NEW MASSIVE STABLE PARTICLES FROM SUPERSTRINGS AND THEIR DETECTION USING A TIME OF FLIGHT SYSTEM

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SUMMARY

Prospects for the existence and detection of massive stable particles are considered. In Section 1 we briefly review some previously postulated massive stable candidates and analyze in some detail the possibility that particles containing the new h quark from E_6 be stable, while satisfying cosmological bounds. Section 2 examines the experimental requirements for the detection of massive long-lived particles using a time of flight (TOF) system in the context of a Snowmass '86 "realistic" detector.

1. THEORETICAL CONSIDERATIONS

1.1 Generalities and superstrings.

A major scientific and technological interest in the exploration of new energy ranges is the search for new particles: massive stable particles must be included among the discoveries which could refute or validate our current understanding of reality at very small distances. Stability must be understood either in its absolute sense or else, more generally, in the consideration that a "stable" particle's lifetime is much longer than that of other particles in a similar mass range. For experimental purposes, a stable particle is one which, after being produced in a pp collision, leaves the detector before it decays. Stable particles don't grow on trees, however: the successes of big bang cosmology severely limit the masses and couplings of any hypothesized fields beyond the standard model. The most popular application of this type of constraint is probably the upper limit on the number of light neutrinos, derived from the study of nucleosynthesis.

The tremendous success and popularity that superstrings[1] have recently acquired are well justified. Not only do they provide a consistent quantum theory of gravity (albeit in the higher dimensional space which uncurls only at distances of the order of 10^{-33}cm), but the whole unification and Kaluza-Klein programs culminate rather happily: chirality of fermions is understood and the gauge group is barely larger than the standard $SU_3xSU_2xU_1$. Problematic puzzles remain, notably the issue of supersymmetry breaking and the evaluation of the various Yukawa couplings in terms of integrals over the compact dimensions. There is little reason, nevertheless, to expect that other research programs will bear any results without a high price in simplicity. Compositeness, technicolor, left-right symmetry, etc. are interesting possibilities which have progressively lost much of their original appeal, failing to explain the relative short-comings of the standard model (e.g. the Higgs sector) in a more satisfactory manner. Open-mindedness should not induce us to rule them out (we can always improve the limits), but neither should it prevent us from evaluating the available theoretical options and making a subjective judgement which could - of course- change. Supersymmetry, however invisible, is nowadays a standard prejudice among most of the theoretical community which will not disappear unless drastically refuted by experiment. Superstrings are likely to remain beyond the reach of experiment, but the different compactification schemes are indeed falsifiable. The discussion below incorporates all of these (explicit and explained) preferences.

1.2 Other stable massive particles.

A word on the stable/exotic particles discussed[2] at Snowmass '84. Mirror fermions could arise[3] from compactification schemes with zero net family number, but there is work to be done in generating and stabilizing the different energy scales. Weak skyrmions remain an attractive massive stable particle, wholly within the standard model. Their production cross-sections are expected to be large and the only requirement for their existence is a very large Higgs mass. Sextet and octet quarks, I=3 Higgs, and technibaryons are not much in vogue, lacking a theoretical framework consistent both cosmologically and phenomenologically. One of the "addons" mentioned in Snowmass '84 has materialized in the extra vector leptons[4] from superstring-induced models, and is not stable. There is no theoretical motivation for fractionally charged leptons. Monopoles are expected to have Planck (=GUT) masses, so they will not be produced at the SSC.

1.3 Stability and masses of h quarks from E_6

We now explore the possibility that the exotic color triplet (quark) fields predicted in superstring-induced models[5] are actually stable. Assuming that the general arguments for Calabi-Yau compactifications of the heterotic string hold, the low energy gauge group of the observable sector is constrained to be E_6/G, where G is some discrete subgroup. Due to the unique way (up to redefinitions) that the U(1) of hypercharge can be embedded in E_6, the gauge group E_6/G is constrained[6] to be of at least rank 5. Requiring the Higgs fields in the spectrum to break the (extended) electroweak gauge group down to $U(1)_{EM}$ rules out rank 6 models[7]. In addition, attempts to reconcile left-right symmetric models (rank 6, originating from an abelian G) with experiments at low energies generally push the W_R mass to a very remote scale ($\simeq$2 TeV), so we focus our attention on models with non-abelian G. In such phenomenologically attractive compactifications of the heterotic string, the low energy gauge group is $SU(3)_cxSU(2)_LxU(1)_YxU(1)_{Y'}$.

Each matter family is constituted by superfields which transform as a full 27 of E_6, which are never really in one 27, even at the unification scale. In addition to the u-type and d-type quarks, the charged lepton and its neutrino (and their charge conjugates), each family contains an extra lepton doublet (and its charge conjugate), a quark which we shall call h (and its charge conjugate) and, remarkably, a fifth neutral lepton n which is a singlet under the SO(10) subgroup of E_6. The h quark is a triplet under $SU(3)_c$ and a singlet under $SU(2)_L$, and has electric charge -1/3 like the d quark, with which it will mix in general

through a mass matrix of the form

$$M_{-1/3} = \begin{bmatrix} \lambda_d\langle N\rangle & \lambda_3\langle\nu^c\rangle \\ 0 & \lambda_h\langle n\rangle \end{bmatrix} = R_\theta^{-1} \begin{bmatrix} m_d & 0 \\ 0 & m_h \end{bmatrix} R_\theta$$

where λ_i are Yukawas, and N is a neutral component of the vector doublet, the usual Higgses.

The mass of the h-quarks is thus equal to (Yukawa)x$\langle n\rangle$, as is the mass of the extra lepton doublets appearing in these superstring induced models. In all supersymmetric unification models, the origin of the vevs for scalar fields can be traced to their masses squared becoming negative from the renormalization group evolution of Yukawa couplings after supersymmetry breaking. Fermion masses are hence of order the supersymmetry breaking scale times a factor less than one. This factor includes a Yukawa, of magnitude unknown. Given the e^+e^- limit on new charged particles, $m_h \geq 23$ GeV, one would expect the stable h to have a rather large mass, between a hundred GeV and a few TeV. This mass range can be admirably covered with the SSC: we will take $m_h \simeq 1$ TeV as a representative value.

Note that each entry in the matrix $M_{-1/3}$ is really a three by three matrix, but for the sake of clarity we deal with one generation losing only Kobayashi-Maskawa information. If $\langle\nu^c\rangle = 0$, then there is no mixing and h is stable (rather, the lightest of the three h quarks is stable) with mass $m_h = \lambda_h \langle n\rangle$. If the combination $\lambda_3\langle\nu^c\rangle \neq 0$, then h and d quarks will mix with angle $\theta_h \simeq \langle\nu^c\rangle/\langle n\rangle$, and h quarks will decay weakly via vector boson emission. Up to factors of order one, the lifetime can be estimated by[8]

$$\tau_h \simeq 2.6\text{x}10^{-27}\ \theta_h^{-2}\ (1\ \text{TeV}/m_h)^5 \quad \text{seconds.}$$

Requiring $\tau_h > 10^{-6}$ s implies $\theta_h < 10^{-10}$ for $m_h = 1$ TeV. Up to a ratio of Yukawas, $\langle n\rangle$ is then bound to be larger than 10^{10} TeV, which puts the "stability" of h in the realm of the unlikely. For the lightest h to be stable, hence, there must be no mixing between h and d quarks. The question is, could a symmetry of the theory forbid d-h mixing?

Some of the <u>discrete symmetries</u> of the resulting low energy theory can be obtained from well established desiderata, such as a long lifetime for the proton. R-parity does the trick naturally[9]. Another definite phenomenological requirement is that there exist light Higgs doublets which acquire a vev at the weak scale, thus breaking $SU(2)_L$ and generating ordinary fermion masses.

An elegant way[10] to forbid baryon-number violating terms in the superpotential is to impose the discrete symmetry D, under which

$$D : h \to -h$$

$$D : h^c \to -h^c$$

The experimental masslessness of one neutral field per family (neutrinos) can be assured with the extension

$$D : \nu^c \to -\nu^c$$

This corresponds to case (A) of ref. 8, with $\lambda_1=\lambda_2=\lambda_4=\lambda_5=0$ in their same notation. A notable difference, however, is that the (scalar component of) ν^c is prevented from developing a vev by the extended symmetry D, so that there is no mixing term betweeen h-type and (d,s,b) quarks! The next question is, what other requirements must the theory satisfy to ensure stability of h?

The allowed terms involving h-quarks are of the form

$$\lambda_h\ h^c\ h\ n\ +\ \lambda_3\ d^c\ h\ \nu^c\ ,$$

so that we must prevent h from decaying into a sneutrino^c and a d, or into a neutrino^c and a d squark. The second possibility is more worrisome because the usual light neutrino mass eigenstate contains an admixture of ν^c. A simple and reasonable requirement is then simply that the stable h quark be lighter than the scalar superpartners of ordinary fermions or, in other words, that m_h be less than the supersymmetry breaking scale in the observable sector. The lightest h quark will thus be stable if it is lighter than the squarks and if the discrete symmetry D is contained in the theory.

1.4 Cosmological constraints.

The main drawback of the scheme above, common to all superstring-induced models, is the difficulty to generate the baryon asymmetry of the universe (BAU). Indeed, since there are no baryon-number violating terms, no version of the usual GUT baryogenesis mechanisms can be implemented. Although no completely satisfactory solution to this problem is known, attractive possibilities for baryogenesis around the electroweak scale seem to exist, with the additional bonus that a low reheat temperature ($\lesssim$10 TeV?) does not prevent succesful baryogenesis. Under these conditions, heavy stable quarks do not present serious cosmological problems.

Indeed, the number of baryons per unit entropy expected from the equilibrium evolution[11] is very small, $n_B/n_\gamma = n_{\bar{B}}/n_\gamma \simeq 3.5\text{x}10^{-19}$. Nucleosynthesis requires, however, $(n_B-n_{\bar{B}})/n_\gamma \simeq (4\text{-}7)\text{x}10^{-11}$ if Ω=1 and $H_o \simeq 50$ km/s Mpc. This notable discrepancy implies there must have been baryon-number violating processes which generated the observed BAU. If h were stable and had been produced with a similar asymmetry $\epsilon = (n_h-n_{\bar{h}})/n_\gamma \simeq 10^{-10}$, then closure of the universe would require $m_h \lesssim \rho_h/\epsilon n_\gamma \simeq 250$ GeV. The same mass density constraint applied to the case where h had not developed an asymmetry would merely imply $m_h \lesssim 10^{12}$ GeV. A strongly interacting particle with the large asymmetry ϵ must be ruled out, however, because of the strict experimental limits on exotic heavy isotopes on Earth, which yield $n_h/n_\gamma \lesssim 10^{-25}$ for $m_h < 100$ TeV, to be compared with $n_h/n_\gamma \simeq 10^{-20}$, the expected relic abundance today. Although one could question the applicability of searches for heavy stable quarks in ordinary matter, a more honest approach is to hint that stable h quarks ought to be heavier than the reheat temperature. Their number density today would be much more diluted and the only other requisite would be, again, baryogenesis at a low temperature.

1.5 Outlook

There are phenomenologically sound compactification routes of the heterotic superstring which require the lightest additional h quark to be stable, with a mass of O(1 TeV). The difference between the standard cosmological intermediate scale, 10^{11} GeV, and the intermediate scale naturally arising from supersymmetry breaking long after compactification

(=unification), 1 TeV, remains to be fully understood..

In addition to the stable hadrons containing an h quark, other massive stable particles could also populate the spectrum at the energy range accessible to the SSC. It is thus important to implement the conditions under which they could be detected, to which we now turn.

2. EXPERIMENTAL CONSIDERATIONS

2.1 General characteristics of massive particle production and behaviour.

The overall features of massive particle production were well established[2,12] at Snowmass '84. It is useful to summarise those features here. We consider only strongly interacting massive particles for which the (pair) production is taken to proceed by gluon-gluon fusion (which at SSC energies dominates over competing processes such as quark-antiquark fusion). At SSC energies and above the "low mass" ($\simeq M_W$) region there is a substantial production of massive particles in the central region (here taken to be $5° < \theta < 175°$ or $|y| > 3$). The distributions of total and transverse momenta for the heavy particles are increasingly broad with increasing mass M, and are centered near M/2. There are correspondingly broad β (=v/c) distributions which become broader and move to lower β values with increasing mass. The β distribution is the essential characteristic considered in this paper for the detection of a new massive particle signal.

We consider here only the problem of detecting "stable" massive particles, with lifetimes $> 10^{-6}$ s. Such particles can escape from the detector before decay. These massive particles have the distinct characteristic of being able to penetrate large distances through matter. Despite their high momenta, a high mass means in general a low velocity and kinetic energy. The energy available in a massive particle - nucleon collision is low and can lie below the single pion production threshold for much of the β distribution. The heavy particle is assumed to be composed of a massive new quark (h) dressed with ordinary light quarks.

These light quarks dominate the interaction between the massive particles and nucleons in matter. The massive particle - nucleon interaction cross-section can then be expected to be a fraction of a typical hadronic cross-section and be dominated by elastic and quasielastic scattering. As the massive particle traverses matter there is then only the occasional hadronic interaction with low energy release. In addition the massive particle will be deflected little from its original direction. Even in the large SSC detectors the bulk of these new massive particles will emerge from such detectors with a small change in energy-momentum.

2.2 Experimental study of massive stable particles.

Experimentally the study of massive particles divides into two levels of difficulty. The first level, and the one addressed in this paper, concerns establishing the presence of a massive particle signal in the face of background. The second level concerns the measurement of the characteristics of the particles (mass, charge, etc.) and is not pursued here. Instead we focus on what could be expected in terms of signal detection from a time of flight system for the type of "realistic" detector emerging from Snowmass '86. The motivation for this work lies in the possibility of obtaining a fairly clean slow particle signal from a TOF system shielded from the interaction point by the thickness of the calorimetry required at SSC energies.

The β distribution for a particle with a mass of 1 TeV is shown in Fig. 2(a). (The histogram shown in the figure is for the fitted values, but differs little from the true β distribution.) The distribution is fairly broad but its peak is still close to $\beta = 1$. The background against which the search for these massive particles must be carried out comes from muons, both "direct" and from decay in flight. Because the TOF system has a finite time resolution, the muon spike at $\beta = 1$ spreads out and cuts into the massive particle β distribution. The extent to which these distributions overlap is controlled by the TOF resolution and the relative rates of massive particles and muons. This study addresses the question of the required time resolution in the context of a specific detector. The active part of the muon system for the "realistic" detector has been proposed to consist of drift tubes with a spatial resolution of 200 microns, giving a time resolution of a few nanoseconds for a typical gas drift velocity. The question is then posed as to whether this system would be adequate as a TOF system for a heavy particle search.

2.3 Detector description.

We have used the GEANT package to simulate the behaviour of a possible SSC detector. The design of the detector follows Model B of ref. 13, although some of the dimensions were changed slightly. A view of the detector is given in Fig. 1. It is fairly conventional with a solenoidal central field (15 KG.), fine and coarse calorimetry and, most importantly for this study, a multi-layer muon/TOF system. The details of the tracking and calorimetry are not important here. The main requirement is that it be thick enough to reduce hadron punch-through to a minimal level.

The muon/TOF system consists of 60 cm steel slabs separated by a layer of scintillator and a layer of muon drift tubes in each gap. Only the TOF scintillators were simulated as active detection elements. The endwall muon system extended in to complete coverage of the range $5° < \theta < 175°$.

The passage of a low β particle from the interaction point to the outside of the muon/TOF system can take several hundred nanoseconds. Since this time is long compared with the interval between beam crossings (16 ns) there can be a large number of interactions occuring while the slow particle crosses the detector. This implies a need for long time scale readout electronics and event buffering which was discussed in ref. 2. We assume here that it is possible to extract from such a system the necessary set of TOF signals to determine the presence of a low β particle.

2.4 Event generation.

A sample of 200 events containing massive particles was generated using ISAJET, which allows for the production of fourth generation quarks via gluon fusion. A mass of 1 TeV was used for which the production cross-section is 2×10^{-9} mb. These events were read into GEANT and the massive particles only were propagated through the detector. The acceptance of the detector was 94%, counting each member of a massive particle pair separately. The output from GEANT for each track consisted of the time of flight to each TOF plane crossed (with no time smearing at this stage) and the position at each TOF plane.

For the background muons it was necessary to assume a form for the single particle inclusive spectrum. The form used was that determined by Frank Paige using

ISAJET :

$$d^2\sigma / dp_T\, dy = 80\, p_T^{-3.5} \quad \text{mb/GeV} .$$

Pions and kaons (10%) generated by this expression were used to produce a decay muon p_T spectrum taking correct account of potential decay length as a function of production angle and detector geometry.

To this p_T spectrum must be added the contribution from "direct" muons (from c, b, Drell-Yan, etc.) for which the μ/π ratio was taken as constant as a function of p_T. A value of 5×10^{-4} was used for this ratio.

The total rate of muons produced within our geometrical cut of $5^\circ < \theta < 175^\circ$ was determined for various p_T cuts using a luminosity of 10^{33} $cm^{-2}s^{-1}$. For a 5 GeV/c p_T cut the decays in flight dominate and the absolute rate was 17 KHz. This is in good agreement with the preliminary estimate of the Snowmass '86 muon group. For a 50 GeV/c p_T cut the direct muons dominate and the absolute rate was 15.4 Hz. This is rather low compared with the muon group figure of O(100 Hz) and presumably reflects their choice of a different μ/π ratio. We have checked, however, that our conclusions are stable against a value of this ratio required to give the higher rate. This is because the TOF time resolution is the dominant factor in determining the low β edge of the background distribution.

A sample of muons was produced with the same information as for the massive particles using the final decay plus direct p_T distribution. It is, of course, necessary to normalise the muon sample to the massive particle sample. First a suitable p_T cut must be chosen. Fortunately the situation is favourable here for a large reduction in the muon background since there are very few massive particles (of mass 1 TeV) at low p_T. A cut was made at p_T = 50 GeV/c bringing the total muon sample down to 1.5×10^6, to be compared with the 200 massive particles events. To track this number of muons through the GEANT simulation would have required a large amount of computing time. To avoid this two alternatives were tried and checked to yield the same result. In one case a sample of 1500 muons was fitted (as will be described below) using only three TOF planes. This gave the β value below which there is a rejection factor of 1:1500 against muon background. Then if two independent sets of three planes each were used, the overall rejection factor below the same β value would be $(1500)^2$, giving the desired result.

In the other case the whole system (in this case five planes) was used at once but each of the 1500 muons was used 1000 times with independent time smearings. The β value for background rejection of $1:1.5\times10^6$ agreed with the result from the first case to within 0.01 in β.

2.5 Results and discussion.

Both the heavy particle and muon TOF samples were treated in the same way to produce the final β distributions. Each TOF hit was smeared by a gaussian with standard deviation σ_t. The distance travelled between TOF planes was calculated assuming a knowledge of the track angle. For tracks with only two TOF hits β was calculated directly. For tracks with three or more hits a linear fit was made for β using the smeared times and calculated plane to plane track lengths. For σ_t below (few x 100) ps the heavy particle β distribution resembles the true distribution closely with only slight broadening and shift to lower β values. On the other hand the muon distribution, after fitting, gains a significant width.

Our results are given in Fig. 2 for the case of a 1 TeV massive stable hadron and σ_t=100 ps or σ_t=500 ps. Clearly for σ_t=500 ps there is little signal visible and, of course, the use of the muon tubes with $\sigma_t \simeq$few nanoseconds is completely ruled out.

It is necessary to achieve σ_t=100 ps: even though the peak region of the signal is obscured, it permits a clear observation of the tail. Fortunately, recent developments and tests[14] of large scintillator systems (3m length) have yielded encouraging results , with σ_t=110 ps.

The signal can be confirmed by assessing the p_T distribution of the remaining events. Massive particle production is little affected by changing the p_T cut from 50 to 100 GeV/c, whereas the direct muon rate falls more than an order of magnitude. Raising the p_T cut removes the lowest β massive particle events and hence provides no palliative to the requirement for a state-of-the-art timing system.

We have used a mass of 1 TeV as being typical for the SSC since it does not suffer too much from either low rate as for higher masses nor severe backgrounds near β=1 as for lower masses. It is, however, interesting to consider the limiting factors to both ends of the detectable mass range. At the upper end the limitation is from the rate of production of the new particles and the total running time. For instance during a run which would give a sample of 200 massive particle events at m_h=1 TeV, only a handful of events would be produced at m_h=2 TeV. The β distribution of the massive particles does, however, move away from the muon edge which can itself be further reduced by a higher p_T cut with no loss of signal. For low masses the rate of massive particle production increases sharply, being several orders of magnitude higher at m_h=200 GeV than at m_h=1 TeV. One can still afford to make a cut at a p_T of 50 GeV/c and only lose about 25% of the signal. Approximately 40% of the remaining signal would fall below the muon edge and be very visible, due to the high rate, as a fairly flat distribution slowly falling off at low β. Thus it should be possible to cover the mass range from the upper end of the Tevatron (estimated to be about $m_h \simeq$200 GeV) up to a limit in the few TeV range as determined by integrated luminosity.

3. CONCLUSIONS

The theoretical and experimental study of massive stable particles remains of fundamental interest. Theoretically, in addition to previously postulated candidates, there are possible new massive stable objects containing the h quarks appearing in the E_6 (modulo discrete subgroup) models resulting from compactification of string theories.

Experimentally it is possible to detect the presence of massive stable particles over a wide mass range, though this will require a state-of-the-art time of flight system. We strongly encourage the designers of SSC detectors to note this last point so that an important piece of the physics available in the TeV scale will not be missed.

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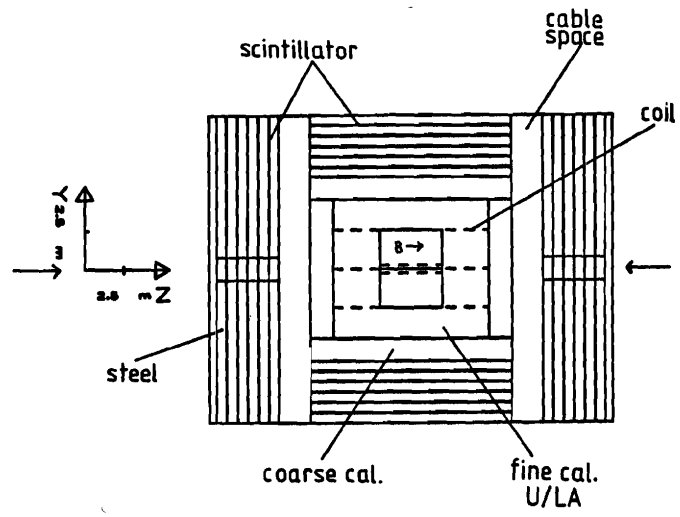

FIG. 1 Side view of detector used in the simulation.

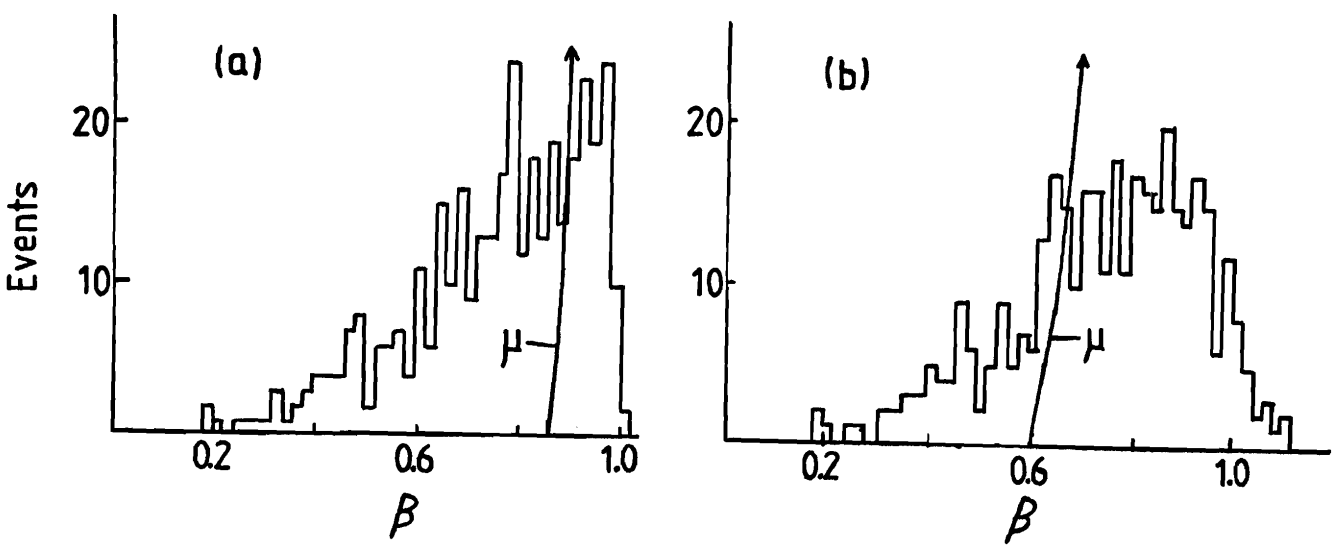

FIG. 2 (a) Histogram of fitted massive particle β values for σ_t = 100 ps and corresponding muon distribution. (b) As for (a) with σ_t = 500 ps.