A VIABLE AXION MODEL

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It is discussed whether an axion-like excitation can be the source for the monoenergetic positrons observed at GSI. Although a direct extension of the original Peccei–Quinn model is experimentally ruled out, it is possible to construct an alternative model which avoids all previous axion bounds, involving quarkonia decays, K decays, nuclear decays and beam-dump experiments. The model predicts, at some level, the possibility of flavor-changing interactions involving charmed quarks and suggests an appealing regularity for the quark and lepton masses. The expectations of the model for resonant e^+e^- scattering are briefly discussed.

The production of positrons in collisions of superheavy ions is a phenomena predicted long ago [1], which has received rather recent experimental confirmation at GSI in Darmstadt. Rather remarkably, these experiments have observed, besides a continuum distribution in positron energies, a sharp positron peak at $E_+ \sim 300$ keV [2]. Such a sharp energy peak could result if an elementary excitation were produced essentially at rest in the heavy ion collision, and then subsequently decayed into e^+e^- pairs. This interpretation has gained credence very recently with the report of the observation of correlated e^+e^- pairs at GSI [3]. Taken at face value, these latest observations are consistent with the production of a particle of mass $M \sim 1.6$–1.7 MeV which then decays into e^+e^- pairs.

The existence of a particle of such low mass begs for an explanation. The most natural supposition is that the particle observed at GSI is an axion. As is well known, if one tries to avoid the appearance of *CP* violation in strong interactions via the imposition of an appropriate chiral symmetry [4], there must arise an almost massless pseudoscalar excitation, the axion [5,6]. In the original model proposed by Peccei and Quinn [4], to avoid strong *CP* violation, all properties of the axion are fixed up to an overall parameter x. However, irrespective of the value of this parameter, this standard axion model is ruled out by experiment [‡1]. This is particularly true if one wants to identify the GSI excitation with the standard axion. In this case, the parameter x must either be of O(20) or $O(\frac{1}{20})$ and one runs immediately into trouble with previous axion searches.

Even though the standard axion model cannot account for the GSI excitation, it is reasonable to ask whether a simple extension of the Peccei–Quinn model can produce a viable axion model. If one restricts oneself to models where flavor-changing Higgs-induced transitions are ***automatically*** excluded, the answer appears to be negative. However, rather remarkably, there exists a simple model which, although it has some flavor-changing Higgs transitions, appears to be perfectly viable phenomenologically. The main purpose of this note is to discuss this alternative axion model.

It is useful to recall a few properties of the standard axion and the reasons why it can be ruled out. To implement the chiral $U(1)_{PQ}$ symmetry one includes two distinct Higgs fields in the standard model: ϕ_1 which couples to up-like quarks and ϕ_2 which

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couples to down-like quarks. If Q_{Li} are the usual quark doublets of different generations i, then the Yukawa couplings

$$\mathcal{L}^{\mathrm{PQ}}_{\mathrm{Yukawa}} = \Gamma^{\mathrm{u}}_{ij}\bar{\mathrm{Q}}_{\mathrm{L}i}\phi_1 \mathrm{u}_{\mathrm{R}j} + \Gamma^{\mathrm{d}}_{ij}\bar{\mathrm{Q}}_{\mathrm{L}i}\phi_2 \mathrm{d}_{\mathrm{R}i} + \mathrm{h.c.} \quad (1)$$

are invariant under the chiral $\mathrm{U(1)_{PQ}}$ transformation

$$\mathrm{Q}_{\mathrm{L}i} \to \mathrm{e}^{-\mathrm{i}\alpha}\mathrm{Q}_{\mathrm{L}i},$$

$$\mathrm{u}_{\mathrm{R}i} \to \mathrm{e}^{\mathrm{i}\alpha}\mathrm{u}_{\mathrm{R}i}, \quad \mathrm{d}_{\mathrm{R}i} \to \mathrm{e}^{\mathrm{i}\alpha}\mathrm{d}_{\mathrm{R}i}, \quad (2)$$

provided that

$$\phi_1 \to \mathrm{e}^{-2\mathrm{i}\alpha}\phi_1, \quad \phi_2 \to \mathrm{e}^{-2\mathrm{i}\alpha}\phi_2. \quad (3)$$

If f_i is the vacuum expectation of ϕ_i and $x = f_2/f_1$, then one can show that the axion mass is given by [8]

$$m_{\mathrm{a}} \simeq 75\ (x + 1/x)\ \mathrm{keV}, \quad (4)$$

and that the axion couples to quarks as

$$\mathcal{L} = (m_{\mathrm{q}}/f)\bar{\mathrm{q}}\mathrm{i}\gamma_5\mathrm{q}\mathrm{a}\cdot x,$$

$$\mathcal{L}_{\mathrm{agg}} = (m_{\mathrm{q}}/f)\bar{\mathrm{q}}\mathrm{i}\gamma_5\mathrm{q}\mathrm{a}\cdot x^{-1}, \quad (5)$$

where the top line above applies to charge 2/3 quarks and the bottom line above applies to charge $-1/3$ quarks. Here $f = (f_1^2 + f_2^2)^{1/2} \sim 250$ GeV, is the scale parameter related to the $\mathrm{SU(2)\times U(1)\to U(1)_{em}}$ breakdown: The coupling of the standard axions to leptons depends on whether one decides to use ϕ_2 or $\tilde{\phi}_1 = \mathrm{i}\tau_2\phi_1^*$ in the lepton Yukawa couplings. The former, more conventional choice, leads to an axion coupling proportional to x^{-1}. If $m_{\mathrm{a}} > 2m_{\mathrm{e}}$, one readily computes the lifetime of the axion, into the $\mathrm{e^+e^-}$ mode, as

$$\tau(\mathrm{a}\to\mathrm{e^+e^-}) = 8\pi f^2 x^2/m_{\mathrm{e}}^2\,(m_{\mathrm{a}}^2 - 4m_{\mathrm{e}}^2)^{1/2}, \quad (6)$$

There are five pieces of evidence that have a bearing on a possible standard axion of mass 1.7 MeV: (i) searches for the decay $\psi\to\gamma\mathrm{a}$; (ii) searches for the decay $\Upsilon\to\gamma\mathrm{a}$; (iii) searches for the decay $\mathrm{K^+}\to\pi^+\mathrm{a}$; (iv) searches for axions in beam-dump experiments; (v) searches for axions in nuclear deexcitations. Because of the axion mass formula (4), either x or x^{-1} must be very large. Then some of the above experiments definitely rule out the axion. Using $m_{\mathrm{c}} = 1.4$ GeV, $m_{\mathrm{b}} = 4.9$ GeV in the Wilczek formula for quarkonia decays [6] one predicts

$$B(\psi\to\gamma\mathrm{a}) = (4.9 \pm 0.8)\times 10^{-5}\, x^2, \quad (7a)$$

$$B(\Upsilon\to\gamma\mathrm{a}) = (2.7 \pm 0.7)\times 10^{-4}\, x^{-2}, \quad (7b)$$

while experimentally the present bounds are [9]

$$B(\psi\to\gamma\mathrm{a}) < 1.4\times 10^{-5}, \quad (8a)$$

$$B(\Upsilon\to\gamma\mathrm{a}) < 3\times 10^{-4}. \quad (8b)$$

Obviously for x, or x^{-1}, around 20 one of these experiments is way below the prediction of the standard axion ‡2. The decay $\mathrm{K^+}\to\pi^+\mathrm{a}$ is rather model dependent, since it involves a non leptonic weak decay. If, as it appears reasonable, one calculates it via the diagram of fig. 1 one has [10]

$$B(\mathrm{K^+}\to\pi^+\mathrm{a}) \simeq 0.8\times 10^{-6}\, x^2 A(m_{\mathrm{c}}, m_{\mathrm{t}}), \quad (9a)$$

where the function $A(m_{\mathrm{c}}, m_{\mathrm{t}})$, which is given in ref. [10], is of O(1). This branching ratio is also above the present KEK limit [11]

$$B(\mathrm{K^+}\to\pi^+\mathrm{a}) < 3.8\times 10^{-8}, \quad (9b)$$

unless x is very small. In beam dump experiments, one can also rule out the existence of the standard axion by about a factor of 10^2, in rate [12]. These bounds can only be avoided if the axion decays sufficiently rapidly so as never to reach the dump. From eq. (6) one has

$$\tau(\mathrm{a}\to\mathrm{e^+e^-}) \simeq 2.9\times 10^{-9}\, x^2\ \mathrm{s}, \quad (10)$$

so for $x^{-1} \sim 20$ one may avoid these bounds, provided the γ factor is not too large. Nuclear deexcitation can proceed via axion emission. However, most axion bounds obtained this way previously [7], are not relevant for axions as heavy as 1.6–1.7 MeV. A notable exception is the experiment of Calaprice et al. [13], which looked for axions originating in the 15.1 MeV

‡2 These bounds assume that the axion did not decay in the apparatus. For a 1.6 MeV axion, there could be a relatively fast $\mathrm{e^+e^-}$ decay mode. However, because the γ factor is so large essentially the stable axion bounds apply.

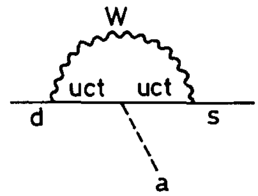

Fig. 1. d–s transition with axion emission.

$1^+, 1 \to 0^+, 0$ and in the 12.7 MeV $1^+, 0 \to 0^+, 0$ transitions in ^{12}C. This experiment was specifically set up to look for the $a \to e^+e^-$ mode and did not find it. However, this negative result can be avoided by having a very short e^+e^- lifetime ($x^{-1} \sim 20$ in eq. (10)). This same comment applies for the experiment of Faissner et al. [14], who also looked for a direct e^+e^- signal in a beam-dump experiment at SIN.

To make a viable axion model, it is necessary to weaken the coupling of the axion to *both* charm and bottom quarks, to substantially decrease the $K^+ \to \pi^+ a$ decay rate and to have a sufficiently short-lived axion that the other experiments are rendered irrelevant. All these requirements cannot be met if one insists on having a model where *no* flavor-changing Higgs transitions appear. To avoid flavour-changing transitions one must couple only *one* kind of Higgs to the charge 2/3 and charge −1/3 quarks. Hence the only extension of the Peccei–Quinn model that is allowed is to introduce yet a different Higgs field ϕ_3, which couples to the leptons [‡3]. This Higgs field must have a different $U_{PQ}(1)$ charge than the fields ϕ_1 and ϕ_2 in eq. (1). To avoid accidental degeneracies, in fact, the PQ charge of ϕ_3 either must vanish or it is three times the PQ charge of ϕ_1 and ϕ_2. It is straightforward to check in these models that, even though the coupling of the axion to charm and bottom quarks is different than that of the standard axion, one still runs into trouble. Instead of eq. (5) one finds now that the factors x, x^{-1} are replaced by

$$x \to A, \quad x^{-1} \to B, \tag{11}$$

where A and B are functions of ratios of the three expectation values in the theory: f_1, f_2 and f_3. However, now instead of by eq. (1), the axion mass is

$$m_a \simeq 75(A + B)\ \text{keV}. \tag{12}$$

Therefore, it is impossible to have $m_a \sim 1.6$–1.7 MeV and not violate one of the bounds (8).

To obtain a viable minimal extension of the axion model, it is necessary to couple both the c_R and b_R quarks to the *same* Higgs field, so that the charmonium and bottomonium bounds can be both simultaneously suppressed. Furthermore, since the limits on strangeness-changing neutral processes are extremely tight, it behooves one to automatically forbid these processes, by coupling d_R, s_R and b_R all to the same Higgs field. To be able to have the possibility of a Peccei–Quinn symmetry either u_R or t_R or both must couple to a second Higgs field. Three possible models ensue, typified by the Yukawa interactions

$$\mathcal{L}_{\text{Yukawa}} = \Gamma^{d}_{ij}(\bar{Q}_{Li}\phi_2 d_{Rj}) + \Gamma^{c}_{i}(\bar{Q}_{Li}\tilde{\phi}_2 c_R) + \Gamma^{u}_{i}(\bar{Q}_{Li}\phi_3 u_R) + \Gamma^{t}_{i}(\bar{Q}_{Li}\phi_4 t_R) + \text{h.c.}, \tag{13}$$

with

$$\phi_3 = \phi_1, \quad \phi_4 = \tilde{\phi}_2 \quad \text{(Model I)},$$

$$\phi_3 = \tilde{\phi}_2, \quad \phi_4 = \phi_1 \quad \text{(Model II)},$$

$$\phi_3 = \phi_1, \quad \phi_4 = \phi_1 \quad \text{(Model III)}. \tag{14}$$

In both models I and II only one pair of quarks has a chiral $U_A(1)$ anomaly, while in model III two pairs of quarks have this anomaly. Hence the axion mass in these models is

$$m_a^{\text{I,II}} \simeq 25\,(x + 1/x)\ \text{keV},$$

$$m_a^{\text{III}} \simeq 50\,(x + 1/x)\ \text{keV}, \tag{15}$$

where x is again the ratio of f_2/f_1 – the ratio of the Higgs vacuum expectation values [‡4].

Since we want to suppress both charmonium and bottomonium decay we must choose x large, *not* x^{-1} large. ($x \sim 70$ for models I, II; $x \sim 35$ for model III). At first sight, such large x values appear to be problematic for the $K^+ \to \pi^+ a$ decay. However, the value quoted in eq. (9a) is due to the contribution of the *charmed* quark. The u-quark contribution in fig. 1 is suppressed by a factor $(m_u/m_c)^4$ and thus is totally negligible, even for a very large value of x. The charmed quark contribution in the new axion model, because of the assignment (13), is now proportional to x^{-2}, *not* x^2, and thus also negligible. The contribution of the t-quark in fig. 1 should normally be small, since it involves both an s–t and a d–t transition. However,

‡3 One can also, in principle, add other Higgs fields that do not couple to the fermions. These fields, however, do not help to make the axion heavier than the standard axion and so are not very useful.

‡4 The possibility of constructing axion models with asymmetrical quark couplings, as done here, was first pointed out long ago by Bardeen and Tye [8].

if $x \sim 70$ and the t-quark contribution is enhanced by x^2 (model II and model III) one might run into trouble. Hence model I, where this contribution is also suppressed by x^{-2}, is safer [‡5].

Although the contribution of fig. 1 is very small in model I, one should worry about other possible contributions to the decay $K^+ \to \pi^+ a$. This matter is rather subtle and there exists a variety of widely separated estimates in the literature for this decay rate. Essentially one tries to relate the $K^+ \to \pi^+ a$ decay to that of $K^+ \to \pi^+ \pi^0$ decay by estimating the amount of a–π^0 "mixing". Naively this gives

$$B(K^+ \to \pi^+ a) \simeq [(f_\pi/f)\, x m_u/(m_u + m_d)]^2 B(K^+ \to \pi^+ \pi^0)$$

$$\simeq 2 \times 10^{-5},$$

which is much above the KEK bound of eq. (9b). However, a more careful treatment of the problem [15] shows that there is an almost total cancellation and that $B(K^+ \to \pi^+ a)$ is *essentially unrelated* to the $K^+ \to \pi^+ \pi^0$ decay. Hence, although a direct estimate of the remaining contributions for $K^+ \to \pi^+ a$ is difficult, we expect this branching ratio to be much below 10^{-6}–10^{-7}. At any rate, it should be pointed out that the KEK bound of eq. (9b) is not relevant here. This bound is obtained assuming that the axion did not decay in the apparatus. In our case, the axion decays very rapidly into e^+e^- pairs (see below), so that the bound of eq. (9b) is irrelevant. To our knowledge even a branching ratio $B(K^+ \to \pi^+ a) \sim O(10^{-6})$, with the axion decaying rapidly into e^+e^- pairs, is allowed experimentally. The very low branching ratio for the process $K^+ \to \pi^+ e^+ e^-$, $B(K^+ \to \pi^+ e^+ e^-) = (2.7 \pm 0.5) \times 10^{-7}$ [16] has a cut on $M_{e^+e^-} < 140$ MeV, while the KEK bound on $K^+ \to \pi^+$ anything [17], $B(K^+ \to \pi^+ \text{ anything}) < 2 \times 10^{-6}$ has a cut on $M_{\text{anything}} < 5$ MeV. It remains to consider the other experiments. Clearly, to avoid troubles one needs a fast decay of $a \to e^+e^-$. If e_R couples to ϕ_2, as assumed in the standard axion model, one is led to a lifetime proportional to x^2 (cf. eq. (10)) which is much too long to avoid the nuclear deexcitation and beam-dump bounds. Hence, it is necessary to assume that the electron couples to $\tilde{\phi}_1$, so that

$$\tau(a \to e^+e^-) \simeq 2.9 \times 10^{-9}\, x^{-2}$$

$$\simeq 6 \times 10^{-13} \text{ s}, \qquad (16)$$

where the numerical value corresponds to the case of model I. Even for γ factors of 10^4, the decay distance is of order of 2 meters, so that no axions get to the dump [12]. Such a lifetime would have also given no visible signal in the Calaprice et al. [13] experiment, which we hope can be repeated taking (16) into account.

We have succeeded in constructing an axion model, where for $m_a \simeq 1.6$–1.7 MeV, one does not run into any trouble with previous axion searches. Two questions need to be answered: (1) Does this model reproduce the GSI data? and (2) Does the model have other predictions or potential troubles? We are presently studying the first issue and shall report on it elsewhere [18]. The problem is not so much the rate, but trying to produce axions essentially at rest in the heavy ion collision. For our model one can readily compute the production cross section due to axion bremsstrahlung at GSI. One finds a cross section which is qualitatively in agreement with the magnitude of the observed effect, but the produced axions have a considerable momentum distribution (a few MeV in width). With such a momentum spectrum, positrons produced from axion decay would never give a sharp energy peak. This difficulty, however, is not unique to our case but is more generally true. The typical collision time for Rutherford scattering at GSI is far too short to "allow" the appearance of such narrow positron peaks [19]. Thus, to reproduce the data, in all cases one must presume that some – yet to be understood dynamics – somehow slows down the relevant production process.

We conclude this note by making some observations on the second point. First we consider a prediction of the model.

The necessity of having an enhanced electron coupling to axions

$$\mathcal{L}_{a\bar{e}e} = (m_e/f)x \cdot \bar{e} i \gamma_5 e a \qquad (17)$$

may make it possible to be able to directly observe axion production in an e^+e^- storage ring, particularly constructed for these purposes [20]. At the resonance, the e^+e^- integrated cross section is given by

‡5 Both models II and III, if they are able to survive the $K^+ \to \pi^+ a$ bounds, are very amusing, since they predict that toponium *primarily* decays into aγ.

$$\int \sigma_{e^+e^-} dE = 2\pi^2\Gamma_{ee}/m_a^2 = \tfrac{1}{4}\pi(m_e/m_a)^2 [(m_a^2 - 4m_e^2)^{1/2}/f^2] x^2 \simeq 0.6x^2 \text{ mb eV} \simeq 3000 \text{ mb eV}. \quad (18)$$

This cross section is isotropic, so that restricting oneself to the backward direction where the background is much smaller only reduces the signal by 50%. Since the Bhabha cross section in the backward direction at $\sqrt{s} = m_a$ is roughly 80 mb, if one could achieve an energy resolution in the eV range the axion signal would be well above background. Whether this is actually technically feasible is at the moment not clear, although it is not totally out of the question [20]. How one would scan for such an effect is also not resolved at present.

This new axion model does have a potential particle-physics problem. Since one couples two distinct Higgs fields to the charge 2/3 quarks, one cannot automatically guarantee that there are no flavor-changing couplings involving the axion and charge 2/3 quarks. In particular, one expects an effective coupling

$$\mathcal{L}_{FC} = (m_c/f)V_{cu}\bar{c}i\gamma_5 ua + \text{h.c.}, \quad (19)$$

where V_{cu} is an unknown mixing angle. Requiring that the transition $c \to ua$ be smaller than the normal c weak decays puts a bound on V_{cu} which is rather stringent [‡6].

$$V_{cu} \lesssim 5 \times 10^{-4}. \quad (20)$$

It is easy, however, to construct "toy" mass matrices which lead to such a small value. Typically, one finds $V_{cu} \sim x(m_u/m_c)^2$, which is of the right order of magnitude. Our impression at the moment is that this problem is probably not serious. Because the up-quark mass-matrix has very large numerical ratios among its eigenvalues, one should perhaps not be so bothered by a limit like (20).

There is an analogous problem in the leptonic sector. One could imagine that also the μ_R and the τ_R fields couple to the $\tilde{\phi}_1$ Higgs field, so that no intraleptonic transitions involving axions ensue. However, the coupling

$$\mathcal{L}_{a\bar{\mu}\mu} = (m_\mu/f)x \cdot \bar{\mu}i\gamma_5\mu a, \quad (21)$$

for x large, leads to too large a $(g-2)$ contribution. From the limits on possible $(g-2)$ discrepancies [22] in fact one finds that, if (21) holds then $x \lesssim 3.7$ [‡7]. Hence, it is necessary that μ_R couples to ϕ_2 not $\tilde{\phi}_1$. Unless one imposes a discrete symmetry or chooses specific PQ assignments for the leptons or more directly requires separate e, μ and τ lepton conservation, in general one would find unacceptable decays of the type $\mu \to ea \to eee$, for which very stringent bounds exist [23].

The model we have been led to suggests an amusing numerological exercise concerning quark and lepton masses. The most natural pattern we have found is to couple all right-handed quarks to ϕ_2 (or $\tilde{\phi}_2$) except u_R and e_R which must be coupled to ϕ_1 and ϕ_1, respectively. Furthermore $f_1 \ll f_2$. This suggests that if instead of quark and lepton masses one looked at Yukawa couplings, one should naturally scale up the u and e masses by a factor of $f_2/f_1 \sim 70$. This factor is in fact too big. If one scales up m_u and m_e by a factor of 8 or so, then the ratios "m_u" : m_d : "m_e" to $m_c : m_s : m_\mu$ to $m_t : m_b : m_\tau$ all roughly agree, provided $m_t \sim 25$–30 GeV. Also the ratio of each family to the next is roughly 20. The significance of this observation, if it has any, is far from clear to us.

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‡6 A similar bound on V_{cu} also follows from the present experimental limit on $D-\bar{D}$ mixing [21], $\Delta M < 1.5 \times 10^{-4}$ eV.

‡7 A value of $x \sim 70$ is allowed by the $(g-2)$ anomaly of the electron.

References

[1] W. Pieper and W. Greiner, Z. Phys. 218 (1969) 327;
S.S. Gershtein and Y.B. Zeldovich, Lett. Nuovo Cimento 1 (1969) 835;
V.S. Popov, Sov. Phys. JETP 32 (1971) 526.
[2] J. Schweppe et al., Phys. Rev. Lett. 51 (1983) 2261;
M. Clemente et al., Phys. Lett. B 137 (1984) 41;
T. Cowan et al., Phys. Rev. Lett. 54 (1985) 761.
[3] T. Cowan et al., Phys. Rev. Lett. 56 (1986) 444.

[4] R.D. Peccei and H.R. Quinn, Phys. Rev. Lett. 38 (1977) 1440; Phys. Rev. D16 (1977) 1791.
[5] S. Weinberg, Phys. Rev. Lett. 40 (1978) 223;
[6] F. Wilczek, Phys. Rev. Lett. 40 (1978) 279.
[7] A. Zehnder, Proc. 1982 Gif-sur-Yvette Summer School.
[8] W.A. Bardeen and S.H. Tye, Phys. Lett. B 74 (1978) 229.
[9] See, e.g. S. Yamada, in: Proc. 1983 Lepton photon Symp. (Cornell University, August 1985).
[10] J.M. Frere, M.B. Gavela and J.A.M. Vermaseren, Phys. Lett. B 103 (1981) 129.
[11] Y. Asano et al., Phys. Lett. B 107 (1981) 159.
[12] P.C. Bosetti et al., Phys. Lett. B 74 (1978) 193;
J. Hansl et al., Phys. Lett. B 74 (1978) 139;
P.F. Jacques et al., Phys. Rev. D21 (1980) 1206.
[13] F.P. Calaprice et al., Phys. Rev. D20 (1979) 2708.
[14] H. Faissner et al., Phys. Lett. B 96 (1980) 201.
[15] R.D. Peccei and T. Yanagida, paper in preparation.
[16] P. Bloch et al., Phys. Lett. B 56 (1975) 201.
[17] T. Yamazaki et al., Phys. Rev. Lett. 52 (1984) 1089.
[18] G. Gelmini, R.D. Peccei, T.T. Wu and T. Yanagida, paper in preparation.
[19] A. Chodos and L.C.R. Wijewardhama, Phys. Rev. Lett. 56 (1986) 302;
J. Reinhardt et al., Phys. Rev. 33C (1986) 194.
[20] G. Voss and K. Wille, private communication.
[21] C. Biino et al., Phys. Rev. Lett., to be published.
[22] T. Kinoshita, B. Nizic and Y. Okamoto, Phys. Rev. Lett. 52 (1984) 717.
[23] W. Bertl et al., Nucl. Phys. B260 (1985) 1.