QUARKS, STRINGS, DARK MATTER, AND ALL THE REST

edited by R. S. Panvini and T. J. Weiler

VIIth Vanderbilt Conference on
Elementary Particle Physics

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Nashville, Tennessee
15–17 May 1986

edited by **R. S. Panvini and T. J. Weiler**

World Scientific

Published by

World Scientific Publishing Co Pte Ltd
P. O. Box 128, Farrer Road, Singapore 9128.

Library of Congress Cataloging-in-Publication data is available.

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ISBN 9971-50-272-0

Printed in Singapore by Kyodo-Shing Loong Printing Industries Pte Ltd.

PREFACE

The VIIth biennial Vanderbilt international conference on elementary particle physics was held at Vanderbilt University in Nashville, Tennessee, on May 15–17, 1986. The title of the conference, "Quarks, Strings, Dark Matter, and all the rest," reflects the growing eclecticism of the field of elementary particle physics, and accordingly, of the speakers' topics. On the experimental side, accelerators now compete with passive underground detectors and astronomical instruments for the discovery of new particles. On the theoretical side, energy scales from a fraction of the eV all the way up to the Planck mass (10^{28} eV) are contained in the same unification theories. The fields of high energy physics, astrophysics and cosmic ray physics have merged. DeRujula symbolized this helter-skelter union in a drawing he presented in his summary talk; the artwork is reproduced on the jacket of the proceedings.

It is not all clear to us where our field is headed (an interesting and challenging situation!) and so we chose topics to "cover almost all bases," as indicated in the conference title. The speakers were evenly split between experimenters and theorists, and between realists and futurists. Besides the physics presentations, the conference featured a banquet catered by Nashville's best caterer followed by the exceptional country honky-tonk piano and vocals of Nashville's own Becky Hobbs. The rapid pace of talks, infused with interludes of food and entertainment, prompted the comic relief of Tom Ferbel who remarked "what is this, a conference or a Jewish wedding?!" With all said and done, we think this was a highly stimulating conference.

The talks are ordered in an ascending order of energy scale. The arrangement is largely arbitrary in that some low energy processes are sensitive to very high energy mass scales.

Thanks go to our advisory committee: Larry Abbott, Ed Berger, Estia Eichten, Tom Ferbel, Ian Hinchliffe, and Paul Langacker suggested to us many of the speakers and topics. As with the past Vanderbilt conferences, the smooth functioning of the day-to-day organizing was almost entirely due to the skills and efforts of Doria Panvini. We are deeply in her gratitude, yet again. Finally, we acknowledge with thanks, the funding support from the Department of Energy, the National Science Foundation, and the Dean of the College of Arts and Science.

Robert S. Panvini and Thomas J. Weiler
Conference Chairmen
November 1986

CONTENTS

Phenomenology of e^+e^- events at GSI: axions and other goodies

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Abstract

I review the experimental results of the EPOS collaboration at GSI indicating the presence of correlated e^+e^- pairs with kinetic energy at about 370 KeV per particle, arising from collisions of different heavy ion systems at about 5.9 MeV per nucleon on stationary targets. I then discuss constraints on nuclear production mechanisms, new results on axion theory and experiment, and finally, experimental constraints on any new elementary scalar particle at 1.8 MeV which couples to electrons.

1. **The EPOS experiment:** The original EPOS spectrometer at GSI was designed to measure the positron spectrum resulting from the collisions of heavy ion beams on stationary thin film targets containing heavy atoms. The hope was that in such collisions, supercritical nuclear configurations would be formed with large enough nuclear charge so that the K shell binding energy would be greater than twice the rest mass of an electron. In this case pairs could be spontaneously created out of the vacuum[1], with the electron binding to the system and the positron being emitted. One of the expected signals for such a phenomenon is the large Z dependence of the rate for this process.[2] Thus, a system was designed which , for different combinations of beam and target, could observe the positron energy spectra emerging from the collision. Beam energies were chosen in the range of 6 MeV per nucleon, which would bring the colliding nuclei together just to their coulomb barriers. The original experimental configuration is shown in fig. 1 [3]:

[1] Also Visiting scientist, Smithsonian Astrophysical Observatory, and Boston University. Research supported in part by DOE contract* DE-AC02-76ERO 3075 and by a Presidential Young Investigator Award.

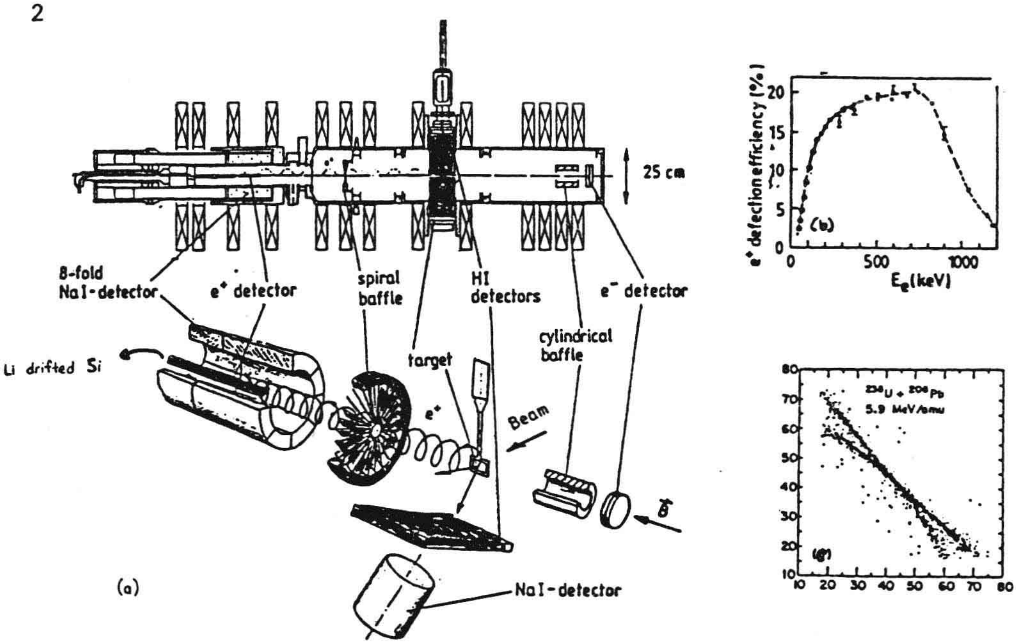

Fig 1: Original EPOS positron transport system

As can be seen here, the incoming beam is targeted on a thin foil, and the outgoing ions are then detected at scattering angles ranging from about 20^0-70^0 off the beam axis. This allows the kinematics of the collision to be determined in coincidence with the positron measurements and in particular, elastic scattering events fall on well-defined curves, as shown in figure 1(c) (for Uranium on lead). Perpendicular to the beam (z) direction, a magnetic field is set up which causes positrons initially travelling with components along either the positive or negative x axis to spiral along the -x direction, passing through a spiral baffle. This baffle is chiral, in the sense that electrons, which will spiral with the opposite chirality in this magnetic field, will not traverse the baffle. (Also very low energy particles are screened out) Finally, a Lithium drifted Silicon detector is located along the x axis, to detect the kinetic energy of the positrons. Because of its location, it is only intercepted by positrons which originate on this axis, which crosses the beam crossing point.

The major surprise of this experiment was the observation of a narrow peak in the positron spectra at around 350 KeV, which maintained its shape and location throughout different runs with different nuclear systems.[4] This phenomena was not suggestive of spontaneous "sparking" of the vacuum, because of its Z independence, but could have been due to some long-lived neutral particle or resonance of energy about 1.7 MeV being produced and subsequently decaying into electron-positron pairs.

To test this conjecture, and rule out others, the experiment was redesigned to measure both the electron and positron spectra in coincidence. The new configuration is shown below in fig. 2; ,

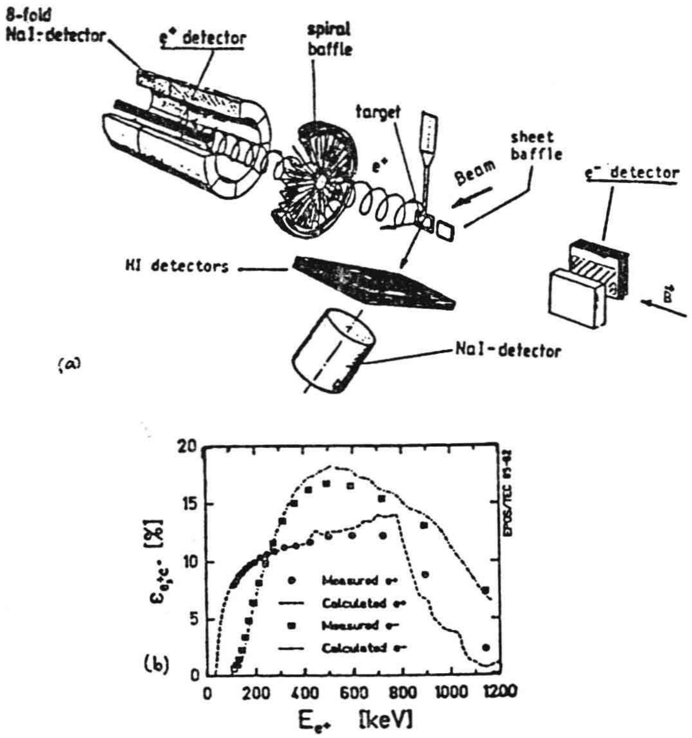

Figure 2: EPOS configuration for coincident e^+e^- measurements

In this new configuration the mirror magnetic field was replaced first by a a sheet baffle to reduce low energy electrons followed by a detector for electrons, located off axis to further reduce the background of narrow spiralling low energy particles. As also shown, the detection efficiency for electrons and positrons was comparable, and the positron energy resolution was 15 KeV, while the electron resolution was 35 KeV.

Using this apparatus, both electrons and positrons could be detected in coincidence with the outgoing heavy ions, with a timing resolution on the order of a nanosecond. The efficiency of detecting a coincidently emitted electron and positron pair compared detecting a positron alone varied from 15%, for correlated back to back emission, to 6% for spatially uncorrelated pairs.

In this new configuration a remarkable series of measurements were obtained. One such example, the kinetic energy spectrum of coincident e^+e^- pairs resulting from collisions of Uranium on Thorium is shown in figure 3 below.[4]

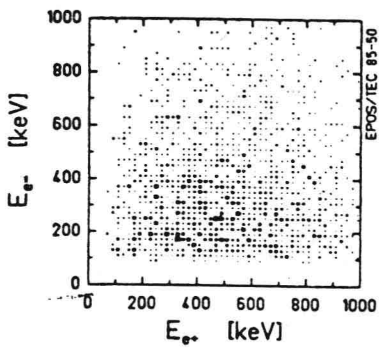

Figure 3: Uncut kinetic energy spectrum for coincident pairs (e^+ energy vs. e^- energy) produced in collisions of U on Th at beam energy of 5.83 MeV/nucleon.

While this uncut spectrum appears to show no obvious special features, if one makes a cut requiring the *electron* energy to be in the range 340<E<420 KeV, as shown in figure 4(a) then the *positron* spectrum (containing the events in the slice shown) displays a sharp peak displayed in figure 4(b), reminiscent of the peak in the original positron experiment. (the dashed curve is a Monte Carlo simulation of the expected background of dynamic positrons and positrons from nuclear pair conversions)

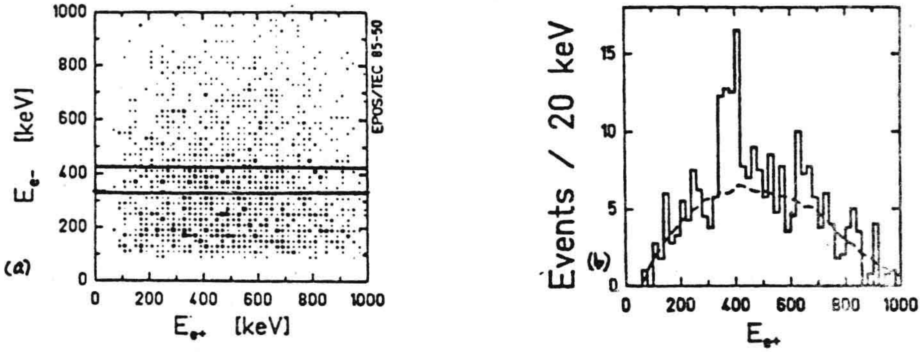

Figure (4): (a) energy cut on electron spectrum, requiring $340<E_e<420$ KeV. (b) resulting positron spectrum for events in the slice from (a)

If one now instead makes the same cut first on the positron spectrum, as shown in figure 5(a), a similar peak appears at the same place in the electron spectrum,

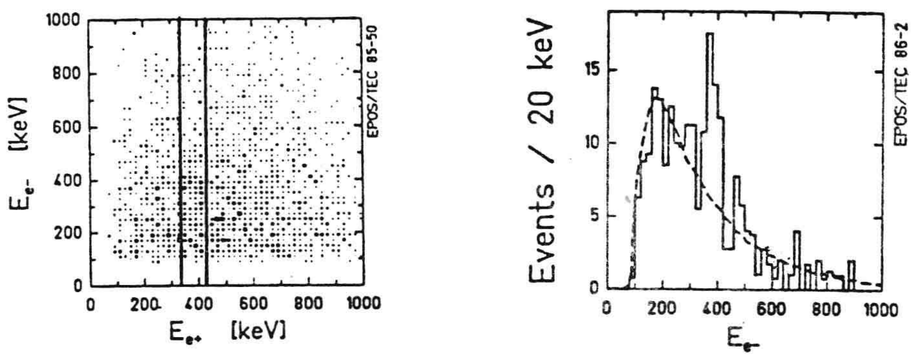

Figure 5:(a) cut on positron spectrum analagous to that in 4(a), (b) resulting electron spectrum.

Similar cuts on the electron or positron spectrum in other energy ranges produce no similar coincident peaks.

More suggestive still are the results obtained by making cuts on the sum and also the difference of the electron and positron kinetic energies. A line drawn at 45^0 on the spectrum in fig (3) will cross events having fixed value of $\Delta = E_{elec} - E_{pos}$. The wedge shape shown on fig. 6(a) encloses events having all values of $\Sigma (= E_{elec} + E_{pos})$ with the requirement that $\Delta < k\Sigma$ (to allow for greater Doppler broadening with greater total kinetic energy). The magnitude of k (the size of the wedge) is chosen so that Δ can vary in the region of the spectrum where the electron and positron peaks are observed by an amount on the order of the width of these peaks. Similarly the parallel lines at -45^0 in fig. 6(b) cross events having a fixed total positron and electron energy, and the slice shown encompasses events having Σ in the range 710-840 KeV for all values of Δ. If the events in 6(a) are plotted vs Σ, and those in 6(b) vs. Δ, the resultant spectra are shown in figure 7.

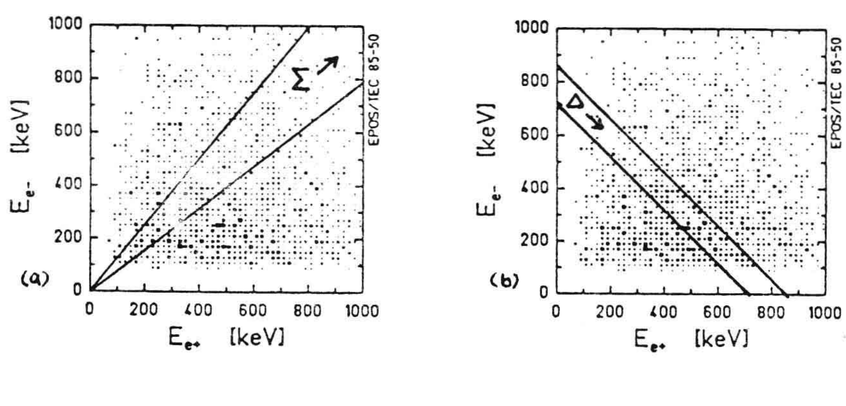

Figure 6: (a) wedge containing events with $\Delta < k\Sigma$ for all S (see text).(lines along 45^0 have constant Δ, those along -45^0 have constant Σ); (b) region in which $710 < \Sigma < 840$ KeV.

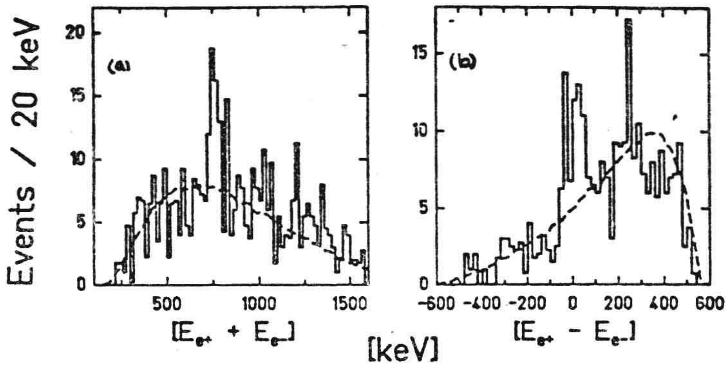

Figure 7: (a) Spectrum projected along points of constant Σ within the wedge in 6(a); (b) Spectrun projected onto points of constant Δ within slice in 6(b)

Significantly, the kinetic energy sum peak in 7(a) is much narrower than the individual electron and positron peaks. This is the type of behaviour one might expect from correlated back to back emission in the center of mass frame, where the first order Doppler shifts would cancel. Even more surprising is the narrow difference peak shown in 7(b). While it is possible, by judicious choice of cuts, to mimic peaks in the individual spectra, and even in the sum spectrum, a narrow peak in the difference spectrum is very difficult to artificially engineer.

These sum and difference peaks do not survive if the regions in figure 7 are moved. Also, if the beam energy is moved from the resonant value of about 5.9 MeV/nucleon, all the peaks disappear. (Note also that the outgoing ions are monitored during these measurements to assure scattering is near the elastic regime.) These phenomena, displayed for Uranium and Thorium here, are reproduced for a variety of *different* systems, with peaks near 350-370 KeV.

Monte Carlo calculations of backgrounds from a variety of possible sources have been done. The only one which is consistent with all the data is production of a neutral particle with kinetic energy of <100 KeV in the center of mass of the system, which subsequently decays into an e^+e^- pair. Such a Monte Carlo prediction is shown in figure 8, assuming a neutral particle of mass 1.8 MeV produced at rest in the CM frame, which decays isotropically into an e^+e^-, and with a production rate normalized so that it's decays produce 3% of the total observed e^+ yield. The agreement with the observations in fgs. 3-7 is truly striking.

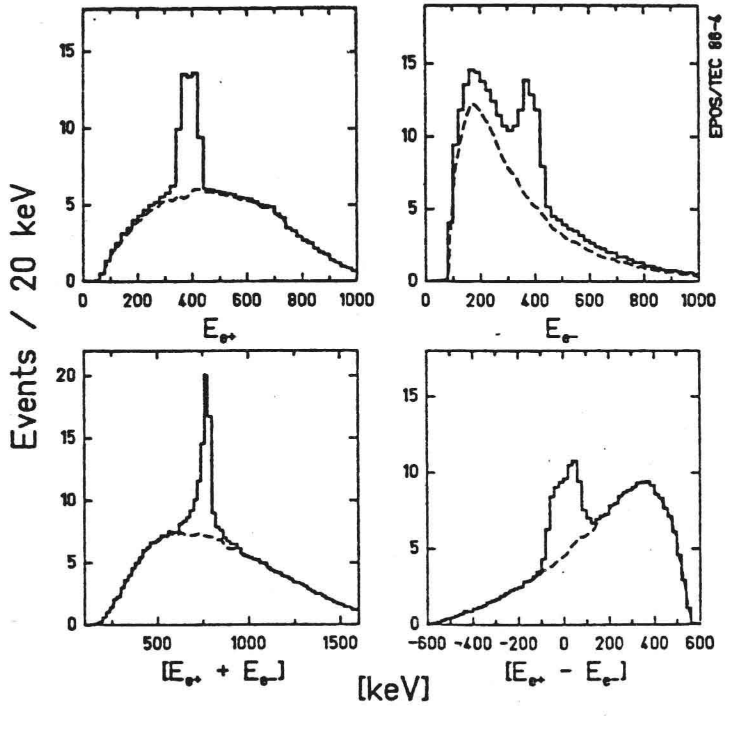

Figure 8: Monte Carlo prediction for Kinetic Energy Spectra resulting from Production and Decay of a new neutral particle. (see text above)

Since these remarkable results were first obtained, the experiment has been repeated by the EPOS collaboration, with much higher statistics. All of the originally observed phenomena have been confirmed, including the narrow peaks in the electron and positron distributions-- now well above the background, the narrow sum-peak and difference peak, and the indications of multiple structure in the peaks.

2. Summary of subsequent discussions

The remainder of my lecture at Vanderbilt involved theoretical discussions of a variety of phenomena from nuclear and particle physics which might be proposed to explain the observed events, and phenomenological discussions of contraints on the elementary particle interpretations of the events using data from experiments in low, medium and high energy physics. The details of most of these discussions appear in several recent preprints I have written [5,6] so I will merely outline the points raised, and refer the reader to these works, and the other references cited for further details.

(a) **Nuclear and electromagnetic explanations**: All standard explanations originating in nuclear-related transitions, or standard electromagnetic production appear inconsistent with the data. In particular, I discussed: (1) internal pair conversion, (2) direct production of scalar particles, both in nuclear transitions, and via the strong electromagnetic fields near the nucleus.[7], (3) production via fission products, notably ^{90}Zr and ^{96}Zr.

(b) **Axions**: I discussed the experimental data from heavy vector meson decays which convincingly rules out standard axions, even short-lived ones. I then discussed a new variant on the standard axion[5,8], with couplings only to up quarks, which appears to avoid these constraints, and which, until recently appeared as a viable a candidate to explain these events.(If a suitable production mechanism could be found.)

(c) **General Phenomenological Constraints**:

(i) **Atomic Physics**: g-2 constraints have been used to limit the couplings of any new scalar particle to electrons.[9] These constraints are rather severe, and limit the lifetime for decay into e^+e^- pairs to be greater than about 5×10^{-14} seconds. I presented similar constraints which could be derived using the observed hyperfine splitting in positronium, which are somewhat less severe, but which hold in a wider range of cases.

(ii) **Medium Energy, Rare K Decays**: I discussed in detail the existing constraints on the decay $K\to\pi a$, where a is a short lived neutral particle decaying into e^+e^-. The present limits are not very severe, and the axion variant of [5,8] can be barely accomodated within them.

(iii) **Beam Dumps:** I finally demonstrated how existing beam dump experiments convincingly *rule out, in a model independent way,* the possibility of a new short-lived neutral particle decaying into e^+e^- pairs, as long as such a particle traverses meters of matter without scattering.

(After this lecture was given, Mark Wise and I combined new experimental results on the decay $\pi^+\to e^+e^-e^+\nu$ with a theoretical prediction of the branching ratio for $\pi^+\to ae^+\nu$, for a short lived axion.[10] This appears to decisively rule out such an axion.)

It thus appears at present that the EPOS data remains live and well, while all theoretical attempts to explain the data have not survived. In particular there is now massive evidence against an explanation of this phenomena in terms of a new elementary particle at 1.8 MeV. In particular, the axion interpretation is ruled out.

I would like to thank Jack Greenberg for making all the illustrations and data presented available for my use, and also for tutoring me on the experiment.

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