SEARCH FOR AXIONS

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1. Introduction

The first Bonn Lepton-Photon Symposium in 1973 witnessed the discovery of weak neutral currents[1]. Since then the simplest gauge theory of the electro-weak interaction[2], based on the group $SU_2 \times U_1$, has passed all experimental tests surprisingly well[3-5]. By the discovery of new quark and lepton flavors, the number of quark and lepton doublets ("generations") has gone up to (almost) three for each of them, and possibly this is all. Last not least, quantum chromodynamics (QCD)[6] has evolved as a valiant candidate for a theory of the strong interaction between quarks and gluons[4,5].

Clearly, combining these aspects of the truth into one grand unified theory, a precious GUT, is the task of the day. SU_5 has been proposed as the unifying group[7], the exceptional group E_7 is an intriguing candidate[8], more complicated schemes, based on O_{18} or O_{22} have been considered too[9]. It is possible, though, that the right answer comes from a still more radical revision of thought, perhaps from super-symmetry[10], which entails a deep analogy between fermions and bosons.

As has been emphasized by Okun[11], at this Conference, all of these approaches have one prediction in common: the existence of a host of scalar gauge bosons over a large spread of masses. This is clear for super-symmetry, where essentially every fermion would be accompanied by a sister boson[10,11]. In general they are connected with the Higgs process of spontaneous symmetry breaking[12]. Experimentally, their most characteristic mark is to interact half-weakly with hadrons and leptons, i.e. with an amplitude proportional to the square root of the weak interaction constant G. We shall refer to such particles as Higgs particles in a wide generic sense.

An example of a light Higgs particle ("higglet") is the axion a^0. It has been predicted by Weinberg[13] and also by Wilczek[14], on the basis of symmetry considerations of Peccei and Quinn[15], which had the objective to save QCD from severe violations of T and P, imminent from instanton effects[16]. The axion has been the object of extended theoretical[17-20], and experimental studies[19-26]. In none of these the axion was seen. In particular, its (theoretically favoured) decay into an electron pair: $a^0 \to \bar{e}e$ is down by about seven orders of magnitude, with respect to the theoretical expectations[22,23]. Of course, hence one can only conclude that the axion has a mass $m_a < 1$ MeV, and cannot decay into an electron pair on energetic grounds. Nevertheless, for a long time the prospects for axions to exist, with the properties endowed to them by Peccei and Quinn[15], were rather dim.

It came as a surprise[27], when an Aachen re-analysis[28,29] of the Aachen-Padova neutrino-electron scattering experiment[30], performed in a neutrino beam of $\langle E_\nu \rangle \approx 2$ GeV from the CERN PS, revealed a small, but statistically significant excess of electromagnetic showers, at small angles ($< 1^o$) to the beam direction, over and above one would have expected from $\overset{(-)}{\nu}_\mu$e-scattering and single γ-background (from neutral current produced π^o's). Since this small angle excess is concentrated at small shower energies[28-32] ($\lesssim$ 1 GeV), its interpretation in terms of (anti-)neutrino interactions does not make sense; as a matter of fact, all explanations along this line, as concocted by the Aachen theorists, failed[31,32]. Therefore, it was suggested[28,29] that these surplus showers might actually stem from a new, penetrating particle (of mass $\lesssim$ 14 MeV) - nick-named the "achion" χ^o - admixed to the neutrino beam, and freely decaying into two photons:

$$\chi^o \to 2\gamma \quad . \qquad (1)$$

This conjecture was confirmed by a dedicated 2γ-decay experiment, run near the 600 MeV-proton beam-dump at the Swiss Nuclear Research Institute SIN, in which some clear 2γ-events, of invariant mass $\lesssim$ 1 MeV, were observed travelling along the beam-dump direction. Part of the results have been published[33], and they have been widely discussed at seminars, and conferences[31,32]. I do not feel like repeating everything what has been said before[‡1], but I shall give the gist of this experiment in Sect. 2. And to the good dozen of 2γ-events reported previously, I can add ten 1γ-events, probably of the same origin, found in the mean-time[34]. Yet, the number of events is still small, and statistical fluctuations are a worry. Therefore it is a great pleasure for me to add some distributions of altogether several thousands of 2γ-events, which have been registered, since nine months, near a small nuclear research reactor at the Kernforschungsanlage (KFA) Jülich, near Aachen. Only a small fraction of them has been presented to the public so far[32,37], and also the present display, in Sec. 3, can cover only the simplest aspects of these intriguing observations. Finally, in Sec. 4, I shall return to CERN, and to Aachen-Padova, again. The hadron-less muon-pairs, I shall present here for the first time, may have a connection to the achion problem. Of course, whether or not all these observations have to do with the theoretical axion - this is an open question. Nevertheless, at the end of my talk I shall embark on this "remote possibility"[27], and derive some conclusions within the framework of what John Ellis from CERN calls "classical axion theory"[13-15,17-20].

2. The SIN result: a clear 2γ-signal of low invariant mass

We decided to perform a dedicated decay experiment at lower energies, namely at the 600 MeV proton AGFF cyclotron at the Swiss Institute of Nuclear Research (SIN) near Zurich. The case for lower energies is clear: a beam dump at these energies would provide a well-defined achion source, and because of the Einstein time dilatation one would expect an enhancement of the decay effect in roughly the inverse ratio of the respective achion energies, i.e. by about an order of magnitude. The shield consisted of 1.8 m of iron, 3.7 m of heavy and 1.3 m of normal concrete.[‡2] After additional 5 cm of lead, we left a free space d = 2 m for the surmised particles to decay. The detector was an almost mass-less optical spark chamber, composed of 40 thin foils of 100 μm Cu (+ 50 μm Al), altogether 0.3 X_0 deep. It could be triggered by a coincidence between the two "picket-fences" of plastic counters C_i and D_i behind the chamber (Fig. 1), such that only particles within an angular range between + 17° and - 35°, with respect to the horizontal, were accepted. This ensured full sensitivity for the slanting beam dump line (- 17° ± 2.5°), but reduced the acceptance for cosmic rays.

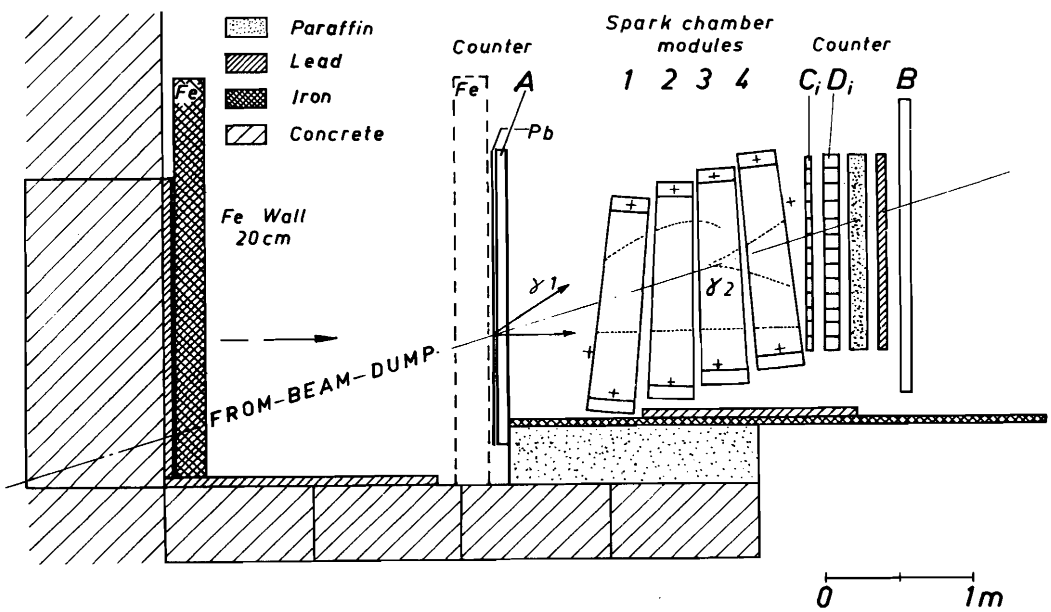

Fig. 1: Experimental arrangement at SIN.[23,33] A complete 2γ-event (class AB) is drawn in. - The 3 × 2 m² large iron wall "Fe" was in front of the decay region (d = 2m), through part of the effect runs, and at its end (dashed) for the "Null-Test" (see text).

With front counter A in anticoincidence we looked for single gammas and had considerable background from cosmic rays, despite the veto-counters B at back and top (not shown in Fig. 1). With A in coincidence with $C_i D_i$ protons, muons, electrons, and electron pairs, could be registered. By selecting the proper time-of-flight (TOF) between counters A and C, only fast particles travelling from front to back were accepted. Thus cosmic ray background could be suppressed to a tolerable level.

The idea in searching for the 2γ-decay of achions/axions (1) was, to have the first γ converting in a 2.5 mm ($= \frac{1}{2} X_0$) lead foil in front of counter A, and the second one in the spark chamber proper. Thus the trigger was a coincidence ($A\bar{B}C_i D_i$), and the TOF selection could be kept. The scanners then provide us with the following classes of events:

A: 1γ-events, characterized by two tracks converging to a point in Pb ($\approx$ A), in either stereoscopic view, whereby at least one of them triggered the $C_i D_i$- counters. (The first electron pair, marked "γ_1" in Fig. 1, would qualify by itself.)

B: 2γ-events, with the 2nd gamma ($= \gamma_2$) converting inside the spark chamber, forming a clear vee. - One or two additional tracks (from γ_1) are admitted, provided they enter through the front face, and point back (within errors) to the same point of Pb as γ_2 does.

AB: A sub-class of these are "complete" events, displaying all four electrons (as sketched in Fig. 1), or three of them.

All our measurements are based on the spatial co-ordinates of sparks. Because of the simple optics, and the 90^o stereo photography, these can be pinned down to better than 1 mm. Lining up sparks to tracks causes no problems, and seldom ambiguities. The angular accuracy is limited by multiple scattering: since it takes $\geq$ 3 sparks (i.e. in average $\geq$ 2.5 foils) to form a track-segment, the corresponding minimal spurious transverse momentum is 1.8 MeV, and hence the (projected) angular resolution $\Delta\Theta = 1.8/\{p\}_{MeV}$, typically 50 mrad ($\cong 3^o$) for 40 MeV-electrons. - This is also the angular resolution for (symmetric) electron pairs of 80 MeV in space. This physical limitation can be eased by utilizing asymmetric pairs, and avoided - for massless 2γ-states - by connecting the two conversion points.[33-35)]

On the other hand, we used multiple scattering for measuring momenta. This was done by measuring entrance and exit angles for each spark chamber module[35)]. Test-runs with monochromatic electrons showed a typical accuracy of $\approx$ 35%. An alternative method relies on the sagitta attained per module.[34,35)]

The gamma ray momentum is taken as the vector sum of the two measured electron momenta of a pair[‡3]. Its projected angles with the beam-dump direction, in either view (α_x and α_y), and the corresponding spatial angle $\alpha=(\alpha_x^2 + \alpha_y^2)^{1/2}$, for $\alpha << 1$, are determined from the actual beam line connecting source centre and conversion point. Hence, with infinitely good angular accuracy, gammas travelling in beam direction would appear as a δ-function at 0^o. In reality we expect a spike, reflecting our resolution of typically 3^o. The finite opening angle $\Theta_{\gamma\gamma}$ from achion/axion decay does not yet enter, since

$$<\Theta_{\gamma\gamma}> \approx m_{\gamma\gamma}/<E_\gamma> < 10 \text{ mrad} \quad . \tag{2}$$

For the first time we have obtained results about 1γ-events of class A, where the electron pair emerged from the Pb converter, passed through the chamber, and managed to trigger the counters behind it.[34)] Their angular distributions are given in Fig. 2. Like those of 2γ-events, given previously[31-33)], they were obtained under the following experimental conditions:

- Fig. 2a) Beam on, SIN shielding strengthened by 5 cm (= 10 X_0) of lead (shaded)[‡4]; then by another 20 cm (= 10 X_0) of iron (open). Either metal shield was preceded by a concrete block of 2 × 2 m^2 cross section, and 1 m depth (see Fig. 1), and by the more than 250 X_0 of beam-dump shield in front of that. Hence there is no a priori reason to regard these "effect runs" as significantly different. Therefore we added them together.
- Fig. 2b) Cosmic ray background, measured directly (practically for the same time as the total of a) with beam off.
- Fig. 2c) "Null-Test", with beam on, but the 20 cm Fe-wall shifted to the end of the decay region (scale adjusted to a/b).

The distributions are plotted in intervals of α^2 (for small α equivalent to cosα), hence isotropy means a horizontal line. The dashed curve is our acceptance for radiation emerging from the shield, mainly a trigger bias. An achion decay effect should appear in the first bin of Fig. 2a ($\cong 7^o$) - and it does indeed. No peak shows up in the background runs (Fig. 2b/c).

These distributions look almost the same as those of the second gammas in 2γ-events, where we saw our first small angle peak at SIN.[28,31-35)] Since they have been the object of heated discussions, we give them again in Fig. 3. The experimental conditions (a-c) were identical to those out-lined above. We introduced, however, a slight difference in the determination of γ-ray directions: Whereas previously we used the reconstructed conversion point of the first gamma in "complete" (i.e. 3e- and 4e-)events as an aid for fitting the direction of the second one[31-33)], the present distributions are based on the measured electron-momenta of the latter alone.[35)] We lose angular resolution that way[33)], but we gain in simplicity, and perhaps also in objectivity. In this spirit we have also

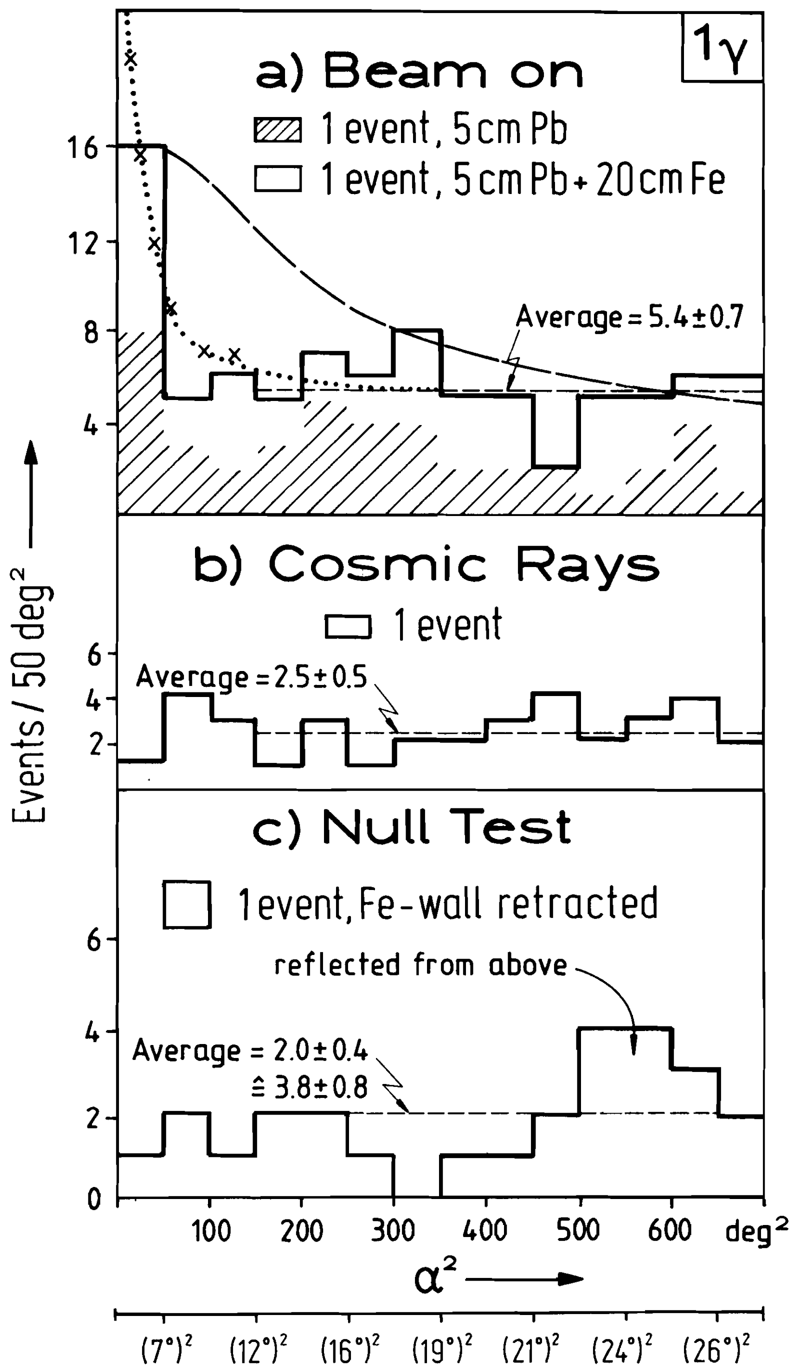

Fig. 2: Angular distribution for 1γ-events (class A): a) effect runs, b) cosmic rays, c) null test (see text). Dashed curve is acceptance, dotted curve angular resolution for γ's of ≈ 150 MeV, as measured in test run[34].

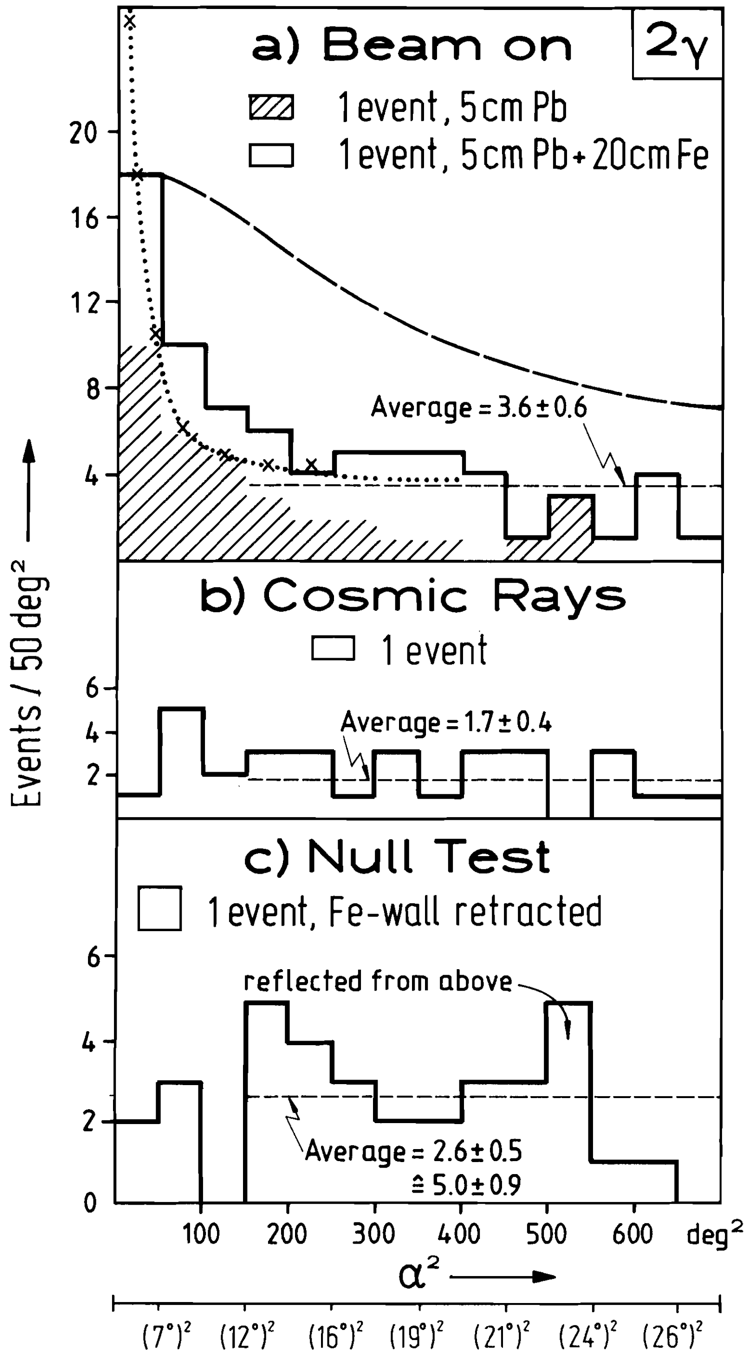

Fig. 3: Angular distribution for the second gammas of 2γ-events (class B). Notation as in Fig. 2. (Resolution was measured with bremsstrahlung > 20 MeV[35])

taken the average between the scanners' measurements, made point by point with the aid of "mangia-spagos" and reconstructed by a computer program, and the direct hand-measurements carried out by physicists. The average difference between repeated measurements of the same γ-direction was 2^o, no matter if these were performed by hand, or by the machine.

Despite the slightly worse angular accuracy of the present angular distributions, we define the candidates for achion decay (1), as before[31-33] by a spatial angle with respect to the beam-dump direction:

$$\alpha < 7^o \quad . \tag{3}$$

We are bound to lose effect hereby, as our (measured) angular resolution curves have not only a roughly Gaussian central part (dotted in Figs. 2a and 3a) - but also a large pedestal, mainly from large single and/or plural scatters[34,35]. Thus the number of candidates N, obtained this way is likely to be a lower limit.

The background B to be subtracted can be determined in many different ways, e.g. by just taking the event numbers accidentally found in the effect bin during the background runs (b and c). Then one would have to test for the difference of two Poisson distributions - and this can be quite frustrating. We can do better than that, if we invest more knowledge about the background, so by measuring outside the effect bins (or in contrôle reactions[3,28-30] - and predict the background B, together with its variance $\sigma^2 \approx B$, by extrapolation into the effect bin. For infinite precision this leads to the one-sided Poisson test, if a number as large (or larger) as the N observed could be explained by a statistical fluctuation of the background number B.[‡5] We decided to determine this number by extrapolating a flat large angle ($150 < \alpha^2 < 700$) background (dashed lines in Fig. 2 and 3) into the small-angle region. Because of the backscattering from the walls (notably from the retracted iron wall in c) this is probably an overestimate. The results are given in Table I. The effect runs do show significant (i.e. $\geqq$ 99% confidence) peaks, whereas the background runs do not.

One derives from table I a small-angle effect of

(10.6 ± 4.6) 1γ events (A) plus (14.4 ± 4.6) 2γ events (B)

in total (25 ± 7) events. The relative frequency of the two classes checks with our Monte Carlo calculation for phase-space produced achions[36].

The energy distributions of these events is given in Fig. 4. The 1γ-events, which have to reach the end counters C_i and D_i, are very much biased towards high energies. This explains also their sharp angular peak, even though they passed (in average) through $\frac{1}{4}$ X_0 of Pb. The Monte Carlos[36] show how the low energy rise, expected from the Lorentz-factor, is overcompensated by the trigger bias. The agreement with observation is not bad at all. The equality of average γ-energies:

$$\langle E_{\gamma_1} \rangle \approx \langle E_{\gamma_2} \rangle \approx (80 \pm 15)\ \text{MeV} \tag{4}$$

Table I: Numbers of 1γ and 2γ decay candidates N ($\alpha < 7^0$), together with background numbers B (from $7^0 < \alpha < 26.5^0$), absolute effect E, number of standard deviations t, and confidence levels that the effect is non-statistical.

Event type	Add. shield	Time h	Beam Coulb.	N	$B \approx \sigma^2$	E = N-B	t = E/σ	confid.[$] level %
A. 1γ	Pb[&]	137	36	8	2.7±.5	5.3	3.1	99.3
1γ	Pb+Fe[§]	301	93	8	2.7±.5	5.3	3.1	99.3
A. 1γ	Effect	438	129	16	5.4±.7	10.6	4.4	>99.9
A. 1γ	Beam OFF	446	0	1	2.5±.5	-1.5	-	-
A. 1γ	Null* Test	206	68	1	2.0±.4	-1.0	-	-
B. 2γ	Pb[&]	137	36	10	1.2±.3	8.8	6.7	>99.9
2γ	Pb+Fe[§]	301	93	8	2.4±.5	5.6	3.4	99.7
B. 2γ	Effect	438	129	18	3.6±.6	14.4	7.5	>99.9
B. 2γ	Beam OFF	446	0	1	1.7±.4	-0.7	-	-
B. 2γ	Null* Test	206	68	2	2.6±.5	-0.6	-	-

& "Pb" = 5 cm (= 10 X_0) Pb behind 1 m (= 10 X_0) of solid concrete.
§ "Pb+Fe" = 20 cm (= 10 X_0) of Fe added behind that Pb.
* the 20 cm Fe-wall shifted to the end of the decay region.
$ From Poisson: Confidence level = 1 - P ($\geq$ N,B).

for class AB events is what one expects for a 2-body decay. It is completely at variance with any attempt to "explain" the second gamma as a brems quantum from the first one.

Of course, we have systematic background tests performed. They are, in fact, more important than the statistical tests described. Even given a significant small-angle peak, everybody would suspect some electromagnetic background from the accelerator to be the reason. Indeed, any observed event could be simulated by some ad hoc concocted background configuration. However, a scientific explanation must give the right distributions of the events - and they must also check with the single γ and e distributions, as measured before. As evinced earlier[31-33], all these background "explanations" are bound to fail.

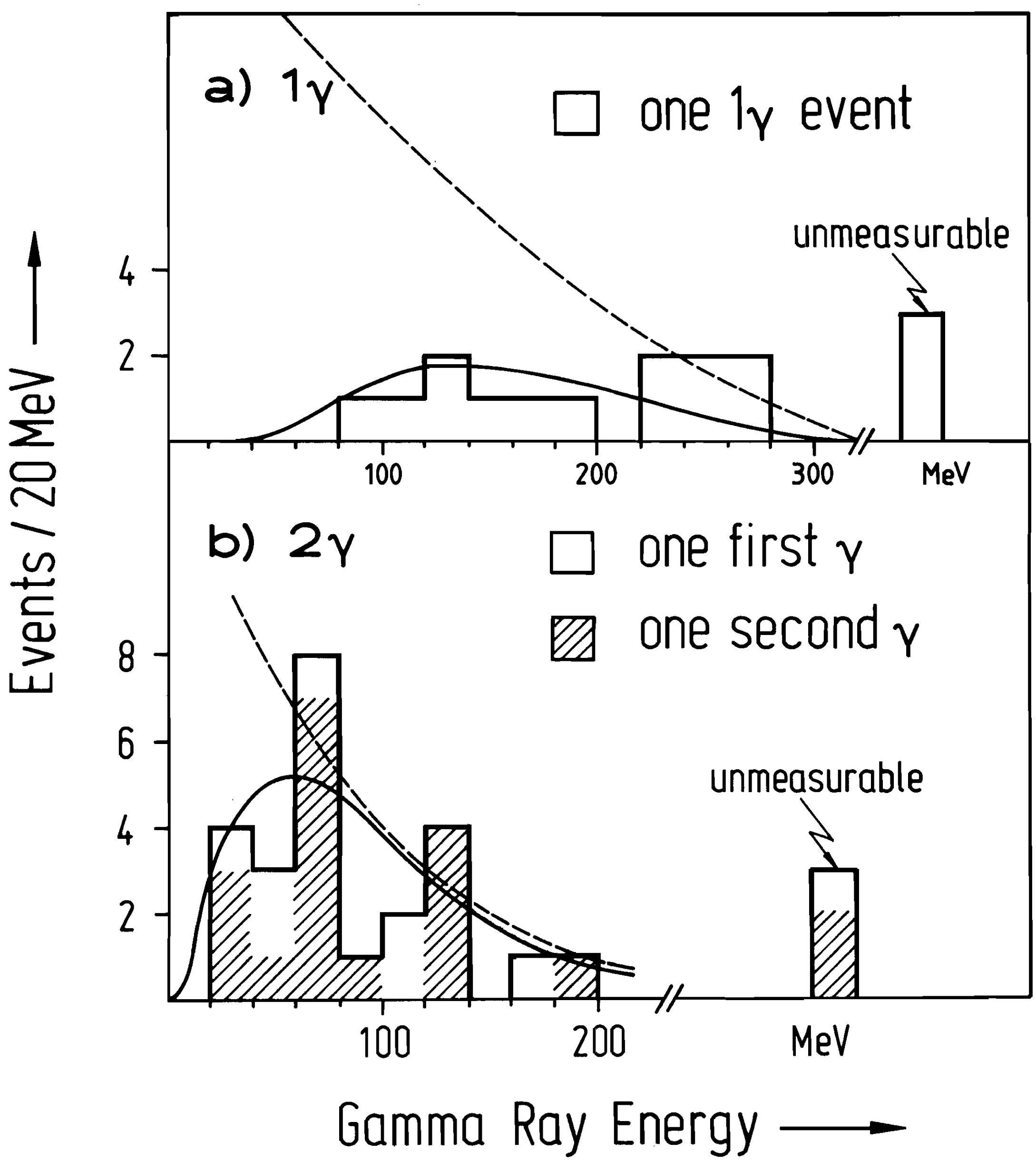

Fig. 4: Energy-distribution for small angle gammas ($\alpha < 7^{o}$) from a) 1γ-events of class A, and b) first and second gammas from 2γ-events (class B). The dashed curve is the Monte-Carlo expectation from $a^{o} \to 2\gamma$ decay, the full curve takes the trigger bias into account.

The main obstacle for them to work is the sharpness of the angular peak itself. In order to maintain any correlation with the original target direction we have to assume that the particles constituting the angular peak (or their parent particles) have penetrated the shield. Directly on the beam line there were at least 20 X_0 (without any cracks or holes). Along this path every charged particle attains a multiple scattering angle of $\Theta_c > 90/\{p\}_{MeV}$, i.e. $> 10^0$ even for (extremely) high energy electrons of 500 MeV. †6 Thus, it does not help that the emission angle of bremsstrahlung is small: the parents' direction is already smeared out, the angular distribution of electrons and electron pairs rather flat, as observed[23,35]. There is evidence for this soft e.m. background radiation not to go through the shield, but preferentially around it. This is corroborated by the observation that demanding a more restrictive signature for the 2γ events, namely a visible first gamma (class AB), makes the background shrink to cosmic ray level. Therefore, we think we have not only understood our effect, but also the background. In Table 2 of our publication[33] we tried to synthesize it even from our observations on single e's and γ's and found good agreement.

3. At a Jülich reactor: 2γ coincidences matching the decay volume, and geometrically defined mass distributions.

Although the SIN experiment established that something new is there, and decays into two photons, it still left much to be desired: more statistics, in particular in the decay tests, and a direct measurement of the new particle's mass. Both has been attempted in an experiment near a nuclear reactor[32,37].

Nuclear reactors should be powerful sources of axions[13,19,21], in fact, of any type of half-weakly coupled (pseudo-) scalar particle, provided its rest mass is smaller than the excitation energy of the fission fragments and n-capture states (≈ 6 MeV), to emit them. A quantitative calculation of this flux is beset with the difficulties of nuclear physics: estimates range from 10^{-4} to 10^{-8} axions per gamma ray.[13,19,21,38] Early limits on reactor axion fluxes were estimated in these papers on the basis of Fred Reines' neutrino experiments. Less incisive limits came recently from a dedicated axion search at ILL (Grenoble)[25].

The Aachen-Jülich Group[37] looked for 2γ-coincidences from achion/axion decay by placing two NaI counters - in various geometries and shielding dispositions - near the 10 MWatt research reactor MERLIN of the Kernforschungs-anlage (KFA) Jülich (near Aachen). The set-up was at a distance of 5.7 m from the light water cooled reactor core of 60 cm height, 37 cm width, and 52 cm depth. The reactor was well shielded, on the "beam-line" there were 3.5 m of concrete.

The detector is sketched in Fig. 5: a NaI crystal of 4" ∅ and length (counter A) is placed in front of another one (counter B), of 10" ∅ and length. The central part of the latter is covered by 10 cm of lead, such that the direct line-of-sight between the two detectors is blocked. The front faces of both detectors (for A also the side) are protected against charged particles by plastic veto-counters D. Counter A can be moved forward on an optical bench, whereby the available decay volume is varied from 46 cm × (50 cm)^2 to zero. Detectors and decay region are enclosed in 5 cm of lead, 1 cm of boron loaded plastic, and 50 cm of concrete. A 2 × 2 m^2 plastic counter C on top of the set-up provides additional rejection against cosmic rays.

The trigger is a moderately fast (τ = 60 nsec) coincidence between the NaI counters A and B, in anti-coincidence (6 μsec) with C and the two D's. The YES-counter pulses had to pass through a window between 0.6 and 6 MeV. This signal (A B $\bar{C}$ $\bar{D}$) gated the slow electronic branch, which measured the time-of-flight (TOF) between A and B to within 7 nsec, and the pulse heights in A and B to 7% (FWHM). Either of them gives the energy deposited by the respective gamma ray in the NaI crystal, (i.e. "visible" energy). The two pulse heights of every event were written on magnetic tape, in pre-set TOF-bins, (in our case in prompt coincidence ± 5 nsec). Accidental coincidences were negligible. The energy values were read off and processed further off-line.

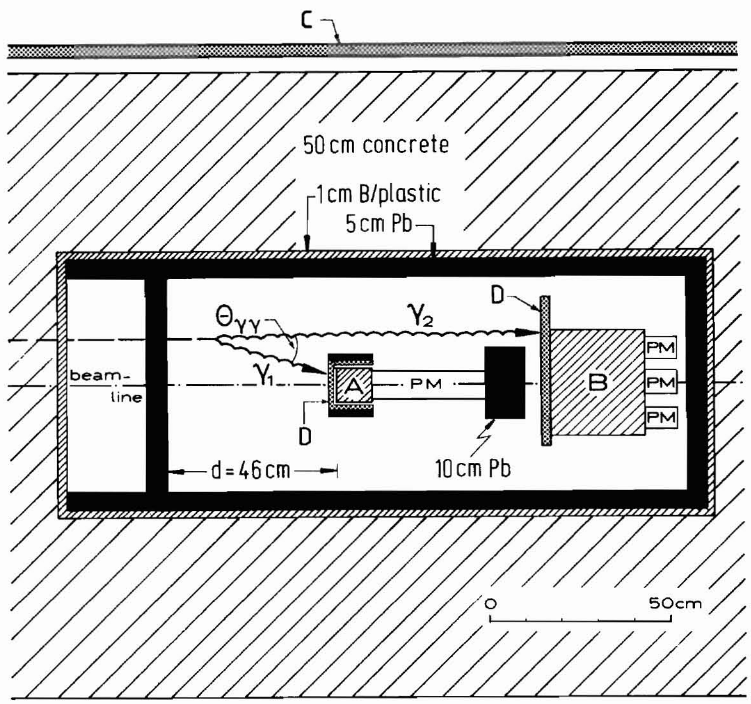

Fig. 5: Set-up for the reactor experiment at Jülich. - A and B are the essential (NaI)-counters, C and D plastic veto-counters.

The simplest result is the energy spectrum of one NaI counter (e.g. A), gated by (A B $\bar{C}$ $\bar{D}$), irrespective of the energy deposited in the other (B). This has been already presented to previous conferences[32,37]. With a decay path of 46 cm, as shown in Fig. 5, there was a small, but significant reactor signal over and above the large cosmic ray background.

A more detailed understanding of what is going on is provided by the correlation between the energies registered in A and B, respectively. This is demonstrated in Fig. 6, which gives the energy spectra, as registered in counter B, in coincidence with selected energy ranges in counter A, namely:

a) $0.66 \leqq E_A < 1.04$ MeV,

b) $1.04 \leqq E_A < 1.49$ MeV,

c) $1.49 \leqq E_A < 3.42$ MeV,

d) $3.42 \leqq E_A < 5.75$ MeV.

For each of these E_A-windows the full E_B-spectrum is given for both, 313 hours of reactor ON (black points), and 2.70 × 116 hours of reactor OFF (open points).

The results are quite intriguing: In the two highest E_A-windows there is no reactor ON-OFF effect discernible at all. In the E_A-region b, containing the γ-energies of Co^{60} (1.17 and 1.33 MeV), also counter B sees these two peaks, and practically with the same height for reactor ON and OFF, respectively. The Co-lines are still seen with the lowest E_A-range (a) selected. This is clear, since crystal A will often absorb (by Compton effect) only a fraction of the full γ-ray energy. However, over and above this trivial contamination, there is also a systematic, positive ON-OFF difference, mainly around $E_B \approx 1.5$ MeV, (and perhaps again at very low energies). This becomes clearer in Fig. 7, where the ON-OFF difference in B for the four E_A-windows is plotted in somewhat larger bins, and with some typical statistical errors.

The background is clear: Most of the 2γ-coincidences analysed come from cosmic rays. In particular, there is no significant reactor effect for $E_B > 2.2$ MeV, for any energy associated with it in counter A, and no effect at any E_B for the highest E_A-region (i.e. for $E_A \gtrsim 3.4$ MeV). This places a very restrictive limit on the flux of achions/axions with energies $E_0 = E_A + E_B \gtrsim 5.5$ MeV. The Co^{60} radiation, showing up in all appropriate energy regions, stems from contamination of some shielding blocks, as was cleared up later. As the two gammas come in cascade, Co^{60} produces genuine (AB)-coincidences, and is, of course, not affected by the veto-counters. But with a life-time as long as 5.27 years, the Co^{60}-rate, like the cosmic ray rate, is not associated with the reactor[‡7], and does not enter the ON-OFF difference (Fig. 7) at all.

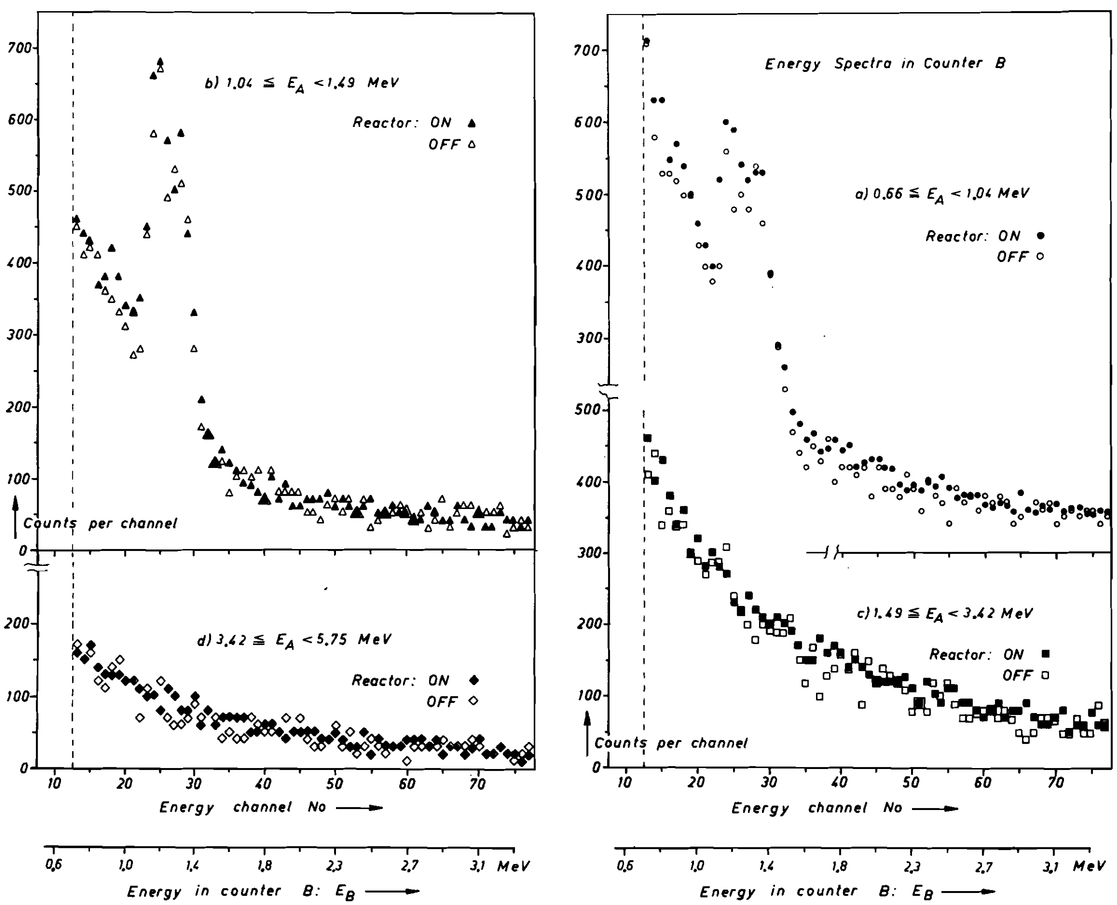

Fig. 6: Energy spectra seen in counter B, when gated by coincidences $(A\ B\ \bar{C}\ \bar{D})$. a to d refer to different energy windows, set (off-line) for the energy in counter A. Full symbols refer to 313 h with reactor ON, open symbols to (2.7 × 116)h with reactor OFF. (1 channel = 43 keV).

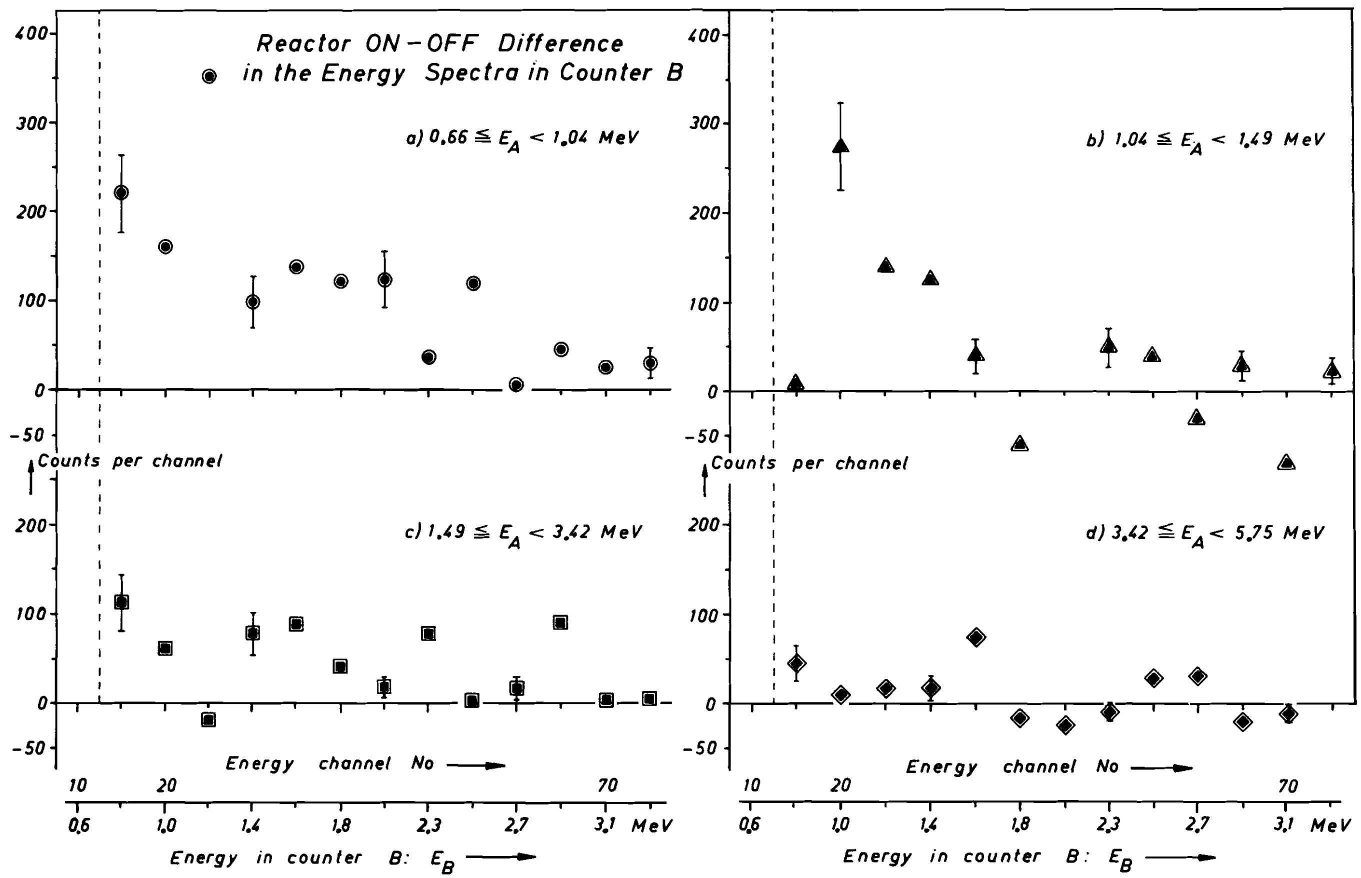

Fig. 7: Reactor ON-OFF effect in the energy spectra of counter B, gated by coincidences ($A\ B\ \bar{C}\ \bar{D}$), as derived from Fig. 6. The energy regions in E_A are the same; but each point has been summed over 5 E_B-channels.

This ON-OFF effect is rather soft. As one gathers from Fig. 7, it is very significant statistically. And also its systematic variation with the two registered energies E_B and E_A is compatible with a two-photon achion decay (1): In a light water cooled reactor one would expect a large contribution from n-capture by free protons[38]

$$n + p \rightarrow d + a^{o} + 2.23 \text{ MeV} \quad . \tag{5}$$

This axion-line at 2.23 will transform itself into a rectangular spectrum for either decay gamma, which extends from zero to the total axion energy, if it is not biased. In the "telescope" geometry used, there are two types of bias involved, a geometrical one favouring asymmetric decays with $E_B >> E_A$, and the electronical thresholds of $E_A^o \approx E_B^o \approx 0.66$ MeV. From Monte Carlo calculations[39] one expects preferentially mildly asymmetric decays with $E_B/E_A \approx 1.5$. As demonstrated by Fig. 8, this is in fact observed. There the reactor ON-OFF difference is given for the energy ratio E_B/E_A. (Actually the square root is plotted, since for our geometry - if unbiased electronically - it is a mass scale, as indicated.) It is clear then that the energy spectrum in counter A, must show an ON-OFF effect only below 1 MeV, and only in association with energies in B between 1 and 1.6 MeV, as observed. Actually, all the ON - OFF energy spectra measured so far under several geometrical conditions[37] are compatible with stemming from a two-photon decay.

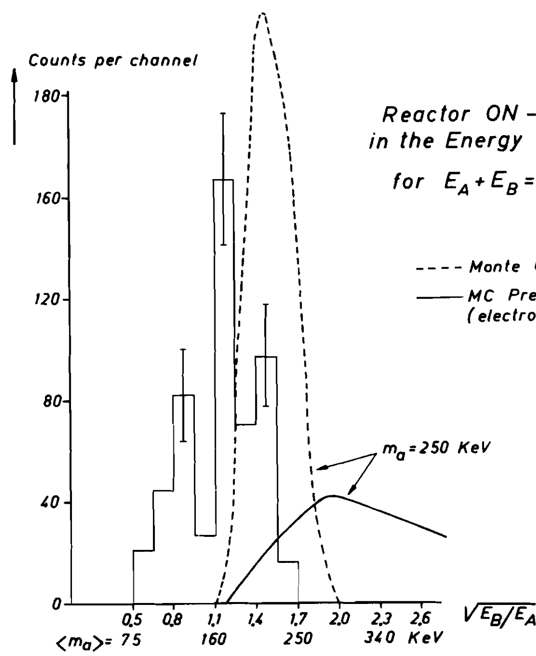

Fig. 8: Reactor ON-OFF difference in the distribution of the energy ratio E_B/E_A measured for each event. ($\sqrt{E_B/E_A}$ is plotted, since it is equivalent to the mass scale, given underneath.) M.C. curve is suggestive.

This inference was corroborated by several geometrical and shielding tests along the lines tried out already at SIN. For example: If counter A was advanced towards the front lead wall (see Fig. 5), the ON-OFF rate dropped accordingly, and vanished, when A touched the wall. Leaving A in place, but moving the lead wall right in front of it, had the same effect.[32,37] Similarly, the reactor effect went drastically down, when counter A looked through a 5 mm thick lead tube of 4" diameter, and 46 cm length. But it stayed, when the walls of the decay volume were lined with 5 mm of lead.[37] As hard as we tried: We cannot think of any background to simulate this decay-like behaviour.

Thus, it seems we are seeing a two-photon decay of a penetrating particle at reactor energies, too. If so, our geometry, in conjunction with the measured energies, fixes the invariant 2γ-mass

$$m_{\gamma\gamma} \approx \Theta_{\gamma\gamma} \sqrt{E_A E_B} \quad , \tag{6}$$

either for each event (when $\Theta_{\gamma\gamma}$ is geometrically fixed), or for the event sample, since $\langle\Theta_{\gamma\gamma}\rangle$ can be taken from geometry[39]. For the telescope geometry of Fig. 5 $\langle\Theta_{\gamma\gamma}\rangle = 0.25$. The ON-OFF distribution of $\sqrt{E_A E_B}$ has an upper edge at 1.2 (± 0.2) MeV - hence $\langle m_{\gamma\gamma}\rangle$ is below 300 keV. Unfortunately, it is electronically biased at the low energy side. But the same bias (in counter A!) distorts Fig. 8 at high masses only! Thus we derive a lower bound from there:

$$\langle m_{\gamma\gamma}\rangle \equiv m_a > 150 \text{ keV} \quad . \tag{7}$$

Perhaps our previous, rather theory dependent guess[31-35]: $m_a \approx 250$ keV is not far off the truth.

4. Conclusions about achion/axion decays - and an outlook to their interactions

The situation does not look too bad: At three different energies, spanning from 1 to 1000 MeV, three different groups, using different techniques, and suffering from different backgrounds, have obtained evidence for the radiative decay of a very light, longlived, penetrating particle. In particular the SIN data leave no doubt that the decay proceeds into two photons. Its total rate $R_{\gamma\gamma}$ is given by the total achion flux Φ_o, an overall 2γ detection efficiency $\varepsilon_{\gamma\gamma}$, and the ratio of decay path d over the average decay length $\Lambda_c = \langle\gamma_o\rangle\, c\, \tau_{\gamma\gamma}$. Making the Lorentz factor explicit, we have:

$$R_{\gamma\gamma} = \phi_0 \frac{d}{c\tau_{\gamma\gamma}} \langle 1/E_0\rangle\, m_0\, \varepsilon_{\gamma\gamma} \quad . \tag{8}$$

In the standard axion theory[13-20] all unknown parameters, in particular axion mass and production cross section depend essentially from one number, the Higgs parameter X. (As a matter of fact, this is an over-simplification, since what in the Peccei-Quinn scheme[15] is indeed the number of fermion generations N(= 3), in more general coupling schemes[17] could be any integer > 0.) But if one sticks to N = 3, the coupling becomes essentially isoscalar, and all unknown quantities in (8) can be simply expressed by X. Investing the event numbers observed at CERN, and SIN (Table I), yields in either case an X compatible with 3.0 ± 0.3 [31-35]. Hence theory infers an axion mass of 250 (± 25) keV, and a lifetime close to 10 msec.

No such detailed analysis has yet been performed for the Jülich measurements. But it is gratifying that the direct estimates of the invariant 2γ-mass fall into the same mass range. Starting from there, we can take a lifetime around 10 msec for granted, without a recourse to X and N.[17] With a provisional detection efficiency of $\varepsilon_{\gamma\gamma} \approx 10^{-3}$, we estimate a total axion flux through the decay volume of

$$\Phi_o \approx 1.5 \times 10^8 \text{ sec}^{-1} \quad . \tag{9}$$

By comparison to the p(n,γ)d γ-flux from a 10 MWatt fission reactor[38]

$$\Phi_\gamma \approx 5 \times 10^{12} \text{ sec}^{-1}$$

we get a ratio of axion to gamma emission of $R \approx 3 \times 10^{-5}$, in surprisingly good agreement with the previous more optimistic estimates. Clearly, a systematic exploitation of the Jülich data will bring us on much safer grounds. Improvements of the present experiments are clearly indicated: lower energy thresholds, still better geometrical definition of the decay configuration, and - most important - lower cosmic ray background.

As soon as that is achieved, one can also think of detecting reactor axion interactions. One of them is obvious, and widely discussed in the literature[13,19,21], axion "Compton" scattering off an electron:

$$a^o + e \rightarrow \gamma + e \quad . \tag{10}$$

Barshay et al.[40] added another one: coherent conversion into a photon off a complex nucleus A:

$$a^o + A \rightarrow \gamma + A \quad . \tag{11}$$

Inelastic axion-photon conversion is conceivable, and it will not be easy to disentangle the different reactions - once they have been found!

But, perhaps they have been seen already? - This astounding question brings us back to CERN, and to the Aachen-Padova neutrino-electron scattering experiment[30)], and its seemingly inexhaustible by-products. In that experiment also hadronless μe-pairs have been disclosed, which are very difficult to explain by neutrino interactions[41)]. The contribution expected from charm production is $\approx$ 1 event out of 8 observed. Recently 21 "naked" $\mu\mu$-pairs joined the flock[42)]. All of them look almost like twobody decays of (variable) invariant mass (around 0.8 GeV). But sometimes (see Fig. 9), one notices a small transverse momentum imbalance of about 50 MeV ($\approx R_{A\ell}^{-1}$!). Apart from that the lepton pairs are coplanar with the beam direction. This facilitates rejection of punch-through from $\mu\pi$-events: with a cut of 50 mrad on the a-coplanarity, the expected contribution to the $\mu\mu$-sample (defined by either muon range $R_{\mu} > 4\Lambda_{o}$) is estimated to be only 2 - 3 events.

All these observations suggest that the lepton pairs in question were perhaps produced by a coherent Bethe-Heitler type of process off $A\ell^{27}$, with the primary gamma replaced by an axion (or achion), as envisaged by Bardeen, Tye, and Vermaseren[18)]. Indeed, there is also the possibility of ρ^{o}-production by neutral currents, with subsequent $\rho^{o} \rightarrow \bar{\mu}\mu$ decay, but because of the additional neutrino in the final state, the kinematics is not quite the same. The softness of the observed $\mu\mu$-rate (Fig. 10) - if it comes from axions at all - is evidence against production by primary or first generation hadrons only: the cascade must be contributing too. But it is hard to decide if it comes from the hadronic or from the electromagnetic part, in particular since the "neutrino-beam-dump" is also a prolific source of neutrons, whose spectrum can only be guessed. The probability for a 0.5 GeV axion to decay, is (with X = 1) about the same as that for a 10 GeV axion to interact.[18)] Thus, comparable numbers of decay and interaction candidates, as apparently observed, seems not quite unreasonable. It remains to be seen, if our axion-interpretation of the 2γ-decays, as resumed by a Higgs parameter $X \approx 3$, will stand up in the face of a more detailed analysis.

For the time being I emphasize the more general aspects of our observations: That achions are neutral, penetrating, and long-lived is proven by direct inspection. An achion mass of around half an electron mass is deduced from the energies measured at Jülich by using relativistic kinematics only. And the SIN and Jülich data suggest strongly that the achion decays into two gammas, and nothing else. Hence we conclude, it is a boson. Since 2γ-decay is forbidden for vector particles, we know also that its spin has to be even; probably the achion is a scalar. Its parity has still to be measured. This will be the experimentum crucis for achions to be identical with pseudoscalar axions, or with some other Higgs particle.

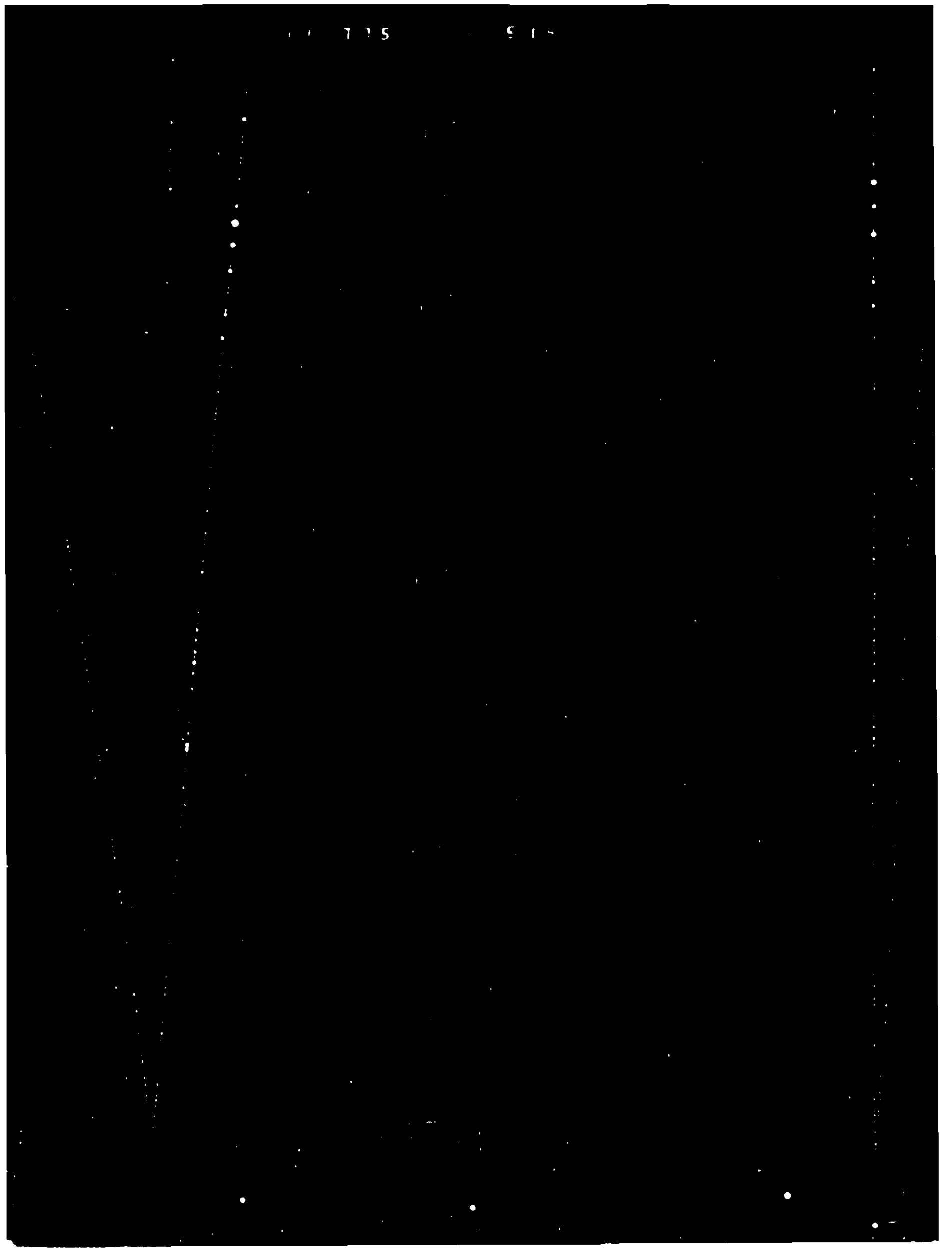

Fig. 9: The two 90^0 stereo views of a "naked" $\bar{\mu}\mu$-pair, produced in the AC-PD Aℓ sparkchamber (with twelve 4 cm Fe plates at the end). Primary neutrals enter from bottom along the direction marked by the crosses. The right-hand side view suggests non-vanishing momentum transfer to the nucleus.

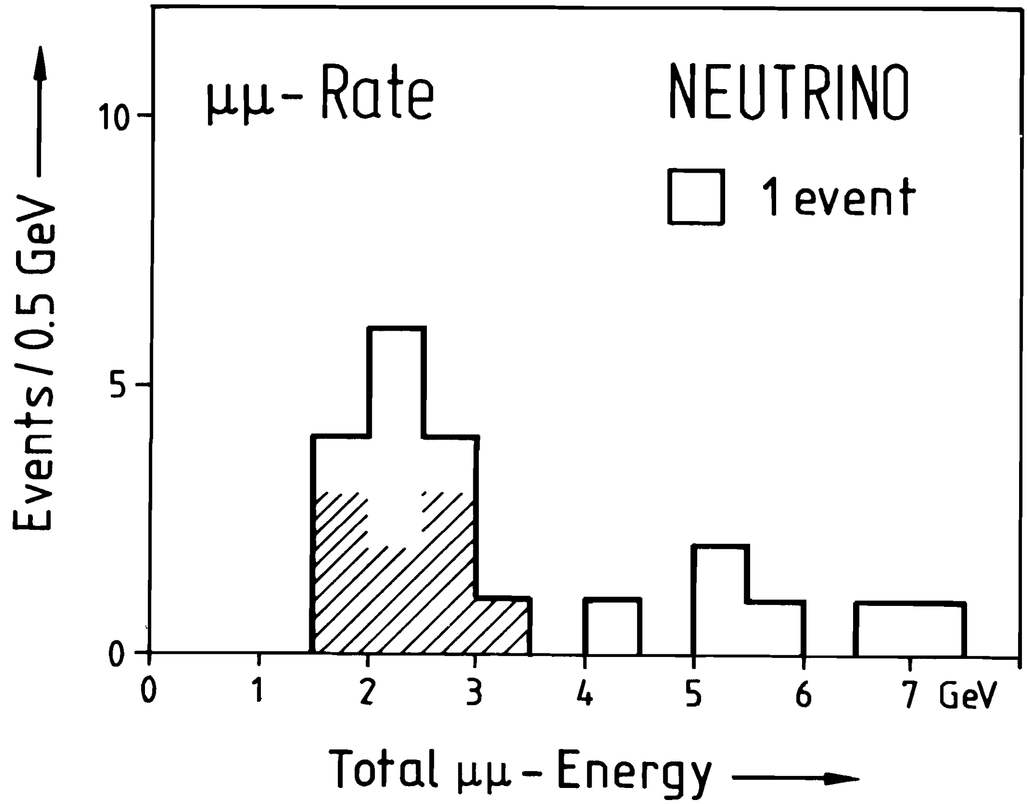

Fig. 10: Total energies of hadronless muon pairs, reconstructed as if 2-body decays. Shaded areas refer to the (well-measured) cases, where one muon stopped, the other energies were estimated from multiple scattering.

Time will come to tell ... Their grand-father, Roberto Peccei, commented about axions (achions?) by quoting an old Italian proverb: "Se son rose, fioriranno", meaning, if they are roses, they will blossom. The famous German experimenter and poet, Johann Wolfgang von Goethe, whose 232nd anniversary we celebrate today, on this 28th of August, knew this saying too. But he translated it into a more optimistic mood:

"Da hilft nun freilich kein Bemüh'n,
's sind Rosen - und sie werden blüh'n."

Acknowledgements:

The Aachion groups are indebted to all the many colleagues who, by their criticism and advise, helped them to understand their data better. Thanks go in particular to Al Abashian, J. Bjorken, Jim Cronin, John Ellis, Titus Heusch, Jack Steinberger, and George Zweig. Special thanks are due to Wolfgang Heinrigs, Doris Samm and Helmut de Witt, as well as to Eduard Hermens and Hellmut Seyfarth for their help in preparing the manuscript. Finally the author wishes to thank Irene Gojdie for typing the manuscript, and Hubert Schulz for drawing the figures. The support from the German Bundesministerium für Forschung und Technologie, and from the NRW Ministerium für Wissenschaft und Forschung was marginal, but welcome. The providing of personnel by the Arbeitsamt Aachen was of great help. The efforts of all the many people involved in the experiments are gratefully acknowledged.

The author is indebted to Professor Wolfgang Paul, and his associates at Bonn University, for inviting him to present the data, as they were at that time, and to K. Heinloth and W. Pfeil for their patience with the manuscript.

Footnotes

ǂ[1] Considering the flood of questions (and complaints) I got after the talk, I wish I had repeated more. The write-up tries to strike a reasonable balance between rehearsing trivial tests and reaching meaningful conclusions.

ǂ[2] The slightly different numbers quoted in Ref. 33 referred to an earlier state. Our shield is stronger than we thought: the "heavy concrete" is 80% Fe by weight.

ǂ[3] In some of the earlier measurements the γ ray direction was simply identified with the bisectrix of the $\bar{e}$e-vee.

ǂ[4] This was the shielding condition left over from our $a^0 \rightarrow \bar{e}e$ search.[23)] We referred to the corresponding drawing (essentially the present Fig. 1) in our 2γ-paper[33)], but did not emphasize that 10 X_0 of lead were already there, before we placed another 10 X_0 moveable Fe in front of the decay region.

ǂ[5] Some of our critics, instead, want us to test, whether or not our background could be simulated by the effect - but we are not interested in that!

ǂ[6] A similar situation emerges from strong interactions, despite the lower number of interaction lengths Λ_0 on the beam line, since the single scattering angles are of order unity.

ǂ[7] There is no evidence so far, that Co^{60} is accumulating during the effect runs.

ǂ[8] All that had not been so clear at the time of the Conference, and the author apologizes for the confusion, he has possibly spread around.

References

1) H. Faissner et al., Proc. 6th Internat. Symposium on Electron and Photon Interactions at High Energies, Bonn 1973, ed. H. Rollnik and W. Pfeil (North-Holland, 1974) p. 550,
G. Myatt, ibid., p. 389;
The subsequent publications of the Gargamelle Collaboration were:
H.J. Hasert et al., Phys. Letters 46B, 121 and 138 (1973).

2) S. Weinberg, Rev. Mod. Phys. 52, 515 (1980),
A. Salam, ibid., p. 525,
S.L. Glashow, ibid., p. 539.

3) See P. Musset and J.-P. Vialle, Neutrino Physics with Gargamelle, Physics Reports 39C, No 1, p. 1 (1978),
J.E. Kim, P. Langacker, M. Levine, and H.H. Williams, Rev. Mod. Phys. 53, 211 (1981).

4) See the Proceedings of the International Neutrino Conferences, 1974 - 1981.

5) See the Proceedings of the International Symposia on Electron and Photon Interactions at High Energies at Stanford (1975), Hamburg (1977), and Batavia (1979).

6) M. Gell-Mann, Schladming Lectures, Acta Physica Austriaca, Suppl. IX, 733 (1972),
H. Fritzsch, M. Gell-Mann, and H. Leutwyler, Phys. Letters 47B, 365 (1973),
W.A. Bardeen, H. Fritzsch, and M. Gell-Mann, Scale and Conformal Symmetries in Hadron Physics, ed. R. Gatto (Wiley, New York, 1973),
H. Fritzsch and M. Gell-Mann, Proc. XVI Internat. Conf. High Energy Phys., Chicago 1972, eds. J.D. Jackson and A. Roberts (Batavia, 1973) Vol. 2, p. 135.
For a brilliant review see E. Reya, Perturbative Quantum Chromodynamics, Physics Reports 69, No 3, p. 195 (1981).

7) H. Georgi and S.L. Glashow, Phys. Rev. Letters 33, 438 (1974),
also H. Fritzsch and P. Minkowski, Ann. Phys. (N.Y.) 93, 222 (1975)

8) F. Gürsey et al., Phys. Letters 60B, 177 (1976), and Phys. Rev. Letters 36, 775 (1976),
P. Sikivie and F. Gürsey, Phys. Rev. D16, 816 (1977).

9) M. Gell-Mann, P. Ramond, and R. Slansky, Rev. Mod. Phys. 50, 721 (1978).

10) J. Wess and B. Zumino, Nucl. Phys. B70, 39 (1974), and Phys. Letters B66, 361 (1977).
For a review see P. Fayet and S. Ferrara, Supersymmetry, Physics Reports 32, No 5, 249 (1977).
For the experimental consequences see P. Fayet, Phys. Letters 69B, 489 (1977), 84B, 421 (1979), 86B, 272 (1979), and in Unification of Fund. Part. Interact, ed. S. Ferrara et al. (Plenum, New York, 1980) p. 587,
G.R. Farrar and P. Fayet, Phys. Letters 76B, 575 (1978), 79B, 442 (1978), and 89B, 191 (1980).

11) L.B. Okun, Contribution to this Conference.

12) P.W. Higgs, Phys. Rev. Letters 13, 508 (1964), and Phys. Rev. 145, 1156 (1966)
also F. Englert and R. Brout, Phys. Rev. Letters 13, 321 (1964) and Nuovo Cimento 43A, 244 (1966).

13) S. Weinberg, Phys. Rev. Letters 40, 223 (1978), also Phys. Letters 82B, 387 (1979).

14) F. Wilczek, Phys. Rev. Letters 40, 279 (1978).

15) R.D. Peccei and H.R. Quinn, Phys. Rev. Letters 38, 1440 (1977), and Phys. Rev. D16, 1791 (1977).

16) A.A. Belavin, A.M. Polyakov, A.S. Schwartz and V.S. Tyupkin, Phys. Letters 59B, 85 (1975);
G. 't Hooft, Phys. Rev. Letters 37, 8 (1976), Phys. Rev. D14, 3432 (1976).

17) W.A. Bardeen and S.H.H. Tye, Phys. Letters 74B, 229 (1978).

18) W.A. Bardeen, S.H.H. Tye, and J. Vermaseren, Phys. Letters 76B, 580 (1978).

19) T.W. Donnelly et al., Phys. Rev. D18, 1607 (1978).

20) I. Antoniadis and T.N. Truong, Ecole Pol. Preprint (1981).

21) G. Micelmacher and B. Pontecorvo, Nuovo Cimento Letters 21, 441 (1978).

22) D.J. Bechis et al., Phys. Rev. Letters 42, 1511 (1979).

23) See H. Faissner et al., Phys. Letters 96B, 201 (1980), and refs. quoted therein.

24) J. LoSecco et al., Phys. Letters 102B, 209 (1981).

25) J.L. Vuilleumier et al., Phys. Letters 101B, 341 (1981).

26) A. Zehnder, Phys. Letters 104B, 494 (1981).

27) CERN Courier (May 1981) p. 161.

28) H. Faissner, Proc. Internat. Neutrino Conf. Erice, 1980, to be published. - Available as Aachen Report PITHA 81/03 (1981).

29) H. de Witt, Doctoral Thesis, Aachen Tech (1981), to be published.

30) H. Faissner et al., Phys. Rev. Letters 41, 213 (1978).

31) H. Faissner, Proc. XVI Rencontre du Moriond at Les Arcs (1981), ed. Tran Thanh Van, in press. Available as Aachen Report PITHA 81/20 (1981).

32) H. Faissner, Proc. Int. Neutrino Conf. Maui 1981, ed. R.J. Cence (Hawaii), in press, available as Aachen Report PITHA-81/32 (1981).

33) H. Faissner, E. Frenzel, W. Heinrigs, A. Preussger, D. Samm, and U. Samm, Phys. Letters 103B, 234 (1981).

34) W. Heinrigs, Doctoral Thesis, Aachen Tech (1981), to be published.

35) D. Samm, Master Thesis, Aachen Tech (1981), to be published.

36) A. Preussger, Master Thesis, Aachen Tech (1980), Internal Aachen Report 81/03.

37) W.R. Ermer, H. Faissner, E. Frenzel, E. Hermens, H.R. Koch, O. Schult, H. Seyfarth, and R. Yogeshwar, Proc. Sympos. on (n,γ) Reactions and Related Topics, Grenoble (1981), ed. T. von Egidy, in press.

38) R. Wilson and J. Selinger, Harvard pre-print (1981), and private communication.

39) E. Frenzel, and H. Bechteler, private communication.

40) S. Barshay, H. Faissner, R. Rodenberg, and H. de Witt, Phys. Rev. Letters 46, 1361 (1981).

41) H. Faissner et al., Z. Physik C10, 95 (1981).

42) Aachen-Padova, unpublished. The data were analysed by M. Grimm and L.M. Sehgal, and I am very indebted to them for discussions and help.

Discussion:

W. L. Mo, Virginia Polyt. Institute

In your SIN experiment I noticed that you installed additional steel shielding at the beginning of the decay volume. Did the event rate change,or remained it constant?

H. Faissner

The normalized rate of both, 1γ and 2γ events, did change by a factor of about three. However, this corresponds to respectively, 1.6 and 2.1 standard deviations only, and is hence compatible with a statistical fluctuation. More important: even after the additional iron there is a significant small angle effect left (see Table I).

O. Nachtmann, University of Heidelberg

I should like to point out that you can couple the muon to the axion with 1/X, and then the muon pair signal would be greatly reduced. Maybe Kleinknecht can also say something on the dimuons observed in the CDHS-experiment.

H. Faissner

If I may answer directly: We have taken already this coupling, the one which makes the expected signal smaller. This eliminates a discrepancy with the old SLAC-experiments, but I am not yet sure if it gives a quantitative fit to our data.

K. Kleinknecht, University of Dortmund

The dimuon production in the CDHS beam dump and antineutrino exposures is at variance with an axion coupled with the Higgs-Parameter X = 3 to muons, even if the muon is coupled to the axion with 1/X.

H. Faissner

I rather doubt that! This argument hinges on the axion production cross section, to which, in principle, axion-pion and axion-η-meson mixing may contribute, as well as axion bremsstrahlung from the electromagnetic cascade. It is presently one of our main worries, to disentangle these components in the "neutrino beam-dump", the possible axion source in the AC-PD experiment.

K. C. Königsmann, SLAC

I would like to point out that the Crystal Ball Collaboration has looked for the axion in radiative ψ-decays. From the absence of any signal an upper limit on the Higgs-Parameter X can be placed: $X < 0.88$. This has strong implications for the interpretation of the SIN experiment: the mass of the axion is only correct to a factor of about two, as you have to take the inverse of X: $X \cong 0.3$. Thus the coupling to pions is not negligible. As the Jülich experiment measures the axion mass directly, this result is correct.

H. Faissner

Well, the axion mass by itself is allright, since it depends on $(X + X^{-1})$. Thus, X and 1/X are exchangeable here, and actually also in the isoscalar coupling, we used to describe the SIN experiment. The trouble starts, when we try to link our achion/axions to leptons - e.g. to $\bar{\mu}\mu$-pairs. (Note added in writing up: With increasing understanding of the possible axion production processes in the AC-PD experiment, these difficulties appear to lighten.) But for any interpretation you need a long chain of theoretical arguments. John Ellis from CERN has warned us all the time that we might run into discrepancies with somebody or another. However, Ellis said also: 'Don't worry, we shall make the axion slightly non-classical, we twiddle a little with the couplings, and we shall fix you up!"

K. Kleinknecht

I have not yet understood the evidence from Jülich. I saw these gamma-spectra, but there was apparently a Co^{60} source in there - I just saw a cobalt-peak ...

H. Faissner

There is, of course, some iron around, in particular in our multiplier-holdings and so on and so forth, and since we are close to the reactor we make Co^{60}. And the Co^{60} gamma rays at respectively 1.17 and 1.33 MeV show up in the single spectra as peaks, which I had no time to explain. They are very nice, since we use them to check the stability of our system. Also you can see that their energy difference of ≈ 10% is easily resolved; this means our resolution is better than that. When you do the reactor ON - reactor OFF subtraction they go away, because Co^{60} has a lifetime which is very long. The only trouble is, you have a higher error on your difference in the Co^{60} bins, which we properly put in. But the reactor effect is just what it is; it has a soft spectrum, but in counter B it shows up at energies higher than the Co^{60}-lines (see Figs. 6 and 7, a!), and is not affected by them at all!