EVIDENCE FOR ACHIONS - OR AXIONS?

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Some electromagnetic showers have been observed at small angles ($< 1^o$) and low energies (< 1 GeV), in excess of what one would have expected from other sources, during a νe scattering experiment at the CERN PS. They do not resemble neutrino interactions. Rather they look like radiative decay gammas from a penetrating, neutral, light particle χ^o, admixed to the neutrino beam. - Clear $\chi^o \rightarrow 2\gamma$ decays have been seen in a 590 MeV proton beam dump experiment at SIN. The (14.5 ± 5) events point back to the source within the angular resolution (2 MeV/p_e); a flat background of 2.0 ± 0.4 comes from cosmic rays, another (3 ± 1) events are accelerator induced. The energy spectrum of either gamma is uniform, the average values ($\approx$ 80 MeV) agree with eachother. A 20 cm iron wall, placed at the beginning of the decay region, had little influence, but removed the effect, when shifted to its end. Analysing the effect in terms of axion production and decay, leads to a Higgs parameter $X = 3.0 \pm 0.3$, and hence to an axion mass of (250 ± 25) keV. Interactions of such a particle might also explain the hadron-less lepton pairs (21 $\bar{\mu}\mu$, 8 $\mu\bar{e}$) observed during ν exposures at the CERN PS.

1) Some Axionatics

There are good reasons, why a new particle, with quite unusual properties, should exist: as Fayet[1] has pointed out, the "axion" [2,3] is a necessary consequence of some symmetry considerations[4,5], motivated by the need to protect QCD from grave violations of T and CP, imminent from instantons - from the vacuum, that is. Many theoreticians find this chain of arguments not absolutely convincing, and some of them have devised other means to save QCD from chaos. However, the axion embodies all the key concepts of the unified theory[6]: it is the Goldstone boson of a spontaneously broken symmetry, the tiny mass corresponding to the small violation, and above all - it is the first example of a real, albeit untypical, Higgs particle (hence the name of "higglet"[7]).

It implies added difficulties: one has to enlarge the Higgs sector[8] of the standard model[6], from one Higgs field χ to two of them, χ_1 and χ_2. The ratio of their vacuum expectation values:

$$X = |\langle 0|\chi_2|0\rangle \; / \; \langle 0|\chi_1|0\rangle| \quad , \tag{1}$$

a real number between zero and infinity, enters all predictions of the theory. For instance, the axion mass is

$$m_a = 0.025 \; (X + X^{-1}) \; N \quad \text{MeV} \quad , \tag{2}$$

where N is the number of fermion generations (probably 3). This mass, in turn, determines the lifetime of $a^o \rightarrow 2\gamma$ decay[7]:

$$\tau_{\gamma\gamma} = 0.71 \times 10^{-5} \; m_a^{-5} \; \text{sec}, \quad (m_a \text{ in MeV}) \quad . \tag{3}$$

X governs also the axion mixing with pions and η-mesons: for N = 3 [2,7]

$$B_\pi = - \; 0.16 \; (X + X^{-1}) + 2 \; X^{-1} \; , \quad B_\eta = 2(X + X^{-1}) \; , \tag{4}$$

and hence the (half-weak) axion production - and interaction - cross sections:

$$\sigma_a = \xi^2 \; \sigma_\pi (B_\pi^2 \; + \; B_\eta^2 \; \frac{\sigma_\eta}{\sigma_\pi}) \quad , \quad \xi = 1.9 \times 10^{-4} \quad , \tag{5}$$

where σ_π (σ_η) are production, or interaction, cross sections for massless π^o (η^o) mesons.

With X essentially unknown, one faces a painful hunt for a particle of unknown mass, with unknown production rate, and unknown decays - as has been described by John Ellis, Mary K. Gaillard, and D. Nanopoulos for "the Higgs" in general[9]. But already the first searches indicated that the axion-higglet cannot be too heavy[10,11]. The conspicuous absence of $a^o \to \bar{e}e$ decay[12] placed a firm limit on m_a of $\leq$ 1 MeV (and hence on X and X^{-1}) [13], and recent beam-dump[14], and reactor[15] experiments pushed this limit further down.

I shall present you evidence that such a light, penetrating particle does exist, and that it decays into two photons. We called it the "achion" χ^o. If it is identical to the axion of the theoreticians, I can use the formulae, quoted above, and derive the Higgs parameter X.

2) Radiative Decay of a Penetrating Neutral Light Particle at CERN?

The first hints for the achion had been found early in 1977 - long before the axion was invented[2,3]. The Aachen-Padova Collaboration had been busy then, for almost three years, to extract from nearly 2 millions of pictures, taken in equal parts in the neutrino and antineutrino beam of the CERN protonsynchrotron (PS), a handful of genuine ν_μ ($\bar{\nu}_\mu$) e scatters:

$$\nu_\mu \, e \to \nu_\mu \, e \qquad (6) \quad , \qquad \bar{\nu}_\mu \, e \to \bar{\nu}_\mu \, e \quad . \qquad (\bar{6})$$

At that time three cases of reaction ($\bar{6}$) had been seen (against an expected background of 0.4) in the pioneer experiment of the GARGAMELLE (GGM) Collaboration[16]; and (strangely enough) only one candidate of (6) (against an estimated background of 0.5 events). The 20-ton aluminum spark chamber of Aachen-Padova was placed into the same beam, behind GGM, mainly in order to improve the statics of $\overset{(-)}{\nu}_\mu$ e scattering. The plate thickness of 1 cm (= X_o/10) was small enough to guarantee a safe distinction between electromagnetic and hadronic showers, and the accuracy of angular measurement ($\pm$ 1^o at 1 GeV), and that of shower energy (by spark counting to $\pm$ 20% at 1 GeV), was comparable to the capabilities of GGM.

However, there was a grave draw-back in the spark chamber: Lacking a magnetic field, it could not distinguish between electrons and electron pairs in a given event. Therefore, a serious background were gammas from neutral current (NC) induced π^o's, with one decay gamma lost. This initiated a detailed study of weak π^o production and decay[17-20]. Clearly, the most dangerous background comes from NC induced π^o production off invisible neutrons (or coherently off the whole nucleus):

$$\nu_\mu \, n \rightarrow \nu_\mu \, n \, \pi^o \searrow \gamma(+\gamma) \qquad (7)\,, \qquad \bar{\nu}_\mu \, n \rightarrow \bar{\nu}_\mu \, n \, \pi^o \searrow \gamma(+\gamma) \,. \qquad (\bar{7})$$

Its angular and energy dependence was obtained empirically from a sample of 850 (110) ν_μ $(\bar{\nu}_\mu)$ produced "naked" π^o's. Hence the absolute number of confusable single gammas, in the angular and energy range selected, was computed by a straight-forward (though lengthy) Monte Carlo program, which involved only 2-body decay kinematics, gamma conversion, and geometry[19,20]. The results of these calculations have been checked with single gammas from NC induced π^o's off protons, and also from single π^o's originating in charged current (CC) ν_μ $(\bar{\nu}_\mu)$ interactions[19-22]. As a result, the single gamma ray background seems to be well under contrôle: If one applies sharp kinematical cuts, it amounts typically to 40% (20%) of the selected ν_μ $(\bar{\nu}_\mu)$ e candidates (Ref. 22, Fig. 2). In order to check consistency and stability of the $\overset{(-)}{\nu}$e effect, less restrictive cuts have been used too (Ref. 22, Table 1); but the correspondingly enhanced background is not germane to the experiment. As you will remember, the ν_μ e and $\bar{\nu}_\mu$ e total cross sections derived were instrumental in pinning the weak neutral current properties down, and they compare quite well with the latest measurements[23].

Yet, one thing disturbed me greatly: These single (e or γ) showers did not behave like a superposition of π^o induced background and ν_μ $(\bar{\nu}_\mu)$ e scattering effect. There seemed to be something else - an excess of events close to 0^o, best visible at shower energies $\lesssim$ 1 GeV. These showers are even more sharply peaked in beam direction than what is expected for electron recoils from neutrino scatters. Obviously, photons from π^o-decay can never give rise to such a peak! In the antineutrino runs the effect is better recognizeable than under neutrino conditions. This would be understandable, if the effect was due to a neutral particle, produced by the primary proton beam (and/or secondary hadron interactions in the shield). Having used comparable amounts of primary protons (4×10^{18}) under either beam condition, one expects - from $\nu/\bar{\nu}$ flux and cross sections - at least twice as much background induced by neutrinos, as by antineutrinos[16-22].

For that reason we consider here the data obtained under antineutrino conditions only.

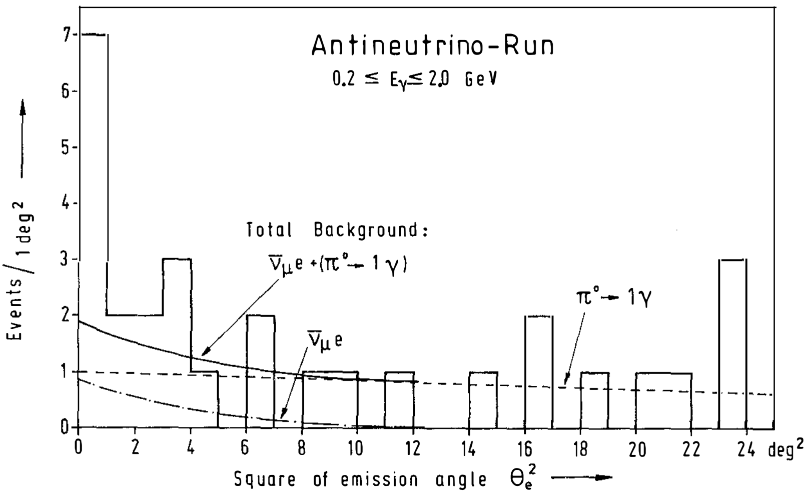

Fig. 1: Angular distribution of single showers, observed in the Aachen-Padova $\bar{\nu}e$ scattering experiment with the energy cut indicated, but without νe selection. The curves are absolute Monte Carlo expectations, as explained in the text.

The angular distribution of single shower events in the $\bar{\nu}$ runs is given in Fig. 1: The histogram is essentially a projection of Fig. 1a of Ref. 22 on the angular axis. The dashed curve gives the background from $\pi^o \to 1\gamma$, evaluated as described, and the full line is the sum of this background and of the $\bar{\nu}_\mu$ e scattering effect, as computed from the total $\bar{\nu}_\mu$ flux with $\sin^2\Theta_W = 1/4$.[23] Whereas the calculation fits the observation reasonably well at large angles, there is this excess below 1^o: The number of single showers observed below 1^o is 7. Instead, the rate one expects from background is 2.0 ± 0.3, where the (systematic) error on this number reflects the statistics of the $\pi^o \to 2\gamma$ background sample, as well as the systematic uncertainties involved in the computation. Statistically the effect is significant: the Poisson probability that the observed number of events is due to a statistical fluctuation of the (well known) background is only 0.1%. As a matter of fact, signal and noise are almost identical to those of our original $\bar{\nu}_\mu$ e scattering study[22]; (the ν_μ e case was always weaker, and the GGM numbers even more so). The effect is largest at energies around and below 1 GeV (Fig. 2). At energies above 2 GeV the observed "naked" one-shower events appear to be satisfactorily explicable by $\bar{\nu}_\mu$ e scattering, and by elastic (or near elastic) interactions of $\bar{\nu}_e$'s. The effect in the neutrino exposures could be of the same size, but does not significantly emerge from the enhanced background.[11)]

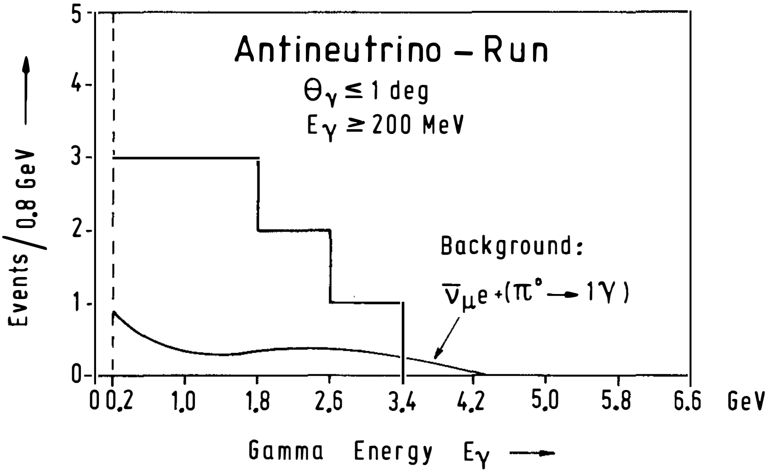

Fig. 2: Very small angle showers (< 1°), observed by AC-PD under $\bar{\nu}$ conditions, as a function of shower energy.

An explanation of this small angle effect observed at low energy in terms of neutrino interactions is well-neigh impossible: Kinematically, small angles are associated with high energies. That the effect is more pronounced under antineutrino conditions - and not in the neutrino runs - is hard to understand for any production process: the ν-flux is twice that of $\bar{\nu}$, and ν-cross sections are generally higher than those of $\bar{\nu}$ [18-20). Coherent production of a meson off the Aℓ-nucleus with a mass > 20 MeV would give a detectable angle to the ν-direction, and can be excluded. Coherent NC mediated gamma production is too small[24)], and has a smoother angular dependence. The same seems true for coherent axion transformation into a photon[25)]. Finally, for νe-scattering such a small angle dominance would mean a high y anomaly - impossible within standard gauge theories, and completely at variance with all available νe data[23].

Therefore, one is naturally lead to surmise the observed small-angle showers are decay products of a neutral particle of small mass, present in the beam. In principle, it could be a (massive) neutrino, which decays, say, according to $\nu_1 \rightarrow \nu_2 + \gamma$ [26]. But even for neutrino masses around 100 eV, phase space is tiny, and with the known limits on muon-number conservation the lifetime becomes unmeasurably large. Thus the small-angle effect observed defied explanation, until the axion was invented[2,3]. If it really has a mass below 1 MeV, it can only decay into two photons: $a^o \rightarrow 2\gamma$, and it may well have escaped detection so far[11]. The two gamma rays would be practically collinear, since the opening angle $\theta_{\gamma\gamma}$ is given (for $\theta_{\gamma\gamma} << 1$) by

$$\theta_{\gamma\gamma} = m_a \ (E_1 \ E_2)^{-1/2} \quad . \tag{8}$$

For $m_a \approx 0.5$ MeV, and $E_1 \simeq E_2 \approx 500$ MeV, this is 1 mrad, far below the angular resolution of the chamber. And since a shower of $\simeq$ 1 GeV is several radiation lengths X_o long, chances are that the second gamma converts inside the first shower, and both merge into one. Thus, the seemingly single showers observed at very small angles could well be examples of two superimposed axion decay gamma rays.

The write-up of the early observations can stop here - notably, since the CERN Courier, in the mean-time, has truthfully printed the whole story[27]. Indeed, the anonymous writer did everything to belittle the significance of these findings. But for me the sharp angular peak of Fig. 1 always had the scent of a light particle decaying.

3) Clear Two-Gamma Decays at SIN!

Rather than to continue such fruitless discussions, I decided to have a look at these presumed decay gammas under more favourable conditions. I gathered a group of students[‡1], and we resolved to go to the 590 MeV proton AGFF cyclotron at the Swiss Institute for Nuclear Research (SIN). The case for lower energies was clear: If the AC-PD-effect was due to a particle decaying, this "achion" was a light particle, and it should be produced at lower energies too. But there the Einstein-Lorentz time dilatation would be much less effective: the decay rate is, in fact, proportional

‡1 E. Frenzel, W. Heinrigs, A. Preussger, D. Samm and U. Samm

to the inverse of the Lorentz factor $\gamma = E_o/m_o$. On the other hand, I entertained still the suspicion that the effect was associated with the neutrino. Therefore, we did not want to go to a low energy accelerator, which would produce no pions (and hence no neutrinos) at all ...

We decided on a beam-dump, shielded by 7.5 m of iron and concrete against an empty decay region of 2 m length. Behind that we put an almost massless "gamma catcher", namely a counter-triggered, thin-foil (0.1 mm Cu) optical spark chamber. The set-up has already appeared in the literature (fig. 1 of Ref. 12). In that paper we described the search for a decay mode, which would actually dominate the axion life-time, if it had a mass > 1.1 MeV, namely the decay: $a^o \to \bar{e}e$. We found nothing (like other people), and concluded $m_a < 1$ MeV.

In order to look for the only remaining decay channel, $a^o \to 2\gamma$, we left everything, as it had been for the $\bar{e}e$-search, (in particular the trigger, a triple coincidence between a counter A in front, and two picket-fences of counter strips, C_i and D_i, behind the chamber) - except for a lead - sheet 2.4 mm (= $X_o/2$) thick, placed right in front of counter A. The idea was to have one gamma (γ_1) converting there, and the second one (γ_2) within the chamber. The scanners had order to register, and measure, all $\bar{e}e$-pairs generated within the fiducial volume, provided not more than 2 additional electrons were coming with it.

As evidenced by Fig. 3 a & b, the trick worked. It worked more or less well: in about half the cases at least one of the electrons generated by the first gamma did show up in the chamber (see Fig. 3a), but in the other events multiple scattering in the lead (and in counter A) made them disappear altogether (Fig. 3b).

A measurement of angle and energy, of course, could be made only on the tracks appearing in the chamber. Despite the small thickness of each foil ($\sim X_o/130$), multiple scattering was appreciable (as $\langle p_e \rangle \approx 40$ MeV), and did limit the angular resolution. Since in practice it takes 3 to 4 sparks to define a direction, one expects, from multiple scattering theory, for the standard deviation in projected angle:

$$\Delta\alpha_x = \Delta\alpha_y = 2 \text{ MeV}/p_e \quad . \qquad (9)$$

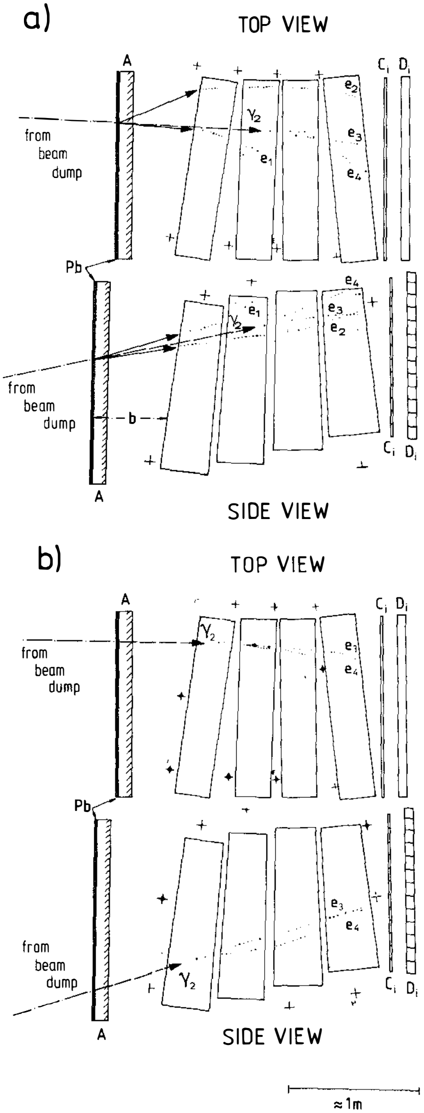

Fig. 3: Spark chamber views of $\chi^0 \to 2\gamma$ candidates (inserts not all to scale):

a) All electrons visible.

b) Both electrons of the first γ lost.

This was born out (except for occasional large angle scatterings) in test runs, in which electrons of known momentum were sent into the chamber and measured.

On the other hand, multiple scattering has been used to assess electron energies by measuring, in either view, the difference between entrance and exit angle for each modul. Inside the chamber this was achieved most accurately ($\delta\Theta < 1^{\circ}$) by connecting the exit spark of the preceding module with the entrance spark of the following one. Only the first and the last direction had to be taken from lining up sparks. Assuming standard scattering theory, the error of one measurement is $\Delta\Theta_{sc}/\Delta_{sc} = \Delta p_e/p_e$, where the angular error stems from both, statistics and from setting: $\Delta\Theta_{sc} \approx \Theta_{sc} + \delta\Theta$. Hence for n independent measurements, and $\Theta_{sc} >> \delta\Theta$:

$$\Delta p_e/p_e = 1/\sqrt{n} = 35\% \ , \quad (\text{for } n = 8) \quad , \tag{10}$$

independently from the electron's momentum (!). But for $\Theta_{sc} \lessapprox 3^{\circ}$, i.e. $p_e \gtrapprox 100$ MeV, the method breaks down. The method samples the electron energy at some apt points, without regard to the particles's fate before or thereafter. The small (e.g. $\approx 10\%$) electron energy loss within the chamber is easily taken care of. Test runs have confirmed these expectations.

The angle α of the second, visibly produced electron pair, was measured, relative to the beam dump direction. The distribution of these spatial angles (Fig. 4a) shows a significant peak in forward direction. The central bin ($\alpha \lesssim 7^{\circ}$) contains 19 events; for higher angles the distribution looks flat, until for $\alpha > 30^{\circ}$ the angular acceptance of the counter strips C_i and D_i starts cutting in. The average rate in the flat region is (4.5 ± 0.6) per bin.

The observed peak cannot be caused by cosmic rays: This has been shown directly by running about the same amount of time, used for measuring Fig. 4a, with the beam off. The result (Fig. 4b) is a flat distribution up to $\approx 30^{\circ}$, as expected, with an average rate of (1.9 ± 0.4) events per $(7^{\circ})^2$.

Now, can the central peak be caused by any accelerator induced background? - This may seem easy for any particular event: a primary electron (or photon) may bremsstrahl in the lead converter, and thus produce an event pattern quite akin to what has been observed.

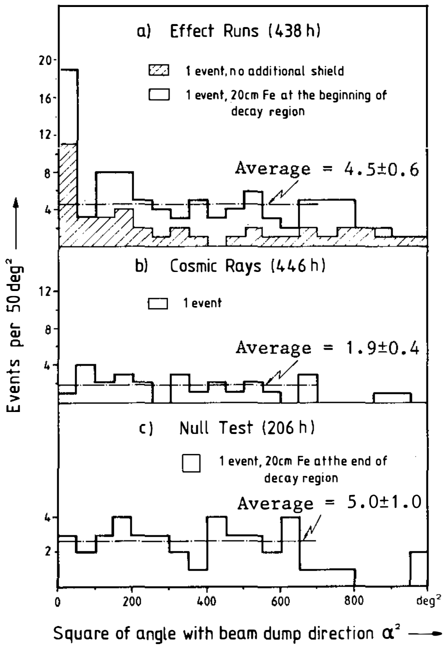

Fig. 4: Angular distribution of gammas converted in the chamber (γ_2), for three different running conditions: a) beam on, b) beam off, c) decay products blocked. (The scale of c) has been adjusted according to the number of Coulombs used.)

However, an explanation of our effect in this manner must fulfill three requirements:

I: It must predict, from measured primary e- and/or γ-spectra, via interaction in the lead, the total and partial (2e, 3e, 4e) rates observed.

II: The energy spectra of the two gammas must fit the expectations.

III: The mechanism assumed has to produce the angular peak in the second gamma, both in position and width.

Using experimental information on single e and γ energy and angular distributions, it becomes clear that no radiation, except the primary beam dump radiation itself, can meet these requirements:

Ad I : The rates (and distributions) of primary electrons and photons have been measured in subsiduary runs (with and without Pb converter). The use of different counter triggers (AC_iD_i and $\bar{A}C_iD_i$) provided a check on our Monte Carlo simulations, and permitted the reconstruction of unbiased spectra impinging on the lead. By Monte Carlo (or by using the test run results directly), absolute rates and distributions of fake 2γ-events were obtained. As evidenced by Table 1, they are hard to reconcile with the data.

Ad II: The energy spectra of the two gammas observed (Fig. 5) are flat and about equal. This statement rests on uneven grounds: Indeed almost all of the 19 events observed under $\alpha \lesssim 7^o$ had a measurable second gamma energy E_{γ_2}. On the other hand, only the 9 "complete" (3e and 4e) events admitted a measurement of E_{γ_1} too. The measured $\langle E_{\gamma_2}\rangle$ = (84 ± 15) MeV is compatible with $\langle E_{\gamma_1}\rangle$ = (83 ± 20). This is, of course, completely at variance with all attempts to understand γ_2 as brems-quantum from a primary γ_1 (or e_1). But it does fit with the two-body decay hypothesis.

Ad III: The sharp angular peak is practically inexplicable by any mechanism involving charged intermediaries: Even if there was a pencil beam of electrons impinging on the lead converter, multiple scattering would, on average, impart a transverse momentum $p_\perp \approx 10$ MeV before bremsstrahlung. Besides, the electron angular distribution was measured to be flat ... And a lead foil cannot render flat things peaked!

Table 1: Background Rates, measured and inferred (normalized to Effect Runs: 129 Coulomb)

Quantity / Primaries	Measured rate in first angular bin ($\alpha < 7^o$)	$\langle E_0\rangle$ MeV	Hence 2γ-effect	2e : 3e : 4e	$E_{\gamma_1} : E_{\gamma_2}$	Angular peak in primary radiation
1e§	130 ± 20	100 ± 30	3.8 ± 0.6	1 : 3 : 0	5 : 1*	No
1γ**	20 ± 6	100 ± 30	0.4 ± 0.1	1 : 3 : 3	5 : 1*	Perhaps
$\chi^o \to 2\gamma$	19 ± 5	167 ± 30	14.5 ± 5.0	1 : 1 : 1	1 : 1	Yes

§ In order to distinguish electrons from protons and muons, a visible multiple scattering angle ($\Theta > 5^o$) was required, and also a time-of-flight corresponding to a velocity v > 0.5 c.

* Because of trigger bias; Bethe-Heitler would give 10:1.

** Measured with counter A in anticoincidence.

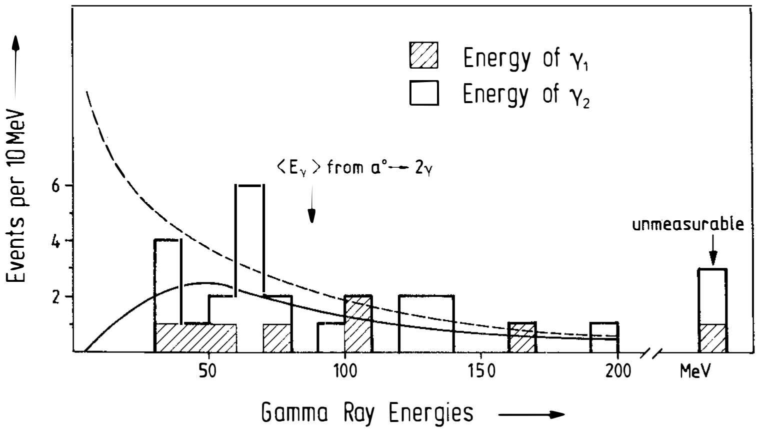

Fig. 5: Energy distribution of the gammas in candidate events ($\alpha < 7^o$), converted in the chamber (γ_2), and in the Pb converter (γ_1). The curves are the Monte Carlo expectations for 590 MeV proton produced axions, decaying into 2γ. The full curve takes the trigger bias into account.

Remains the possibility to have some sort of focussing, conceivably by narrow cracks or holes in the shielding. If so, one expects a non-uniform distribution of γ-conversion points, as projected onto the front face of the chamber. But experimentally this distribution is perfectly uniform in the horizontal (y), and only slightly biased (by the coincidence C_iD_i) in the vertical direction (x). As an additional check a massive iron wall of $3 \times 2\ m^2$ size and 20 cm thickness (11 X_o) was placed against the concrete shielding, right in front of the decay region. As evidenced by the blank parts of the angular distribution (Fig. 4a), the peak stayed on. - But it must disappear, if one shifts the iron wall from the beginning of the decay region to its end. We ran this "Null-test", and the peak vanished (see Fig. 4c). The (properly normalized) rate of Fig. 4c is only slightly higher than the value of (4.5 ± 0.6) events/bin derived earlier from the wings of Fig. 4a. By triggering on single gammas we checked that the Fe wall reflects soft radiation into the chamber, and more efficiently so, if it stands closer. Thus a constant background of (5 ± 1) events/bin, as taken directly from Fig. 4c, may be a slight overestimate.

In conclusion:

- We have found (14.5 ± 5) genuine two-photon events, associated with the beam dump direction, and not explicable by background.
- The energy spectra of both photons are flat and equal to each other. This is incompatible with any bremsstrahl interpretation, but in line with a two-body decay.
- The 2γ-effect is not much influenced by placing a 20 cm Fe wall at the beginning of the decay region, but completely removed by shifting the wall to its end. This suggests that the photons originate in between.
- For complete (3e and 4e) events an improved line of flight can be constructed by connecting the two conversion points. Hence a direct limit on the invariant 2γ-mass was obtained:

$$m_{\gamma\gamma} < 1 \text{ MeV} \quad . \tag{11}$$

Although we have not yet proven that our 2γ-events have a fixed mass, all circumstantial evidence suggests a new, penetrating, neutral particle with quite a long lifetime. If this "achion" is identical to the theoretical "axion" (or to a similar "higglet"), remains to be seen.

4) If Achions are Axions ... and Interact!

If we were to stay at a strictly phenomenological level - we would be finished: Neither a production cross section σ_a nor a 2γ decay width $\Gamma_{\gamma\gamma}$ could we deduce from our SIN 2γ-rate $R_{\gamma\gamma}$ - not even their product $\sigma_a \Gamma_{\gamma\gamma}$, since the time dilatation depends on the unknown mass. We are forced, therefore, to narrow our frame of reference down to a specific model, and we choose the "classical axion model", as described in the literature[2,3,7,10], by Fayet[1], and summarized in the Introduction (Sect. 1). In this model both, the production cross section σ_a and the axion mass m_a, depend on the same Higgs parameter X, and $\Gamma_{\gamma\gamma}$ is uniquely determined by the mass [eq. (3)]. Even though we have to fix yet another parameter, namely the number of fermion generations N. We accept the present prejudice N = 3. Within this narrow frame of mind we can resolve the quest for X, and compute all interesting quantities.

We tried already, when we placed our limit on $a^o \to \bar{e}e$ decay[12) - but we were rather naive then: we assumed axion-pion mixing to dominate, and fixed its strength a priori. As John Ellis pointed out to us, this is not particularly meaningful, since the final result - a limit on $m_a \Gamma_{\gamma\gamma}$ (or a definite value for it) - may force us to revise our original assumptions. Therefore, we changed our line of attack, considered both, π^o and η^o mixing - and had the surprise that for N = 3 η^o-mixing dominates, unless $0 < X << 1$, a value excluded by Ellis'black list[13). Hence eq. (5) reverts to

$$\sigma_a = \xi^2 \sigma_\pi B_\eta^2 (\sigma_\eta/\sigma_\pi) \quad . \tag{12}$$

We have kept the cross section σ_π for (mass-less) π^o's since it has been derived by us[‡2], from pion production data, as described in Ref. 12, and approved of by John. The η^o-cross section, instead, is not known, and one has to borrow a ratio of η^o/π^o cross sections from other experiments[29).

The analysis proceeds then as follows. The measured rate $R_{\gamma\gamma}$ is the product of the total number of axions N_a times the decay distance d over the decay length $\gamma c\tau_{\gamma\gamma}$, and a known overall efficiency $\varepsilon_{\gamma\gamma}$, explicitely:

$$R_{\gamma\gamma} = N_a \varepsilon_{\gamma\gamma} d\, m_a \langle E_{\gamma\gamma}^{-1}\rangle / c\, \tau_{\gamma\gamma} \quad . \tag{13}$$

Investing the experimental numbers: $d\sigma_\pi/d\Omega = 1.6 \times 10^{-26}$ cm^2/sr per Cu-nucleus[12), $d\Omega = 0.015$ sr, $\varepsilon_{\gamma\gamma} = 4.4\%$, $\langle E_{\gamma\gamma}^{-1}\rangle^{-1} = 125$ MeV, d = 2m and $R_{\gamma\gamma} = 14.5 \pm 5.0$, we get, after taking the square root:

$$B_\eta m_a^3 = (\sigma_\pi/\sigma_\eta)^{1/2} (5.3 \pm 1.4)\, 10^{-2} \text{ MeV} \tag{14}$$

as the result of the SIN experiment. Writing B_η and m_a in terms of X leads to a simple relation for $(X + X^{-1})$:

$$(X + X^{-1})^4 = (\sigma_\pi/\sigma_\eta)^{1/2} (63 \pm 16) \quad . \tag{15}$$

With $\sigma_\pi/\sigma_\eta = 4 \pm 2$ [29) we get $X + X^{-1} = 3.4 \pm 0.4$, i.e. $X = 3.0 \pm 0.3$, and hence may infer:

$$B_\eta = 6.8 \pm 0.8; \quad m_a = (250 \pm 25) \text{ keV}, \quad \tau_{\gamma\gamma} = (7.3 \pm 3.7) \text{ msec} . \tag{16}$$

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‡2 Actually by Elisabeth Frenzel, who - alas - left us for Munich.

The errors should comprise all experimental uncertainties, including that of σ_π/σ_η, but they do not reflect the full band-width of theoretical choice. On the other hand, inclusion of $B_\pi \approx 0.13$ (for N = 3) does not alter X at all. For higher N, its influence gets larger. All in all, the axion parameters derived appear reasonable, and avoid a clash with other experiments[2,10-15]. But one has to bear in mind that they follow from a long and non-trivial chain of theoretical arguments.

This would be a good place to stop - had not Vermaseren asked the question[30]: "If this value of X holds true - why did Aachen-Padova not observe hadron-less $\bar{\mu}\mu$-pairs, looking almost like 2-body decays, and stemming from axion transformation in the Coulomb field of a nucleus?":

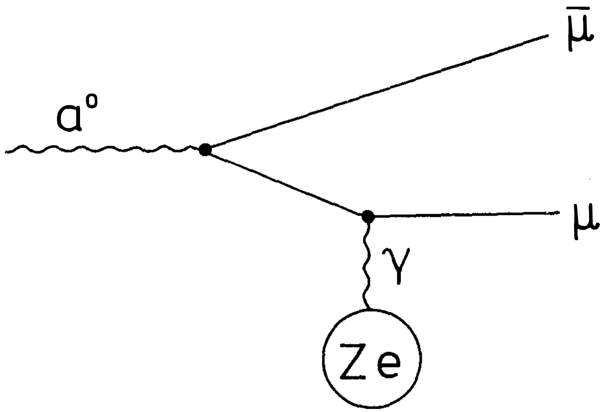

Fig. 6: $\bar{\mu}\mu$-pair production by primary axions in the Coulomb field of a nucleus.

I was startled, because Aachen-Padova did! As a matter of fact, candidates for such "naked" lepton pairs had been around at CERN since

1963, and have caused gross confusion[ǂ3]. Naked μe-pairs were put on firm footing by Aachen-Padova[31)]. If axion induced they would mean a violation of lepton flavour, an oddity one step over and beyond what we are discussing now.

Therefore, we turned to the less abdominable hadron-less muon pairs. They look really almost like 2-body decays. But, as evidenced by Fig. 7, some of them do show a definite transverse momentum $p_{\perp}$ ($\lesssim$ 100 MeV). And

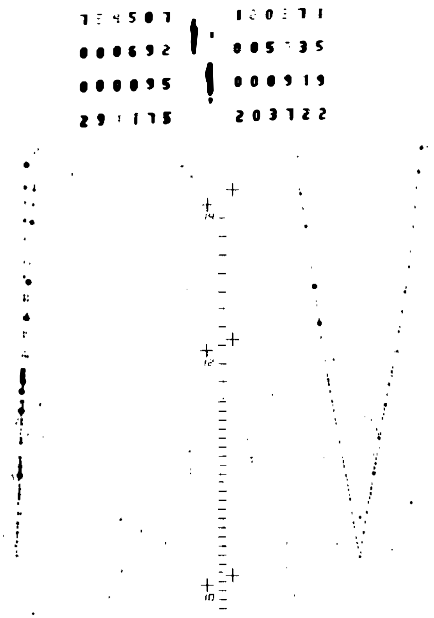

Fig. 7: The two 90° stereo views of a $\bar{\mu}\mu$-pair, produced in the AC-PD Aℓ sparkchamber (with twelve 4 cm Fe plates at the end). In the view to the left the pair is seen edge-on, and shows non-vanishing momentum transfer.

ǂ3 With a light intermediate vector boson of course. In the final discussion of the Siena Conference (1963) Gilberto Bernardini said: "We have lepton pairs, indeed. But if they mean the vector boson, we do not know ..." - and this remark was not well received, at that time[32)].

if one reconstructs the invariant μμ-mass, getting the momenta from the occasional μ-stops, and from multiple scattering again, - one obtains a continuum of masses $m_{\mu\mu}$ around 1 GeV, not a line! Thus, $m_{\mu\mu}$ is a dynamical effect, detached from the rest mass of the primary particle. Just that had been predicted by Bardeen, Tye, and Vermaseren [33] more than three years ago. I wished, I could conclude with a second determination of X from these 21 μμ's, but we still do not know the axion spectrum associated with the CERN PS ν beam: it stems mainly from surviving protons (and mesons) impinging on the front face of the shielding wall (and their descendents!). A tentative evaluation suggested X ≧ 2. This is not too bad for a start - and neither for an end. Besides, with such an X there is no clash with the numerous limits obtained so far either[13) ǂ4]. Let us hope then for achions appearing in front of non-Aachen eyes too!

I thank Profs. Tran Thanh Van and Turlay for inviting me to the stimulating atmosphere at Les Arcs, where I profited much from discussions with Jim Cronin, John Ellis, Pierre Fayet, Jack Steinberger, and others. For help with the write-up I am indebted to my co-workers, notably to Helmut de Witt. The typing did diligently Irene Gojdie, the figures Hubert Schulz.

ǂ4 Fayet[1] spoiled everything by bona fide accepting an unjustified beam-dump limit on σ_a.

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