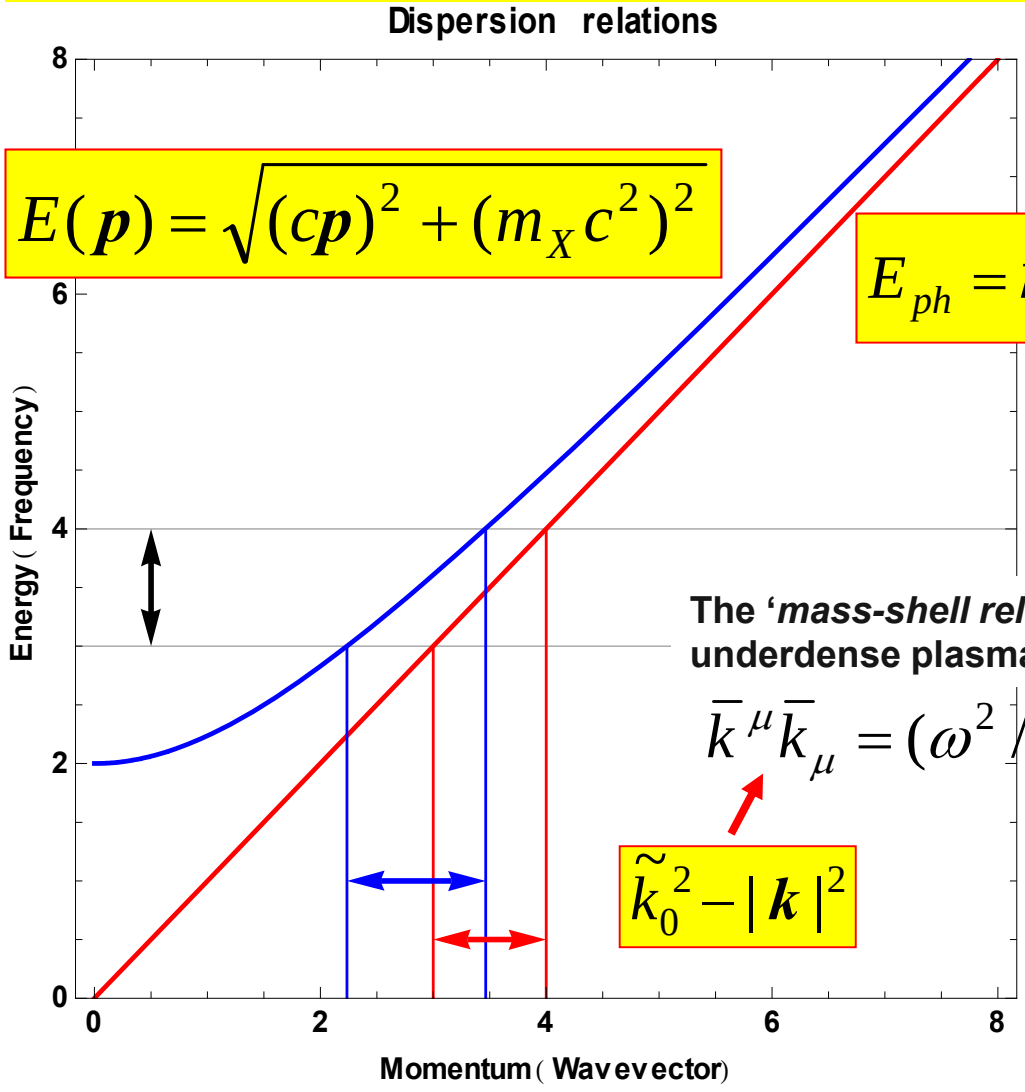
Dispersion relations, rest mass; electrons, photons, plasmons.



$$E(\boldsymbol{p}) = \sqrt{(c\boldsymbol{p})^2 + (m_X c^2)^2}$$

$$E_{ph} = \hbar c \sqrt{|\boldsymbol{k}_{ph}|^2 + 0^2}$$

$$n_m(\omega) = \sqrt{1 - \frac{\omega_X^2}{\omega^2}}$$

The '*mass-shell relation*' of e.m. radiation in an underdense plasma *does not depend on the frequency* !

$$\bar{k}^{\mu}\bar{k}_{\mu} = (\omega^2/c^2)(1 - n_m^2(\omega)) = (\omega_X^2/c^2)$$

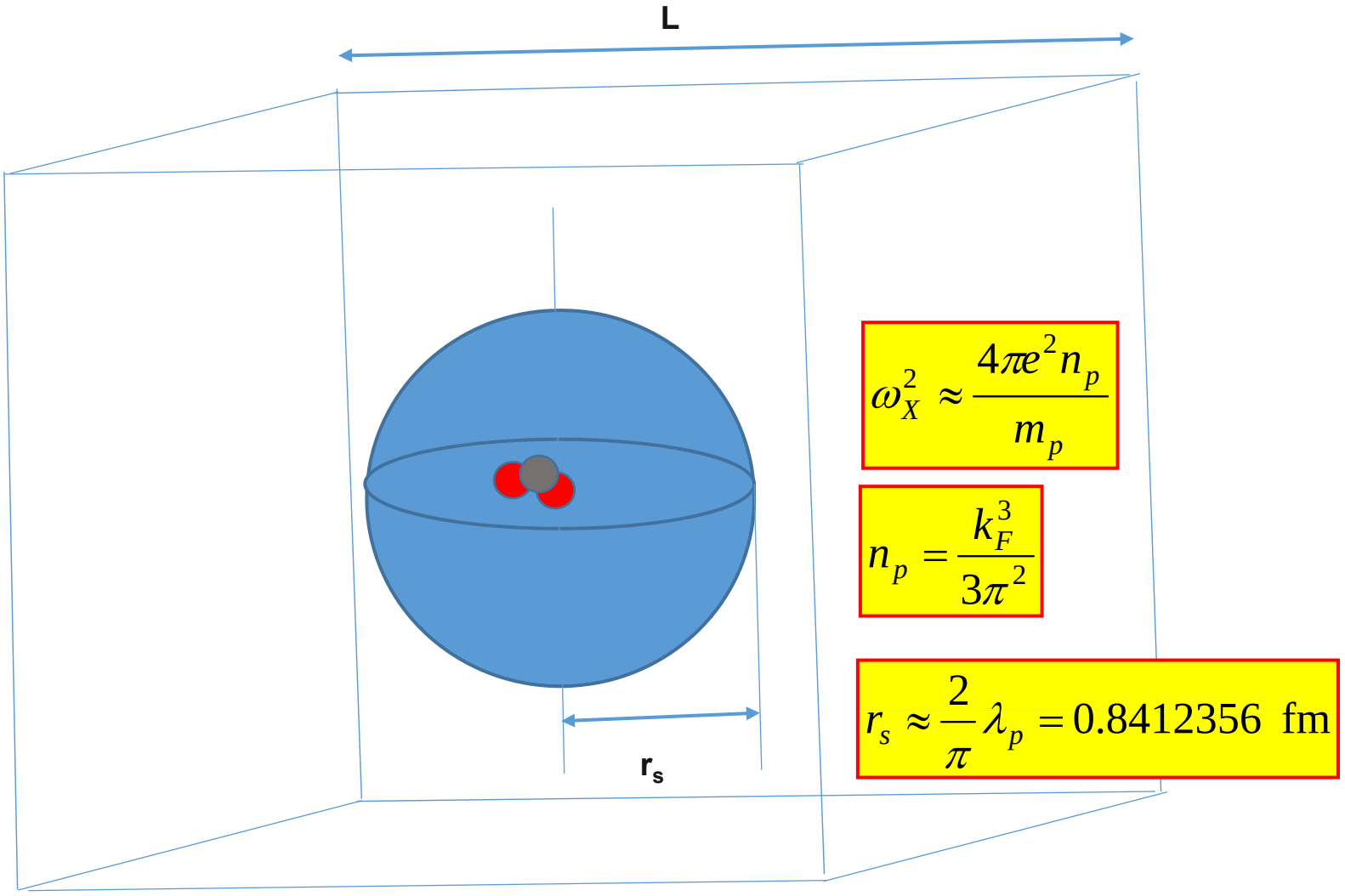
$$\tilde{k}_0^2 - |\boldsymbol{k}|^2$$

$$\omega(\boldsymbol{k}) = \sqrt{\omega_X^2 + c^2 |\boldsymbol{k}|^2}$$

'rest mass': $m_X = \hbar\omega_X / c^2$

[In the above figure the energy unit is one half of the rest energy. In the formula κ is the Compton wave number.]

To the normalization: one particle in the interaction sphere. The Compton frequency of the X17 field is analogous to the classical plasma frequency in the free electron Drude model.



$$\omega_X^2 \approx \frac{4\pi e^2 n_p}{m_p}$$

$$n_p = \frac{k_F^3}{3\pi^2}$$

$$r_s \approx \frac{2}{\pi}\lambda_p = 0.8412356 \text{ fm}$$

A kölcsönható „töltött Dirac-részecske + kvantált elektromágneses síkhullám” rendszer *egzakt állapotai*: „Kvantált Volkov–állapotok”.

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[3 + 1 QED] Exact, analytic solution of the Dirac equation of a system „charged particle + quantized electromagnetic plane wave modes". Basics (~ textbook).

$$i\hbar\partial\Psi/\partial t = H\Psi \qquad \Psi \in \mathscr{H}_e \otimes \mathscr{H}_{rad}$$

$$H = c\boldsymbol{\alpha}\cdot(\hat{\boldsymbol{p}} - e\hat{\boldsymbol{A}}/c) + \beta mc^2 + \hat{H}_{rad}$$

Vector potential of two co-propagating plane waves (photons) with orthogonal polarizations.

$$\hat{\boldsymbol{A}}(\boldsymbol{r}) = c\sqrt{\frac{2\pi\hbar}{\omega V}}[\boldsymbol{\varepsilon}_1(a_1 e^{i\boldsymbol{k}\cdot\boldsymbol{r}} + a_1^+ e^{-i\boldsymbol{k}\cdot\boldsymbol{r}}) + \boldsymbol{\varepsilon}_2(a_2 e^{i\boldsymbol{k}\cdot\boldsymbol{r}} + a_2^+ e^{-i\boldsymbol{k}\cdot\boldsymbol{r}})]$$

„Free mass-shell relation" in vacuum.

$$\omega = ck_0 = c\,|\,\boldsymbol{k}\,|$$

Energy operator of the photon modes.

$$\hat{H}_{rad} = \hbar\omega(a_1^+ a_1 + \tfrac{1}{2}) + \hbar\omega(a_2^+ a_2 + \tfrac{1}{2})$$

Momentum operator of the photon modes.

$$\hat{\boldsymbol{p}}_{rad} = \hbar\boldsymbol{k}(a_1^+ a_1 + a_2^+ a_2 + 1)$$

The total energy H and the total momentum p + p_{rad} are constants of motion, i.e. [H, p + p_{rad}]=0. Thus, the stationary states can be choosen as simultaneous eigenstates of the total energy H and the total momentum P = p + p_{rad} .

$$\psi_{E,\boldsymbol{P}} = \exp[-i\boldsymbol{k}\cdot\boldsymbol{r}(a_1^+ a_1 + a_2^+ a_2 + 1)]\left\{1 + g\frac{\not{k}}{2(k\cdot p)}[\not{\varepsilon}_1(a_1 + a_1^+) + \not{\varepsilon}_2(a_2 + a_2^+)]\right\}u_p$$

$$\times S_1(\theta)S_2(\theta)D_1(\tau_1)D_2(\tau_2)\left|n_1, n_2\right\rangle \exp\{i[\boldsymbol{p} + g_{\boldsymbol{p}}(n)\boldsymbol{k}]\cdot\boldsymbol{r}\}$$

[1] S. Varró, Theoretical study of the interaction of free electrons with intense light. (Ph.D. dissertation, 1981). (in Hungarian) Hungarian Physical Journal XXXI, 399-454 (1983). [2] J. Bergou, S. Varró:J. Phys. A: Math. Gen. 14, l469-l482 (1981) . [3] J. B. S. V., *Ibid.* 14, 2281 (1981). [4] Varró S, Proposal for an electromagnetic mass formula for the X17 particle. *Universe* 2024, *10*, 86 (2024). [https://doi.org/10.3390/universe10020086].

Derivation of the electromagnetic mass formula on the basis of quantized Volkov states. I. Contributions of the sub-systems to the energy and momentum.

Stationary states of the system (joint eigenstates of the total energy and momentum):

$$\psi_{E,\boldsymbol{P}} = \exp[-i\boldsymbol{k}\cdot\boldsymbol{r}(a_1^+a_1 + a_2^+a_2 + 1)]\left\{1 + g\frac{\not{k}}{2(k\cdot p)}[\not{\varepsilon}_1(a_1 + a_1^+) + \not{\varepsilon}_2(a_2 + a_2^+)]\right\}u_p$$

$$\times S_1(\theta)S_2(\theta)D_1(\tau_1)D_2(\tau_2)\left|n_1, n_2\right\rangle \exp\{i[\boldsymbol{p} + g_{\boldsymbol{p}}(n)\boldsymbol{k}]\cdot\boldsymbol{r}\}$$

Total energy :

$$E/\hbar c = K_0 = \bar{p}_0 + k_0\sqrt{1+2b}\,(n_1 + n_2 + 1)$$

Total momentum:

$$\boldsymbol{P}/\hbar = \boldsymbol{K} = \bar{\boldsymbol{p}} + \boldsymbol{k}(n_1 + n_2 + 1)$$

Coupling constant

$$g = \frac{e}{\sqrt{\hbar c}}\sqrt{\frac{2\pi}{k_0 V}}$$

$\bar{k}_0$

$$\bar{k}_0^2 - |\boldsymbol{k}|^2 = 2bk_0^2$$

Dispersion of „Massive Photon”:

(mass)² term of the radiation subsystem

Parameters of the S squeezing (Bogoliubov transformation) and D displacement operators:

$$e^{2\theta} = \sqrt{1+2b} \qquad b = g^2/(k\cdot p) \qquad \tau_{1,2} = p_{x,z}g/(k\cdot p) \qquad g_p(n) = \sqrt{1+2b}\,(n+1-\tau^2)$$

[Talk presented at ISMD 2023 - 52nd International Symposium on Multiparticle Dynamics – August 21-25 2023 - Gyöngyös, Hungary.]
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On the derivation of the electromagnetic mass formula. II.
Summing up with respect to the charged particle's quantum numbers.

$$\bar{k}_0^2 - |\boldsymbol{k}|^2 = 2bk_0^2$$

The mass term $2b(k_0)^2$ does not depend on the frequency ω, and ('of course') it is the same for any occupation numbers n_1, n_2 = 0, 1, 2, ... ('multiplicity') of the dressed radiation quanta.

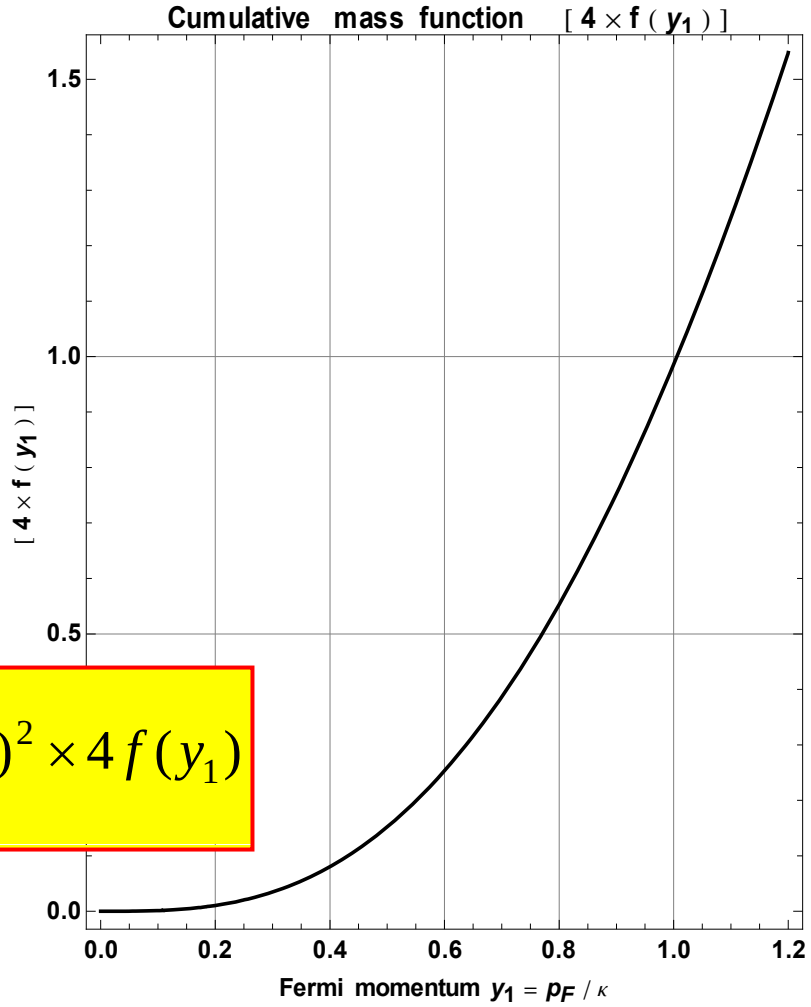
$$2bk_0^2 = \frac{e^2}{\hbar c}\frac{4\pi}{V}\frac{1}{p_0 - p_z}$$

$$p_0 = \sqrt{\boldsymbol{p}^2 + \kappa^2}$$

$$\boldsymbol{y} := \boldsymbol{p}/\kappa \qquad y := |\boldsymbol{y}|$$

$$\hbar^2 c^2 \times \sum_{spin,\ momentum} \frac{\kappa}{p_0} 2bk_0^2 = \frac{1}{\pi}\frac{e^2}{\hbar c}(mc^2)^2 \times 4f(y_1)$$

$$f(y) = \sqrt{1+y^2}\,\log(\sqrt{1+y^2} + y) - y$$



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Determination of the Fermi momentum from the normalization: One particle in the 'interaction sphere' of radius r_s.

Particle density is obtained by integrating the usual (Lorentz invariant) phase-space density with respect to the momentum parameter, and summing up with respect to the spin.

$$n = (\kappa^3 / \pi^2) g(y_1)$$

$$g(y) = \tfrac{1}{2}[y\sqrt{1+y^2} - \log(y+\sqrt{1+y^2})]$$

[We have plot the functions multiplied by 27.6560 !]

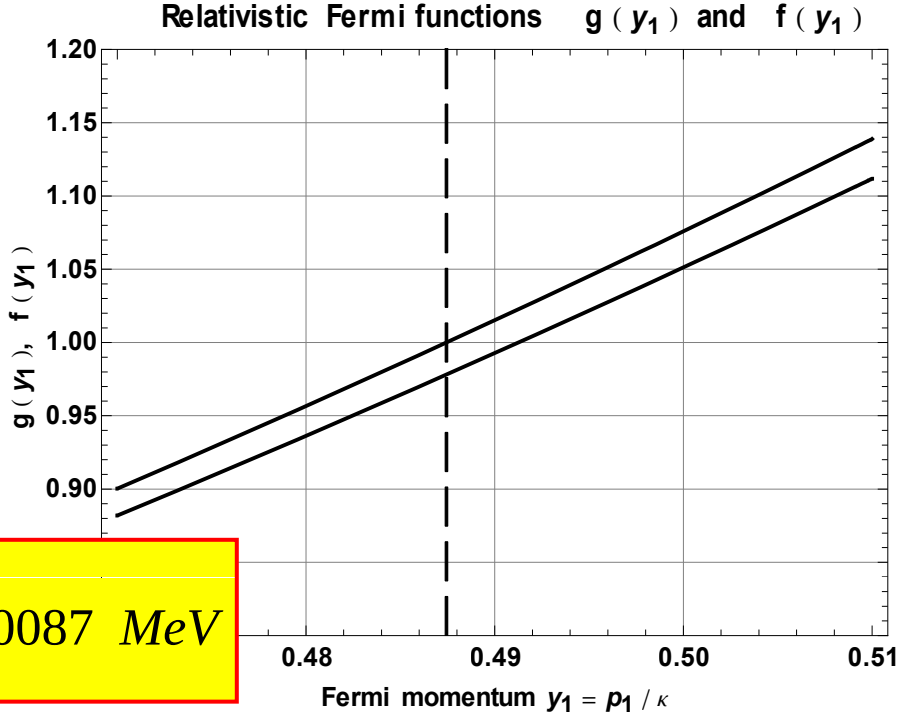
Normalization to one particle in the interaction sphere:

$$V = \frac{4\pi}{3} r_s^3$$

$$\frac{4(\kappa r_s)^3}{3\pi} g(y_1) = 1$$

We have taken $r_s = 4 / \kappa$. From the normalization condition we have determined the Fermi momentum, $y_1 = 0.487446$, which we put to the mass formula for the X17:

$$m_X c^2 = \sqrt{\frac{e^2}{\pi\hbar c}} (m_p c^2) \sqrt{4 f(y_1)} = 17.0087 \ \ MeV$$



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Newton’s Fifth Rule of Reasoning.

>>> We are to admit no more causes of natural things, than such as are both true and sufficient to explain their appearance.<<<

[Occam’s razor.]

Kvantált Volkov-állapotok alkalmazása a neutron kvarjaira. A hipotetikus „E38 részecske”. [Quantized Volkov states applied to the quarks of the neutron. The hypothetical E38 particle.]

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Photon pair spectra around the invariant mass 38 MeV / c^2.

EPJ Web of Conferences **204**, 08004 (2019) https://doi.org/10.1051/epjconf/201920408004
Baldin ISHEPP XXIV

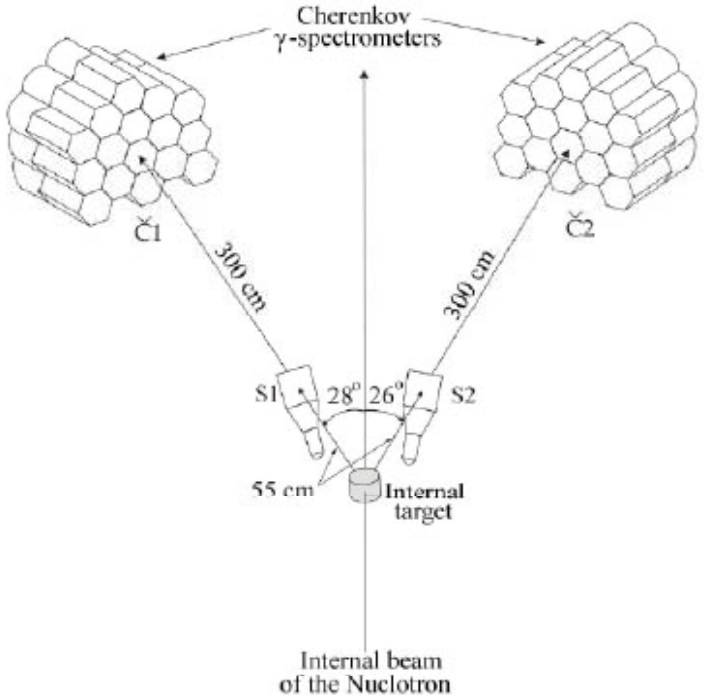


Figure 1. The schematic drawing of the experimental PHOTON-2 setup. The S1 and S2 are scintillation counters

[2] Abraamyan K, Austin C, Baznat M, Gudima K, Kozhin M, Reznikov S and Sorin A, Check of the structure in photon pairs spectra at the invariant mass of about 38 MeV/c2. EJP Web of Conferences 204, 08004 (2019).

Invariant mass distribution of $\gamma\,\gamma$ pairs from decay of E38; d + Cu events

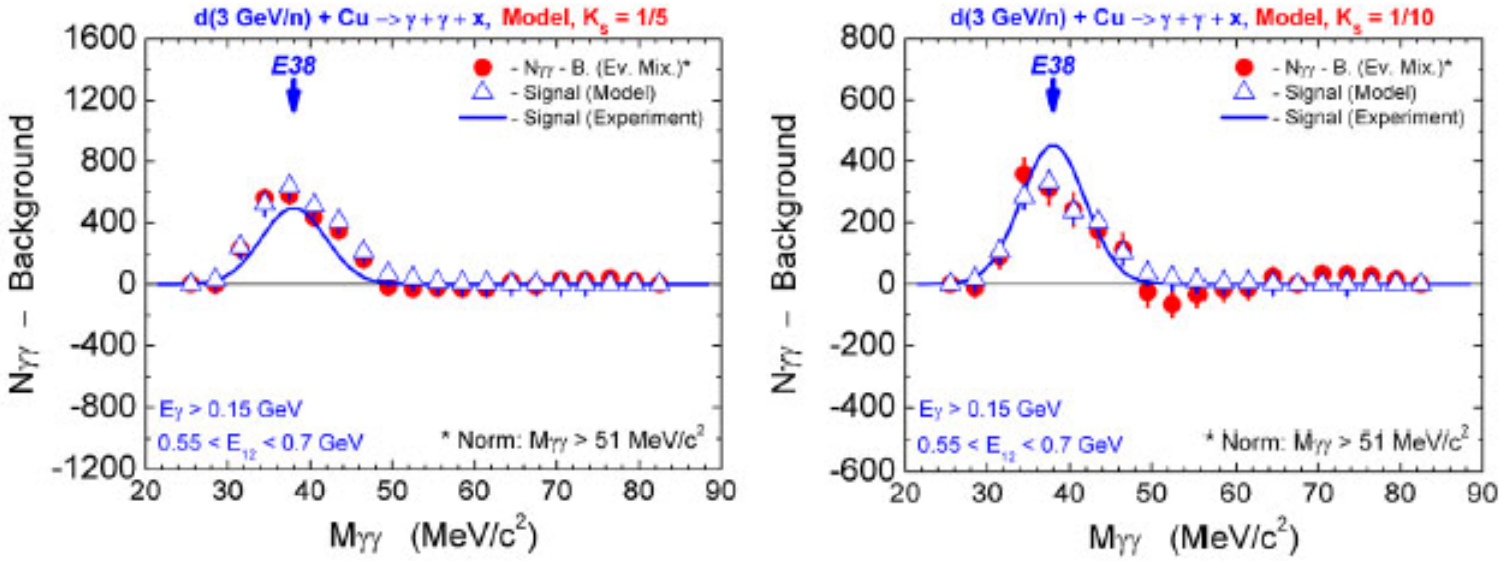


Figure 6. Invariant mass distributions (per 3 MeV/c^2) of $\gamma\gamma$ pairs from the decay of E(38) under the real experimental conditions: △ - pairs $\gamma\gamma$, selected by means of labels of photons applied in the model; ● - the result of processing the simulated data with the method applied to the experimental data. The curves are the experimental signal after the background subtraction (Gaussian approximation) proportional to the number of d + Cu events containing a pair of $\gamma\gamma$ in the required energy range. The signal in the simulated data reduced by a factor $K_S = 1/5$ (among the events, containing a photon from the decay of E(38), each 5th event was taken) (left figure) and by a factor $K_S = 1/10$ (right figure)

[2] Abraamyan K, Austin C, Baznat M, Gudima K, Kozhin M, Reznikov S and Sorin A, Check of the structure in photon pairs spectra at the invariant mass of about 38 MeV/c2. EJP Web of Conferences 204, 08004 (2019).

Simple plasma and statistical consideration on E38. We take the Neutron = udd. All these results can also be derived from the Dirac equation for a single charge, as above.
[This procedure can be justified the Dirac-Fock-Podolsky many-time formalism (equivalent with the Tomonaga-Schwinger eq.)]

Composit plasma:

$$e \to e\sqrt{(2/3)^2 + (1/3)^2 + (1/3)^2} = e\sqrt{2/3}$$

Additional statistical factors: 1 for singlet, and Sqrt [3] for triplet of the dd quarks.

$$m_E c^2 = (1+\sqrt{3})\frac{2}{3\pi}\sqrt{\frac{\frac{2}{3}e^2}{\hbar c}}(m_n c^2) = 37.9937 \;\; MeV$$

Nete that: The difference in comparison to the functional form of the mass formula of the X17 particle is only the factor:

$$(1+\sqrt{3})\sqrt{2/3}$$

Varró S, Proposal for an electromagnetic mass formula for the X17 particle. [Talk presented at ISMD 2023 - 52nd International Symposium on Multiparticle Dynamics – August 21-25 2023 - Gyöngyös, Hungary.] This article belongs to the Special Issue "Multiparticle Dynamics", Edited by Csörgő T, Csanád M and Novák T; https://www.mdpi.com/journal/universe/special_issues/3R2XYDMCV9]. Varró S, Proposal for an electromagnetic mass formula for the X17 particle. *Universe* 2024, *10*, 86 (2024) [https://doi.org/10.3390/universe10020086].

Összegzés.

● A kvantált e.m. sugárzással kölcsönható proton Dirac-egyenletének egzakt megoldásából a sugárzás effektív tömegére analitikus formulát származtattunk, amely igen jól közelíti az X17 (vektor bozon) tér invariáns tömegét:

$$m_X c^2 = \frac{2}{3\pi}\sqrt{\frac{e^2}{\hbar c}}(m_p c^2) = 17.0087 \;\; MeV$$

● Ugyanezt a módszert alkalmazva, az E38 részecske tömegére levezetett analitikus formula szintén igen közel van a mért értékhez:

$$m_E c^2 = (1+\sqrt{3})\frac{2}{3\pi}\sqrt{\frac{\frac{2}{3}e^2}{\hbar c}}(m_n c^2) = 37.9937 \;\; MeV$$

● A proton [neutron] „statisztikus sugarára” ~ (2 / π) × (Compton hullámhossz) –at kell vennünk, ahhoz hogy az X17 [E38] invariáns tömegére a fenti analitikus formulával (a mért értékkel) egyezést kapjunk. Igy, „mellékeredményként”, a proton rádiuszra 0.846299 fm-t, a neutron rádiuszra 0.845135 fm-t kaptunk.

Köszönetnyilvánítás. Acknowledgement. I thank several interesting and useful discussions with Prof. A. J. Krasznahorkay, Prof. T. Csörgő, and Prof. Ch-Y Wong at the at ISMD 2023 - 52nd International Symposium on Multiparticle Dynamics – August 21-25 2023 - Gyöngyös, Hungary.
I also thank several very thorough discussions on the subject, also this year 2024, with Prof. Dr. W. Schleich (Uni-Ulm), Prof. Dr. Wolschin (Uni Heidelberg), Prof. Dr. G. Alber (TU Darmstadt).

Varró S, Tömegformula az X17 vektor bozon-térre. [XVII Magyar Magfizikus Találkozó 2024, ATOMKI, Debrecen, 3-5 Sept. 2024. Szept. 5.., Csütörtök 11:20h.] [File:”Varro_S_X17_Talk_ATOMKI_Magfiz_05_Sept_2024_v_1.ppt”]

Appendix.

Derivation of the electromagnetic mass formula for X17 on the basis of quantized Volkov states. Sum over the charged particle's momentum and spin.

$$(m'_\gamma c^2)^2 = \hbar^2 c^2 \times 2 \sum \Delta n_x \Delta n_y \Delta n_z \frac{\kappa}{q_0} k_0^2 2b = \frac{1}{\pi} \frac{e^2}{\hbar c} (mc^2)^2 \times 4 f(y_1)$$

$y_1 = p_F / \kappa$ is the Fermi momentum, and f(y) is given as:

$$\sqrt{\frac{1}{\pi} \frac{e^2}{\hbar c}} (m_p c^2) = 45.2206 \ MeV$$

$$f(y) = \sqrt{1+y^2} \log(\sqrt{1+y^2} + y) - y$$

Here we have taken m_p as the proton mass. This is 'Wentzel-type' mass term, though we did not consider vacuum polarization. Rather, we have taken a real positive energy charge.

Normalization: one particle in the interaction sphere:

$$V = \frac{4\pi}{3} r_s^3$$

$$\frac{4(\kappa r_s)^3}{3\pi} g(y_1) = 1$$

Particle density:

$$n = (\kappa^3 / \pi^2) g(y_1)$$

$$g(y) = \tfrac{1}{2}[y\sqrt{1+y^2} - \log(y + \sqrt{1+y^2})]$$

From the normalization condition (see previous and right hand side of this dia) we have determined the Fermi momentum, $y_1 = 0.487446$. In the non-relativistic approximation, f (y) = y3 / 3 and g (y) = y^3 / 3, and then the proposed mass formula for the X17 comes out:

$$m_X c^2 = \frac{2}{3\pi} \sqrt{\frac{e^2}{\hbar c}} (m_p c^2) = 17.0087 \ MeV$$

The Compton frequency of the X17 field is completely analogous to the classical plasma frequency (f/g=0.98):

$$\omega_X^2 = \frac{4\pi e^2 n_p}{m_p} \times \frac{f(y_1)}{g(y_1)}$$

Varró S, Proposal for an electromagnetic mass formula for the X17 particle. [Talk presented at ISMD 2023 - 52nd International Symposium on Multiparticle Dynamics – August 21-25 2023 - Gyöngyös, Hungary.] This article belongs to the Special Issue "Multiparticle Dynamics", Edited by Csörgő T, Csanád M and Novák T; https://www.mdpi.com/journal/universe/special_issues/3R2XYDMCV9]. Varró S, Proposal for an electromagnetic mass formula for the X17 particle. *Universe* 2024, *10*, 86 (2024) [https://doi.org/10.3390/universe10020086].

Semi-classical and quantized Volkov states.
Tools for describing „strong-field phenomena”.
[E.g. High-harmonic and attosecond pulse generation.]

[16] Varró, S. Theoretical study of the interaction of free electrons with intense light. (Ph.D. dissertation, University of Szeged, 1981). *Hung. Phys. J.* 1983, *31*, 399-454. [17] Bergou, J.; Varró, S. Nonlinear scattering processes in the presence of a quantized radiation field: I. Nonrelativistic treatment. *J. Phys. A Math. Gen.* 1981, *14*, 1469–1482. [18] Bergou, J.; Varró, S. Nonlinear scattering processes in the presence of a quantized radiation field: II. Relativistic treatment. *J. Phys. A Math. Gen.* 1981, *14*, 2281–2303. [21] Varró, S. Quantum optical aspects of high-harmonic generation. *Photonics* 2021, *8*, 269.

Terminology; Volkov states [1935]. Exact solutions of the Dirac equation of a charged particle interacting with a *Classical Plane Electromagnetic Field*.

$$[\gamma_\mu (i\partial - \varepsilon A)^\mu - \kappa]\left|\Psi\right\rangle = 0$$

$$\varepsilon \equiv e/\hbar c \qquad \kappa \equiv mc/\hbar$$

$$A(\xi) = e_x A_0 f(\xi) \qquad \xi = k_\mu x^\mu = \omega(t - z/c)$$

$$\Psi_{ps}^{(\pm)}(x) = \left[1 \pm \frac{\varepsilon \not{k} \not{A}(\xi)}{2k\cdot p}\right] u_{ps}^{(\pm)} \exp(\mp i S_p^{(\pm)})$$

$$S_p^{(+)}(x) = p\cdot x + \int I_p^{(\pm)}(\xi) d\xi$$

$$I_p^{(\pm)}(\xi) = (1/2k\cdot p)[\pm 2\varepsilon p\cdot A(\xi) - \varepsilon^2 A^2(\xi)$$

Wolkow D M, Über eine Klasse von Lösungen der Diracschen Gleichung. *Zeitschrift für Physik* 94, 250-260 (1935). [Application to strong-field and multiphoton processes: from ~1960...]

Exact solutions of the Dirac equation in a quantized plane wave. Nonlinear Compton scattering (HHG) beyond the semiclassical description (1981). The generalization of the Klein–Nishina formula. [The effect of depletion of the laser field; e.g. altered kinematics (spectrum) .]

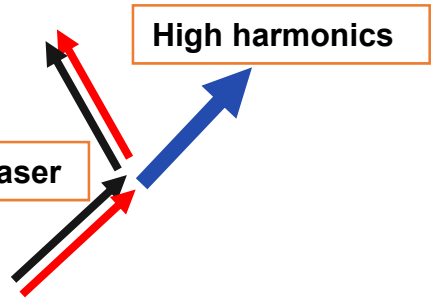
The calculation of the nonlinear Compton process was based on the Exact solutions for the 'Dirac electron + quantized e.m. radiation mode' system [1-3]:

$$\psi_{E,\boldsymbol{P}} = \left[1 + g\frac{\not{k}\not{\varepsilon}}{2Qk}(\hat{a}e^{i\boldsymbol{k}\cdot\boldsymbol{r}} + \hat{a}^{+}e^{-i\boldsymbol{k}\cdot\boldsymbol{r}})\right] u_Q e^{i[\boldsymbol{Q}+\boldsymbol{k}g(n)]\cdot\boldsymbol{r}} \hat{S}_\theta \hat{D}_\tau |n\rangle$$

$$\omega'_n = \frac{n\omega_0 + \omega_C \mu_0^2 \Delta}{1 + \left(2\frac{n\omega_0}{\omega_C} + \frac{\mu_0^2}{2}\right)\sin^2\frac{\theta}{2}}$$

$$\Delta = \frac{n_0 - n}{n_0}$$

,depletion factor' [1-3]



The simplest generalization of the Klein–Nishina formula (complete depletion):

$$|t_{fi}^{(n)}|_{av}^2 = \frac{1}{4}\left[\frac{n\omega_0}{\omega'} + \frac{\omega'}{n\omega_0} - 2 + 4(\boldsymbol{\varepsilon}\cdot\boldsymbol{\varepsilon}')^2\right]\frac{(nb)^n}{n!}e^{-nb}$$

$$b = \tfrac{1}{2}\mu_0^2 |\hat{\boldsymbol{k}}'\cdot\boldsymbol{\varepsilon}|^2$$

[1] S. Varró, Theoretical study of the interaction of free electrons with intense light. (Ph.D. dissertation, 1981). (in Hungarian) Hungarian Physical Journal XXXI, 399-454 (1983). [2] J. Bergou, S. Varró:J. Phys. A: Math. Gen. 14, l469-l482 (1981) . [3] J. B. S. V., Nonlinear scattering processes in the presence of a quantised radiation field: II. Relativistic treatment. *Ibid.* 14, 2281 (1981).

The matrix elements of the squeezing operator between photon number eigenstates. Expression in terms of classical Gegenbauer polynomials.

$$S = \exp(\tfrac{1}{2}\xi a^{+2} - \tfrac{1}{2}\xi^* a^2) \qquad H_{\text{int}} = g(a^{+2}\mathrm{e}^{i\varphi} + a^2\mathrm{e}^{-i\varphi})$$

$$\langle m|S(\xi)|n\rangle = \mathrm{e}^{-\eta/4}(-2\mathrm{e}^{-i\varphi}\tanh|\xi|)^{\lambda}\frac{\Gamma(\lambda+\frac{1}{2})}{\Gamma(\frac{1}{2})}\sqrt{\frac{m!}{n!}}C_m^{(\lambda+\frac{1}{2})}\left(\frac{1}{\cosh|\xi|}\right) \qquad m \le n, \quad \lambda = \tfrac{1}{2}(n-m)$$

$$\langle m|S(\xi)|n\rangle = \mathrm{e}^{-\eta/4}(2\mathrm{e}^{i\varphi}\tanh|\xi|)^{\alpha}\frac{\Gamma(\alpha+\frac{1}{2})}{\Gamma(\frac{1}{2})}\sqrt{\frac{n!}{m!}}C_n^{(\alpha+\frac{1}{2})}\left(\frac{1}{\cosh|\xi|}\right) \qquad m \ge n, \quad \alpha = \tfrac{1}{2}(m-n)$$

Remark: SU(1,1); SL(2,R) group. Lorentz group in 2 + 1 dimensions (osc. repr.).

$$K_+ = \tfrac{1}{2}(a^+)^2, \quad K_- = \tfrac{1}{2}(a)^2, \quad K_0 = \tfrac{1}{4}(aa^+ + a^+a), \quad [K_0, K_\pm] = \pm K_\pm \quad [K_-, K_+] = 2K_0$$

General transformation:

$$U(g) = \exp(-itK_0)S(\xi), \quad U(g_1)U(g_2) = U(g), \quad g = g_1 \circ g_2$$

Varró S, Coherent and incoherent superposition of transition matrix elements of the squeezing operator. *New Journal of Physics* 24, 053035 (2021). *E-print*: arXiv: 2112.08430 [quant-ph] . 29th Int. Las. Phys. (LPHYS'21). J. Phys. Conf. Ser. 2249 012013 (2022).

Wentzel's deduction of the 'non-vanishing self-energy of the photon' (1948).

PHYSICAL REVIEW VOLUME 74, NUMBER 9 NOVEMBER 1, 1948

New Aspects of the Photon Self-Energy Problem

GREGOR WENTZEL
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received June 29, 1948)

A finite but non-vanishing value for the self-energy of the photon, corresponding to a finite rest-mass, can be deduced from the new invariant formulation of quantum electrodynamics developed by Tomonaga and Schwinger, in the e^2 order approximation. The implications of this result are discussed.

state considered, divided by κ_0^2. Therefore, a photon of momentum $\hbar\boldsymbol{\kappa}$, having the total energy $\hbar c\kappa_0 = \hbar c|\boldsymbol{\kappa}|$ in the zero-order approximation, appears in the second-order approximation as having the energy

$$\hbar c\kappa_0\left(1+\frac{1}{8\pi^2}\frac{e^2}{\hbar c}\frac{\mu^2}{\kappa_0^2}+\cdots\right)$$

$$=c\left[(\hbar|\boldsymbol{\kappa}|)^2+\frac{1}{4\pi^2}\frac{e^2}{\hbar c}(mc)^2\right]^{\frac{1}{2}}. \quad (25)$$

This corresponds to a "photon rest-mass" amounting to one electron mass divided by

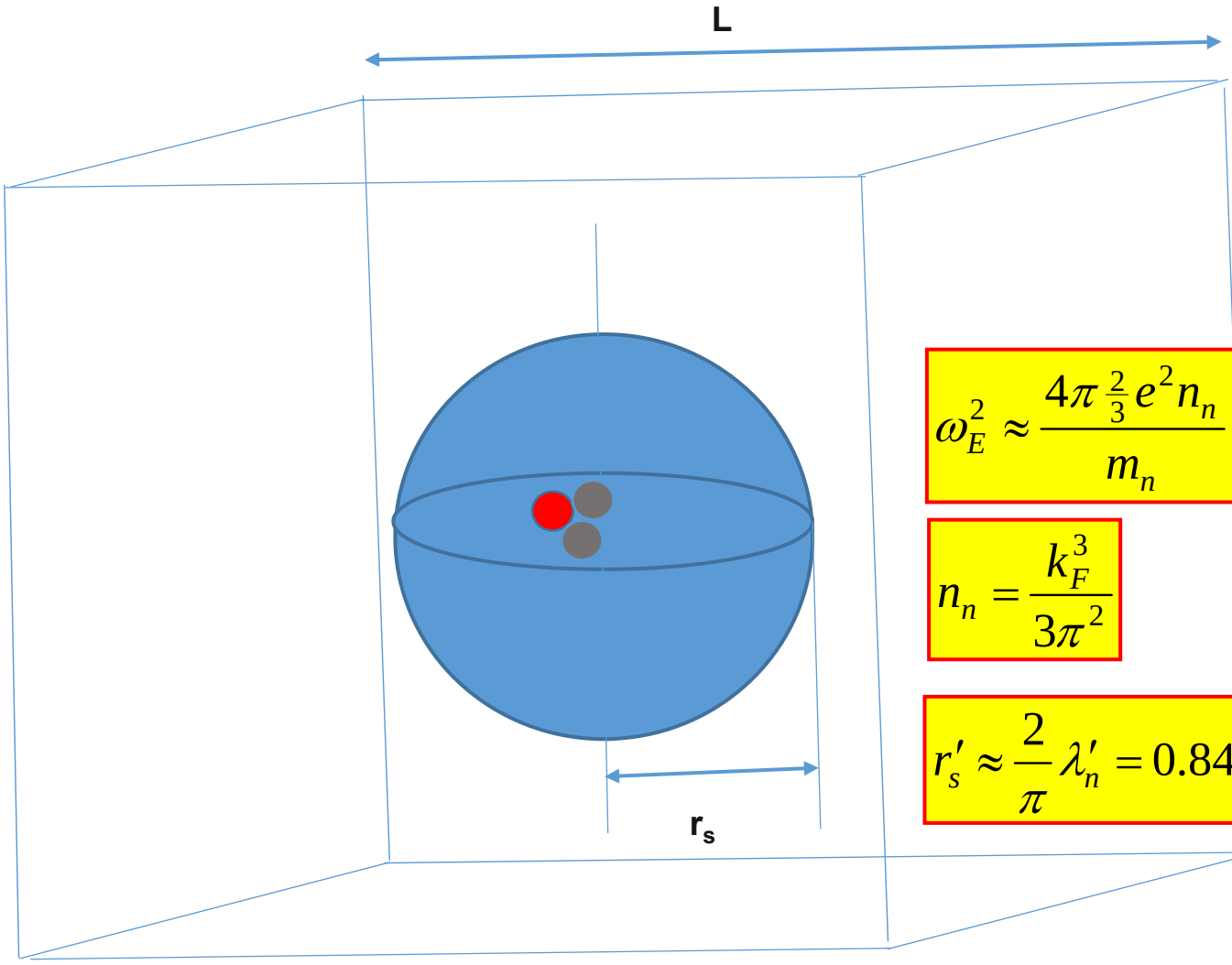
Perturbation theory plus an extrapolation:

$$m_\gamma = \sqrt{\frac{e^2}{\pi\hbar c}}m_e = \frac{m_e}{\sqrt{\pi 137}}$$

"CONCLUSION. The results of the last section are hardly encouraging in view of higher approximations. We have tried to take the quantum theory of fields seriously, without admitting any ad hoc subtractions inconsistent with the principles of quantum mechanics. The outcome shows that the empirical fact, that the photon has no rest-mass, does not fit naturally into the framework of quantum electrodynamics. It seems questionable to what extent the predictions of such a theory in higher order effects are trustworthy.
Finally, it should be remembered that the pair creation of other charged particles (mesons, protons) is likely to contribute to the photon selfenergy. Therefore, the phenomena involving electrons, positrons, and photons only, can hardly be expected to be quite independent, in the higher order effects, of the existence of other particles and their nature."

Wentzel G, New aspects of the photon self-energy problem. Physical Rewiev 74 (1), 1070-1075 (1948).

Normalization: one particle in the interaction sphere. The Compton frequency of the X17 field is completely analogous to the classical plasma frequency



$$\omega_E^2 \approx \frac{4\pi \frac{2}{3} e^2 n_n}{m_n}$$

$$n_n = \frac{k_F^3}{3\pi^2}$$

$$r_s' \approx \frac{2}{\pi} \lambda_n' = 0.845135 \text{ fm}$$

ELI-ALPS. [July 2024]. ”Milestones” in front of the ELI-ALPS site building in Szeged.

New experiments are also pointing to the existence of the X17 vector boson. Considerations on the fifth force explaining the ATOMKI anomaly...

PHYSICAL REVIEW C **106**, L061601 (2022)

Letter

New anomaly observed in ^{12}C supports the existence and the vector character of the hypothetical X17 boson

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PHYSICAL REVIEW D **102,** 036016 (2020)

Dynamical evidence for a fifth force explanation of the ATOMKI nuclear anomalies

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Ch-Y Wong, QED meson description of the anomalouos particles and the X17 particle.

Article

QED Meson Description of the Anomalous Particles at ~17 and ~38 MeV †

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† Based on a talk presented at the 52nd International SymposiumonMultiparticle Dynamics, Gyongyos, Hungary, 20–26 August 2023;

Abstract: The Schwinger confinement mechanism stipulates that a massless fermion and a massless antifermion are confined as a massive boson when they interact in the Abelian QED interaction in (1+1)D.If we approximate light quarks as massless and apply the Schwinger confinement mechanism to quarks, we can infer that a light quark and a light antiquark interacting in the Abelian QED interaction are confined as a QED meson in (1+1)D. Similarly, a light quark and a light antiquark interacting in the QCD interaction in the quasi-Abelian approximation will be confined as a QCD meson in (1+1)D. The QED and QCD mesons in (1+1)D can represent physical mesons in (3+1)D when the flux tube radius is properly taken into account. Such a theory leads to a reasonable description of the masses of *π0, η, and η' , and its extrapolation to the unknown QED sector yields an isoscalar* QED meson at about 17 MeV and an isovector QED meson at about 38 MeV. The observations of the anomalous soft photons, the hypothetical X17 particle, and the hypothetical E38 particle bear promising evidence for the possible existence of the QED mesons. Pending further confirmation, they hold important implications on the properties on the quarks and their interactions.

[4b] Wong Ch-Y, QED meson description of the anomalous particles and the X17 particle. ISMD 2023 - 52nd International Symposium on Multiparticle Dynamics, Aug 21-25 2023 - Gyöngyös, Hungary. https://indico.cern.ch/event/1258038/timetable/#20230822.detailed

Covariant formalism for the massive vector field

$\kappa \equiv \omega_p / c$

Lagrange density:

$$\mathscr{L} = -\frac{1}{16\pi} F_{\mu\nu} F^{\mu\nu} + \frac{\kappa^2}{8\pi} A_\mu A^\mu - \frac{1}{c} j_\mu A^\mu ,$$

Field strength tensor:

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

Field equations (Euler-Lagrange equations):

$$\partial^\mu F_{\mu\nu} + \kappa^2 A_\nu = \frac{4\pi}{c} j_\nu , \qquad \partial^\alpha F^{\beta\gamma} + \partial^\gamma F^{\alpha\beta} + \partial^\beta F^{\gamma\alpha} = 0$$

No gauge freedom (only Lorentz gauge) if the current is conserved (continuity).

$$\partial_\mu j^\mu = \frac{c\kappa^2}{4\pi} \partial_\alpha A^\alpha$$ **That is, if** $$\frac{\partial \rho}{\partial t} + \nabla \cdot \mathbf{j} = 0$$ **, then** $\partial_0 V + \nabla \cdot \mathbf{A} = 0.$

Inhomogeneous Klein-Gordon equation for each components:

$$(\partial^2 + \kappa^2) A_\mu = \frac{4\pi}{c} j_\mu , \qquad \partial^2 = \frac{1}{c^2} \frac{\partial^2}{\partial t^2} - \nabla^2 .$$

Lánczos C, Die tensoranalytischen Beziehungen der Diracschen Gleichung. *Z. für Physik* **57**, 447 (1929). Proca A, Sur la théorie ondulatoire des électrons positifs et négatifs. *J. Phys. Radium* **7**, 347-353 (1936). See recent review Goldhaber A S and Nieto M N, Photon and graviton mass limits. RMP **82,** 939 (2010).

Radiation modes of the free massive vector field. $\omega_k / c = \sqrt{\kappa^2 + \boldsymbol{k}^2}$

Two transverse, and one longitudinal polarization. $\kappa_{X17} = \kappa \equiv \omega_p / c$

$$A^{(r)} = \sum_{\boldsymbol{k}} (2L^3\omega_k)^{-\frac{1}{2}} \left[\left(\sum_{\alpha=1,2} a_{\boldsymbol{k},\alpha} \boldsymbol{e}_{\boldsymbol{k},\alpha} + \frac{c\kappa}{\omega_k} a_{\boldsymbol{k},3} \boldsymbol{e}_{\boldsymbol{k},3} \right) e^{i\boldsymbol{k}\cdot\boldsymbol{r}} + c.c. \right]$$

General: Energy density, energy flux density:

$$u = \frac{1}{8\pi}[\boldsymbol{E}^2 + \boldsymbol{B}^2 + \kappa^2(V^2 + \boldsymbol{A}^2)], \qquad \boldsymbol{S} = \frac{1}{4\pi}[\boldsymbol{E} \times \boldsymbol{B} + \kappa^2 V \boldsymbol{A}]$$

Green's function of the Klein-Gordon equation; Invariant functions Δ, introduced by Jordan and Pauli (1928). The wake-field described by the Bessel function J_1.

$$\Delta_P(\boldsymbol{r}, t; \boldsymbol{r}', t') = \frac{1}{|\boldsymbol{r} - \boldsymbol{r}'|} \delta\left[\left(t - \frac{1}{c} |\boldsymbol{r} - \boldsymbol{r}'| \right) - t' \right] - \Theta c\kappa \frac{J_1(\kappa s)}{s},$$

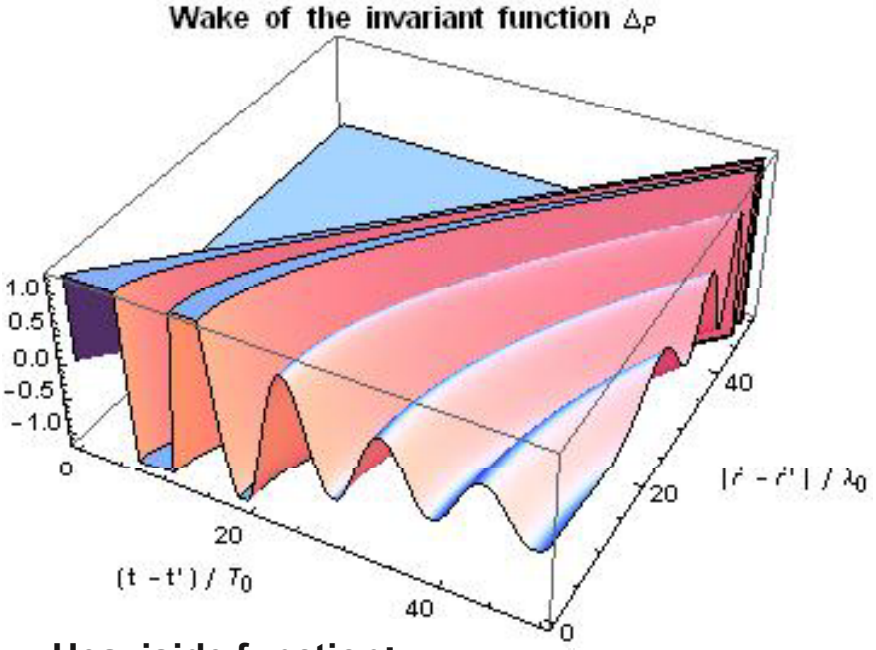
$$\Theta \equiv \Theta\left[\left(t - \frac{1}{c} |\boldsymbol{r} - \boldsymbol{r}'| \right) - t' \right], \qquad s^2 \equiv c^2(t - t')^2 - (\boldsymbol{r} - \boldsymbol{r}')^2.$$

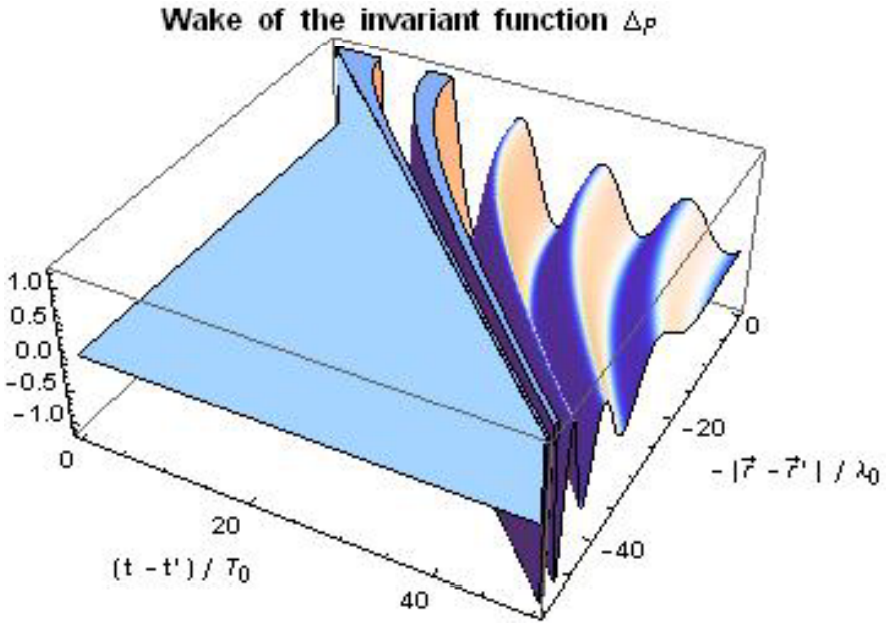
Stueckelberg E C G, Théorie de la Radiation de Photons de Masse Arbitrairement petite. *Helv. Phys. Acta* 30, 209 (1957). Krause D E, Kloor H T and Fischbach E, Multipole radiation from massive fields: Application to binary pulsars. *Phys. Rev. D* 49, 6892 (1994).

The wake-field part of the Jordan-Pauli invariant function Δ_P. [$\omega_p / \omega_0 = 0.1$]

Besides the usual (retarded) Liénart – Wiechert term, there is a wake-field in the Geen's function:

$$\Theta \frac{J_1\left(2\pi(\omega_p/\omega_0)\sqrt{(T/T_0)^2-(R/\lambda_0)^2}\right)}{2\pi(\omega_p/\omega_0)\sqrt{(T/T_0)^2-(R/\lambda_0)^2}}$$





Heaviside function:

$$\Theta\left[\left(t-\frac{1}{c}|\boldsymbol{r}-\boldsymbol{r}'|\right)-t'\right]c\kappa\frac{J_1(\kappa s)}{s},$$

$$s^2 \equiv c^2(t-t')^2-(\boldsymbol{r}-\boldsymbol{r}')^2$$

Varró S, Tömegformula az X17 vektor bozon-térre. [XVII Magyar Magfizikus Találkozó 2024, ATOMKI, Debrecen, 3-5 Sept. 2024. Szept. 5.., Csütörtök 11:20h.] [File:"Varro_S_X17_Talk_ATOMKI_Magfiz_05_Sept_2024_v_1.ppt"]

The question of the constancy of the speed of light. The work of Zoltán Bay; the new standard for the meter (1983).

PHYSICAL REVIEW D VOLUME 5, NUMBER 4 15 FEBRUARY 1972

Frequency Dependence of the Speed of Light in Space

Z. Bay and J. A. White*
National Bureau of Standards, Washington, D. C. 20234
(Received 16 August 1971)

To characterize the possible dispersion of the velocity of light in space (vacuum) a Cauchy-type formula, $n^2 = 1 + A/\nu^2 + B\nu^2$, is used. It is shown that relativity only allows a nonzero A term, independent of the nature of the waves or a quantization thereof. Recent experimental data provide upper bounds for A and B, limiting thereby the dispersion in the microwave, infrared, visible, and ultraviolet regions of the spectrum to less than one part in 10^{20}.

„From this it follows that $(n^2-1)\nu^2=A$, where A is a relativistic invariant and therefore the only possible dispersion formula for vacuum is

$$n^2 = 1 + \frac{A}{\nu^2}$$

if the special theory of relativity is correct. Causality requires $A < 0$. (For $A > 0$ the group velocity exceeds c_0 and a signal may appear to propagate backwards in time to some observer.)"

Bay Z and White J A, Frequency dependence of the speed of light in space. PRD 5, 976 (1972)

The question of the constancy of the speed of light. The work of Zoltán Bay; the new standard for the meter (1983). Remark on the dispersion formulas in Aether models (1836-1842).

»This fact provides additional experimental support for the **suggestion made recently that c be used in metrology to connect the unit of time (the second) and the unit of length (the meter).** The connection is made by assigning an agreed upon value to c in m/sec. The results of this paper show that in the above-mentioned broad spectrum this assignment can be made without reference to frequency.«

Bay Z and White J A, Frequency dependence of the speed of light in space. PRD 5, 976 (1972).

[Note that in our notation the group velocity is $v_{group} = cn_m<c$, and $v_{phase} = c/n_m>c$.]

Remark on the first dispersion theory based ***on mechanical Aether models***. [Cauchy, Sur la dispersion de la lumiére (1836), Neumann F E (1841), O'Brien M (1842)

$$\rho \frac{\partial^2 \boldsymbol{e}}{\partial t^2} = n \frac{\partial^2 \boldsymbol{e}}{\partial x^2} - C\boldsymbol{e}$$

$$\boldsymbol{e} \sim \exp[i\omega(t - x/V)]$$

$$\frac{n}{V^2} = \rho - \frac{C}{\omega^2}$$

'mass term' in the 'Klein-Gordon equation' (1841) responsible for dispersion

Sir Edmund Whittaker, *A History of the Theories of Aether and Electricity*. (Thomas Nelson and Sons Ltd, London, 1951).

“Tief ist der Brunnen von Vergangenheit. Sollte man ihn nich unergründlich nennen?”
[Thomas Mann, Joseph und seine Brüder.]

Massive Photons and the Hypothetical X17 Particle.

Sándor Varró
Extrem Light Infrastructure, ERIC, ALPS Facility, Szeged, Hungary.

Abstract. As an introduction to the subject of the talk, first we discuss „quantum optics with free electrons”, by showing that the minimal coupling with the quantized electromagnetic radiation naturally leads to the appearance of displaced (coherent) and squeezed states. On the basis of the exact analytic solutions of the Schrödinger or Dirac equations, we show that the transverse radiation aquires an effective mass, which is proportional with the plasma frequency. This circumstance plays an important role in various nonlinear processes, like the production of high-harmonics of an intense laser field, generation of attosecond pulses and the compensation of the so-called attochirp..

Next, we extend the scope from the connection of quantum optics and plasmons to the electrodynamics of „genuine massive photons”, which may be described as Lánczos-Proca vector bosons with three ortogonal polatizations. Besides summarizing the basics of their history, we show the subtleties of emission and propagation of such vector bosons, and mention their relevance even in metrology.

In the third part of the talk we deal with the explanation of anomalous angular correlations at large relative angles of electron-positron pairs, stemming from the excited nuclear fusion products of reactions like 7Li(p,e+e-)8Be. This anomaly (in comparison with direct gamma decay accompanied with pair creation) has been explained by assuming the existence of a neutral boson, the “hypothetical X17 particle”, having an invariant mass around 17 MeV/c^2. This X17 boson would mediate energy and the necessary extra momentum from the decaying products. Recently we have taken the proton as the interacting charge in the Dirac equation, and, in order to find the exact solutions, we have used the same elimination technique mentioned above, which is based on the application of displacement and squeezing operators. With the help of these solutions we have derived an analytic formula, yielding the value 17.0087 MeV/c^2 for the invariant mass of the dressed radiation, which may be identified with the X17 particle as a vector boson. We note that, besides the Sommerfeld fine structure constant and the proton mass, the derived formula contains merely an elementaty statistical factor.

The present talk is a contribution to the Colloquium at TU Darmstadt honoring Prof. Dr. Gernot Alber 11-12. 07. 2024. The author dedicates this talk to Gernot with great pleasure and appreciation of his very broad scientific activity over decades, with many interesting and important results in the theory of light-matter interaction, quantum optics and quantum information science.

Varró S, Massive photons and the hypothetical X17 particle. [TU-Darmstadt, Fest Kolloquium, honoring Gernot Alber. 12 July 2024, Friday] [File:”Varro_S_Talk_Darmstadt_12_July_2024_v_1.ppt”]