Possible Observation of Light Neutral Bosons in Nuclear Emulsions

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Electron-positron pairs apparently resulting from the decay of light intermediate neutral particles emitted in relativistic heavy-ion collisions have been reported by El-Nadi and Badawy. The events, observed in nuclear emulsions, are similar to data from 35 years ago that caused the π^0 lifetime estimate to be wrong by almost 2 orders of magnitude for about a decade. The data are consistent with the production and subsequent decay of short-lived neutral bosons with masses around 1.1, 2.1, and 9 MeV and with lifetimes of the order of 10^{-16}–10^{-15} s.

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Interest in the possible existence of light neutral particles has been revived with the surprising observations at Gesellschaft fur Schwerionenforschung (GSI), Darmstadt, of correlated e^+e^- pairs emitted in superheavy collision systems.[1] An explanation of these might be the production of elusive neutral particles with masses[2] between 1.5 and 1.9 MeV, for example, the axion.[3] In dedicated experiments[4,5] no evidence for a connection to axions was found. Recently a narrow peak at 1.062 MeV has been observed by a Stanford-Berkeley group[6] in the sum energy for collinear photon pairs resulting from U+Th heavy-ion collisions at 6 MeV per nucleon incident energy. Even more recent is a report from a Cairo group[7] on e^+e^- pairs produced in relativistic heavy-ion collisions (kinetic energy $\sim$3.5 GeV per nucleon) with emulsion nuclei, possibly showing indications for the creation and decay of light neutral bosons with average kinetic energies ($E=E_+ + E_-$) around 300 MeV, traveling distances (L) in the 5-65-μm range and partition asymmetry $y=\Delta E/E$, with $\Delta E = |E_+ - E_-|$, mostly near zero. The present paper summarizes a critical analysis and interpretation[8] of these last-mentioned data in confrontation with the literature and with reference to a striking puzzle in the early days of pion physics.

The Cairo data[7] involve 700 secondary interactions of mainly $Z=2$ fragments emitted from about 1400 ^{12}C and 1200 ^{22}Ne primary interactions at 4.5 and 4.2 GeV/c per nucleon incoming momentum. In total thirteen e^+e^- pairs were found at some distance from the vertex of the secondary interaction. In addition, seven pairs were identified in a study of 1600 primary interactions of α particles under the same conditions. The events from the secondary interactions are reported[7] to be consistent with the e^+e^- decay of a neutral boson with mass 1.6 ± 0.6 MeV and lifetime $(1.5 \pm 0.1) \times 10^{-15}$ s, while the pairs induced by primaries are considered as background. In view of the interesting ramifications we investigated these data in some detail. Contrary to Ref. 7 we do not distinguish between primary and seondary interactions and include all reported events equivalently in our analysis.

In principle, the Cairo e^+e^- pairs (Table I of Ref. 7) could arise from (i) Dalitz decay of π^0's and (ii) conversion of γ rays. The number of π^0's produced in the Cairo data set can be estimated[8] as typically less than unity. Then if we overestimate that the π^0's would have an average energy of 1 GeV, the mean π^0 decay length would be less than 0.2 μm. For the 2300 measurements with one π^0 per vertex on average, the probability to find even a single Dalitz pair removed from the vertex by more than 5 μm is negligible (3×10^{-8}).

The γ rays possibly responsible for the e^+e^- pairs, could have resulted either directly from the collision process or from the main decay mode of emitted π^0's. Direct photon production can be neglected relative to the production from $\pi^0 \to \gamma\gamma$ decay. The mean free path for conversion in emulsion is 5 cm and practically independent of energy.[9] Not more than typically two events are expected for the Cairo data set from γ rays due to π^0's within $\sim 65 \mu$m from the vertex. A lower cutoff at 50 MeV has been assumed as observational bias removing $\sim$50% of the pairs.[8] This low number of background pairs is corroborated by the far from uniform neutral-path-length (L) distribution (twelve events below 20 μm, one with 20–40 μm, and five with 40–61 μm), resulting in a 3.8σ deviation from the expected uniformity in γ-ray induction. In addition, the absence of observations in the upper half of the 0–120-μm interval[7] (the field diameter of the microscope) while twenty pairs are found in the lower part, would imply a more than 4σ deviation, with the assumption of no observational bias. Moreover, the strong prevalence towards equal energy partition corresponds to a 3.7σ effect with respect to the expected distribution for γ rays.[9] The reduced opening angle ($x=\omega/\omega_0$), where ω_0 is the most probable angle[9] (in degrees) $=117/E$ (in megaelectronvolts) for photon-induced pairs has for a group of five (out of twenty) events each a more than 2.5σ deviation from the normalized γ ray distribution. Altogether we have to conclude

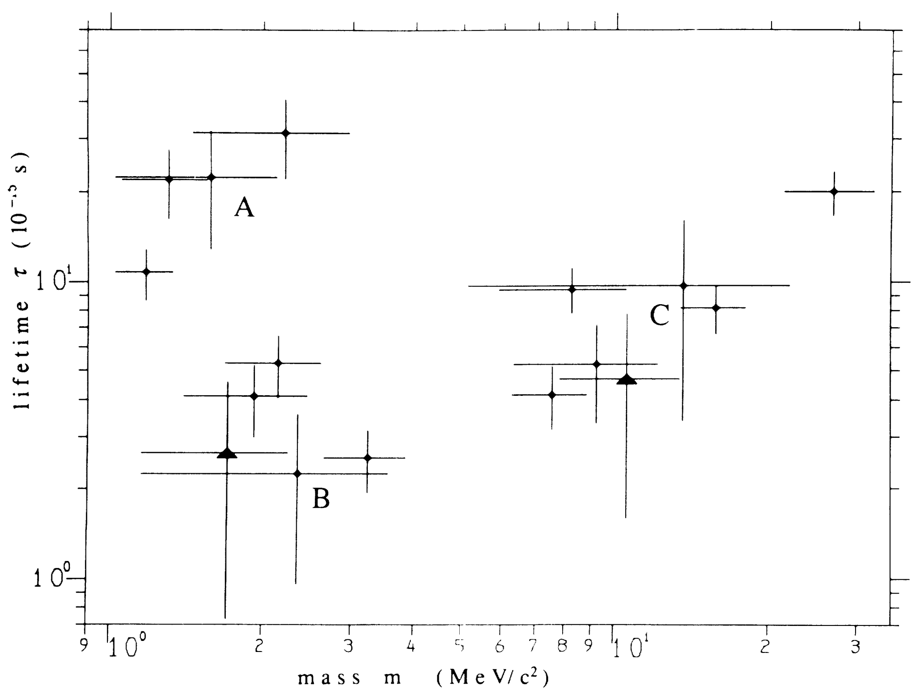

FIG. 1. Plot of mass vs lifetime for the fourteen complete Cairo events showing clusters A, B, and C. Triangles represent individually specified (Ref. 10) Bristol events.

that both the estimated number and the kinematic details of the Cairo events make it unlikely that more than just a few of them are due to γ conversion.

In a speculative scenario where the Cairo pairs arise from two-body decay of neutral bosons, the mass (m) and lifetime (τ) of the intermediate particles can be calculated straightforwardly for the fourteen complete events, with E_+, E_-, and ω measured. The resulting values with appropriately calculated errors[8] are two-dimensionally displayed in the mass-lifetime plot of Fig. 1. In this (m,τ) plane a remarkable three-cluster structure shows up. Five remaining (incomplete) events support a related cluster structure in the (L,ω) plane.[8] An event at 27 MeV, not obviously related to one of the clusters, is presently ignored. For the different clusters in the error-weighted mass and lifetime averages are

Cluster	m (MeV)	τ (10^{-16} sec)
A	$1.14^{+0.18}_{-0.07}$	13 ± 3
B	2.1 ± 0.4	3.0 ± 0.5
C	9.2 ± 1.4	6.0 ± 1.0

The three clusters could be manifestations of three or more neutral objects. We notice that cluster A is consistent in energy and lifetime with a neutral system at 1.062-MeV invariant mass responsible for the $\gamma\gamma$ peak in the Stanford-Berkeley experiment.[6] If both (e^+e^- and $\gamma\gamma$) signals originate from a common source particle with mass just above threshold, the two possible decay branches would have been observed for nuclear collisions in widely different energy and mass regimes. Cluster B is compatible[2] with the GSI peaks (1.52, 1.63, 1.78, and 1.83 MeV). For cluster C, which is a more than 7σ anomaly[8] with respect to the ω dependence for γ-induced pairs (the aforementioned group of five events), we have no reference to existing data.

A recent review[11] on the discovery of the pion brought to our attention that during nearly a decade the lifetime of the π^0 was thought to be almost 2 orders of magnitude longer than the now well established value of 8.7×10^{-17} s. Measurements of e^+e^- pairs in nuclear emulsions bombarded by cosmic rays were analyzed by Anand from the Bristol group[10] on the basis of the assumption that these were "direct" π^0 (Dalitz) pairs. From the measured invisible path lengths for the 62 direct pairs, the π^0 lifetime was (as we know by now, incorrectly) deduced as 5×10^{-15} s. The fit by Anand to the path-length histogram is shown in Fig. 2 together with the curve for the correct π^0 lifetime and the normalization based on the estimate[10] of 7000 for the total number of π^0's and the known branching ratio of $(1.21\pm0.03)\%$ for the Dalitz decay. It is already apparent from this curve that at most a few events could be π^0 Dalitz pairs. Reduced ionization due to charge cancellation near the origin of the pairs could simulate or extend neutral path lengths. As estimated by Perkins[12] this effect for the data of Anand is less than 1 μm. With present-day

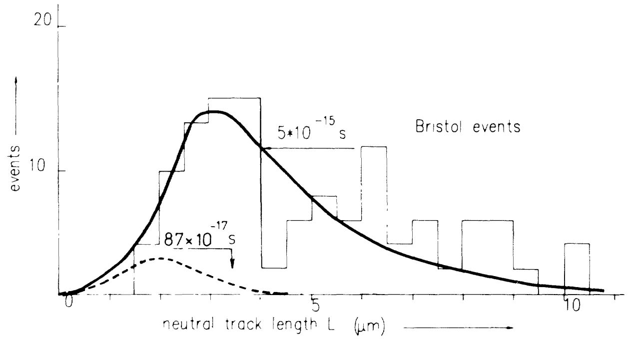

FIG. 2. Histogram of the 62 Bristol events (Ref. 10) vs the neutral path length (L), from which the π^0 lifetime was erroneously derived to be typically 5×10^{-15} s (drawn curve). The dashed curve corresponds to the now well established value of 8.7×10^{-17} s. Clearly, most of the events cannot be due to π^0 Dalitz decay.

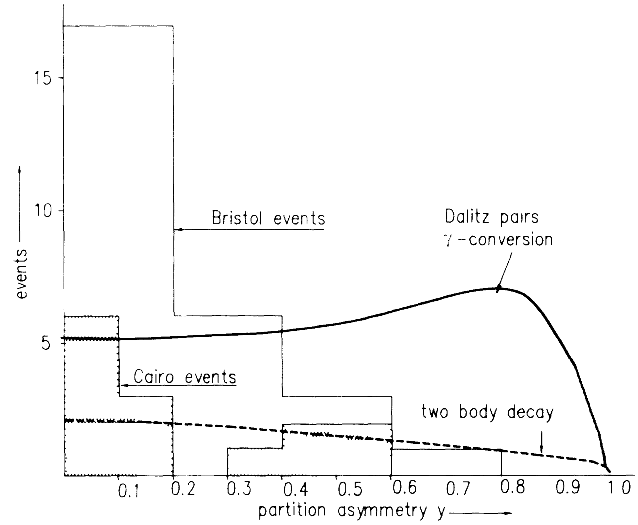

FIG. 3. A comparison of the energy partition symmetry $y=\Delta E/E$ with $\Delta E=|E_+-E_-|$ for the Cairo and Bristol pairs. The full curve is the distribution for Dalitz pairs, while the dashed curve gives the phase-space prediction for two-body decay.

knowledge the events with $L\geq 4$ μm cannot be ascribed to Dalitz decay but they are consistent with clusters B and C in the (L,ω) plane.[8] In Fig. 3 a histogram is shown for the energy-partition asymmetry (y) of the Bristol events, which has been copied from Ref. 10. It was already noted[13] in 1955 that the pairs from Anand have a strongly symmetrically peaked energy partition contrary to what was expected for Dalitz decay. The deviation (at the 7σ level) from the calculated y distribution[14] for Dalitz pairs as well for 300-MeV γ rays (which are roughly equal) is—after 35 years—-remarkable, particularly when confronted with the similar distribution of the Cairo events. However, both deviate from a calculated phase-space distribution for neutral-particle decays if we assume the mass and energy distribution from the Cairo data. If the strong symmetric peaking for both data sets would not be due to observational selectivity, the clusters B and/or C might arise from nonzero-spin (aligned) neutral-particle decay.

For two typical Bristol events full kinematics have been published.[10] We calculated in the scenario of two-body decay the mass-lifetime values and plotted these in Fig. 1 as triangles. We found it amusing that these events nicely fall in the cluster structure of the Cairo data.

If we conjecture that the above discussed clusters could represent previously unknown neutral objects, a confrontation with other experiments is called for. First we notice that other cosmic-ray studies in the fifties also yielded π^0 lifetimes of order 10^{-14}-10^{-15} s. The question arises why such neutrals would not also appear in the later measurements which gave the correct π^0 lifetime. In these experiments, though (in contrast to proton-nuclear collisions), selective π^0 production processes were used such as $K^+\rightarrow\pi^+\pi^0$ decay and (π^-,π^0) charge exchange. Any rare neutral-particle production is then easily overshadowed by the preferred π^0 production channel.

From the upper limit on any anomaly in the $g-2$ values of the electron, a lower limit[2] of 10^{-14} s can be derived for the lifetime of a light neutral pointlike particle. However, if two (or more) of these particles exist with opposite parity, the contributions to the $g-2$ value might cancel. In the simplest case that just two particles correspond to the clusters A and B, cancellation can only occur if we assume, respectively, negative and positive parity for a 1.1 and a 2.1-MeV particle.

A tighter lower bound[2] of order 10^{-15} s for the lifetimes of neutral—not necessarily pointlike—particles with masses of 1-2 MeV, follows from the absence of any anomaly in the positronium hyperfine splitting. This bound holds for pseudoscalar (0^-), vector (1^-), and axial-vector (1^+) particles, which all yield contributions of the same sign. Since scalar (0^+) particles are the only ones that do not contribute to the splitting, cluster B at the very short lifetime of 2.7×10^{-16} s, could only be consistent with scalar character. If the 1.1-MeV cluster is related with the Stanford narrow $\gamma\gamma$-sum peak, the latter branch requires a pseudoscalar character for the possibly associated particle. Surprisingly, a striking anomaly in the external pair production cross section above threshold is consistent[15] with a $\gamma\gamma$ resonance at 1.06 MeV decaying into e^+e^- pairs.

Tight upper limits are given for the lifetimes and masses of neutral particles on the basis of electron-beam dump experiments. Lifetimes as low as 5×10^{-15} s for 1-MeV and 10^{-13} s for 9-MeV particles can be excluded.[16] Particles with short lifetimes as given in the table above, though, are likely to have escaped detection in this study. Moreover, if the conjectured neutral particles are extended objects the bounds can be invalidated.[15]

A 9-MeV particle associated with the C cluster might still be a candidate for a nonstandard[3] axion (a). Except for two recent experiments most axion searches have been insensitive for its mass-lifetime combination. However, the nonobservation[5] of $\pi^+ \rightarrow ae^+\nu$ decay virtually excludes isovector axions; the upper limit of 4.5×10^{-7} for $K^+ \rightarrow a\pi^+$ decay[17] rules out coupling to strange quarks. Indeed, the lifetime for the 9-MeV cluster (0.84×10^{-15} s) is much closer to expectation[3] for a variant axion model with coupling only to the light flavors (2.5×10^{-15} s) than to the value for a model where it couples to two quark generations (10^{-14} s). In summary, if the 9-MeV boson represents an axion, it should have isoscalar character and a mere coupling to the light quarks.

It has been suggested[18] that the Stanford $\gamma\gamma$ peak[6] as well as the GSI e^+e^- peaks,[1] observed in heavy-ion collisions at typically few megaelectronvolts/nucleon beam energy, could represent different excitations of a single composite system. In spite of the much higher collision energy (few gigaelectronvolts/nucleon) it is tempting to postulate that the events discussed in this paper are manifestations of closely related—if not the same—phenomenon as behind the GSI and Stanford observations. It would certainly require more data, probably of the emulsion type, to testify on any of the here discussed indications for short-lived neutral particles.

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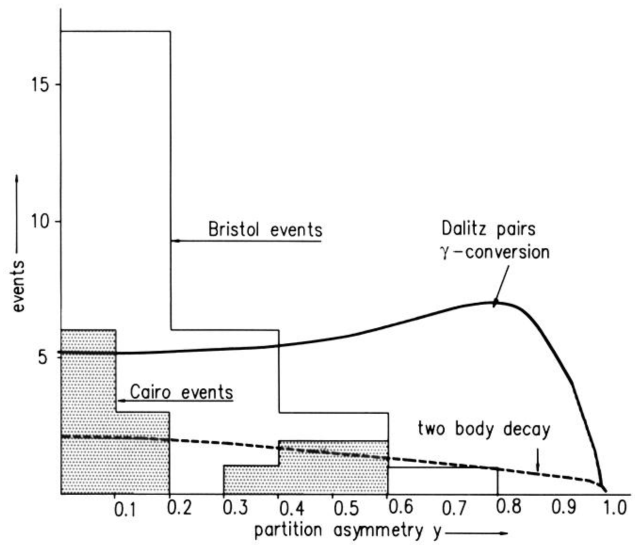

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