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New weakly decaying particles and subnucleons

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A model of heavy, highly electrically charged hadron constituents termed "subnucleons" was proposed previously. Recently experimental evidence has been obtained for new particles with lifetimes $\sim 10^{-12}$–10^{-14} sec. Here, a possible classification for them is given in terms of the above-mentioned model. The most prominent of the new particles is predicted to have a mass slightly below 990 MeV and to decay into $\pi^{\pm}\pi^0$, $\pi^{\pm}\eta$, $e\nu$, and $\mu\nu$. Experimental searches for highly electrically charged subnucleons are also discussed. It is pointed out that a very recently observed highly ionizing particle of a Berkeley-Houston group may be a subnucleon. Scaling, e^+e^- interactions, and the J and ψ resonances are briefly discussed. Comments on quarks, charm, the quark-parton model, and monopoles are also made.

I. INTRODUCTION

Several groups have now reported evidence for new hadrons which decay weakly but more rapidly than previously observed weakly decaying particles. The evidence involves direct track measurements made with nuclear emulsions.[1–4] It also involves the observation of prompt lepton production in pp collisions,[5] of dimuon production in $\nu_\mu N$ and $\bar{\nu}_\mu N$ collisions,[6] of e^+ production in a $\nu_\mu N$ collision,[7] and of $e\mu$ production in e^+e^- collisions.[8] Lifetimes of the order of 10^{-12}–10^{-14} sec are inferred from the direct track measurements,[1–4] and these are consistent with upper limits set by the other data.[5–8]

These particles are not classifiable in the quark model based on SU(3) because all the ground-state configurations of that model are occupied by other particles or resonances, and excited-state configurations must necessarily be occupied by resonances. It has been suggested that they may be classifiable in a generalized quark model which includes "charm" and which is based on SU(4).[3,6,7] Such a suggestion, if confirmed, would be important because it would have a direct bearing on the spectrum of fundamental hadrons. The charm hypothesis would require the existence of a charmed quark.

At this time the masses and decay modes of the particles reported in Refs. 1–8 are not precisely determined. However, the masses and decay modes of would-be charmed particles have been predicted, and experimental searches based on these predictions have very recently been made, with negative results.[9,10] It therefore seems improbable that the data of Refs. 1–8 can be interpreted in terms of the charm hypothesis.

In this paper an alternative possible explanation of the data is proposed. The alternative scheme predicts masses and decay modes for the new particles that are not inconsistent with the data of Refs. 9 and 10. It is based on a model of the author[11] which, like the charm model, predates Refs. 1–8. The model of Ref. 11 involves hadron constituents termed "subnucleons." In the following it is referred to as the subnucleon model or SM.

Subsequent to the observation of new weakly decaying particles, a Berkeley-Houston group reported the observation of a heavy, highly ionizing particle which they concluded was not a nucleus. They suggested that it was a magnetic monopole, even though that suggestion is in severe conflict with the results of previous searches for monopoles.[12] Here an alternative possible explanation for their published data is reported. It does not conflict with previous observations. In the SM referred to above, the predicted subnucleons were assumed to be heavy and highly electrically charged. It is accordingly pointed out here that the particle observed by the Berkeley-Houston group may have been a subnucleon of the SM.

The plan of the paper is as follows: In Sec. II the SM is reviewed, and in the following section weak interactions are discussed in this context. In Sec. IV the new weakly decaying particles are considered. The final section is devoted to experimental searches for highly electrically charged subnucleons and to general discussion of related topics, such as scaling and the J and ψ resonances. It is in this section that the above mentioned particle of the Berkeley-Houston group is considered.

II. REVIEW OF THE SUBNUCLEON MODEL

The subnucleon model of Ref. 11 was constructed with the intention of providing a modified form of conventional quantum electrodynamics in which divergences are absent. It was argued (but not proven) that it might be possible to construct a finite theory if, besides the usual leptons, there exists a class of spin-$\frac{1}{2}$ highly electrically charged elementary particles. The recognition that such particles would interact strongly with one another, and also form tightly bound states, suggested a possible identification of them as constituents of commonly observed hadrons. The model of Ref. 11 was constructed on this basis. It is similar in several respects to the independently proposed "dyon model" of Schwinger,[13] and a comparison of the two models was made recently.[14]

In Ref. 11 a classification scheme for hadrons was proposed which is not based on SU(3) or SU(4). The recent observations, mentioned above, of particles which quite probably lie outside the SU(3) and SU(4) schemes provide clear motivation for considering alternate schemes, and the classification scheme of Ref. 11 is accordingly reviewed here. It is similar to, but not identical with, Schwinger's scheme.[13] Six spin-$\frac{1}{2}$ subnucleons are assumed to exist, with charges g, $2g$, $3g$, $4g$, $g+e$, and $4g+e$, respectively. Six corresponding antisubnucleons are also assumed to exist. Here e is the positron charge, and g is determined by the requirement that vacuum polarization be finite, and is assumed to be of order $10e$ in magnitude (i.e., $g^2/4\pi$ is assumed to be of order unity in units where $e^2/4\pi=\frac{1}{137}$). The resultant strong Coulomb attraction between subnucleons and antisubnucleons is assumed to be the binding mechanism, and on this basis a hadron classification may be made. This yields, for example,

$$\begin{aligned}
\pi^+ &= 4_+\bar{4}_0\,,\\
n &= 4_0\bar{2}\bar{2}\,,\\
p &= 4_+\bar{2}\bar{2}\,,\\
\Sigma^+ &= 4_+\bar{3}\,\bar{1}_0\,,\\
\Xi^0 &= 3\bar{2}\,\bar{1}_0\,,\\
\Omega^- &= 2\,\bar{1}_0\bar{1}_+\,.
\end{aligned} \tag{1}$$

Here, as in Ref. 11, subnucleons with charges g, $2g$, $3g$, $4g$, $g+e$, and $4g+e$ are denoted by 1_0, 2, 3, 4_0, 1_+, and 4_+ respectively, and antisubnucleons by $\bar{1}_0$, $\bar{2}$, etc. As was stated in Ref. 11, this classification includes some previously unobserved or unidentified states, e.g., $2\,\bar{1}_0\bar{1}_0$.

The SM as presented in Ref. 11 may be summarized as an alternative to the quark model with the following characteristics:

(i) Strong and electromagnetic interactions are unified in a finite quantum field theory.

(ii) Hadron constituents are assumed to be heavy and highly electrically charged.

(iii) The binding mechanism is physical and saturates.

(iv) The Pauli principle is satisfied and the constituents are few in number.

(v) The dynamical equations are essentially the familiar Schwinger-Dyson equations of conventional quantum electrodynamics. They are, of course, not easily soluble, especially at low (i.e., nonasymptotic) energies

(vi) The symmetry is SU(2)⊗ SU(2)⊗ U(1)⊗ U(1) ⊗ U(1)⊗ U(1) and some particles are required to exist which are not classifiable in the SU(3) and SU(4) quark models.

(vii) The structure of weak interactions possibly is simple.

To the above list the following more recently made[15] observations may be appended, under the assumption that the model is valid:

(viii) Hadron constituent masses are approximately proportional to the squares of their charges, with the lightest one approximately in the range 10–100 GeV, and the heaviest one approximately in the range 200–2000 GeV.

(ix) The asymptotic energy regime is above present machine energies, and well above present SLAC energies.

(x) SLAC experiments to date on ep collisions have been of insufficient energy to reveal the fundamental structure of the proton. (This is discussed further in Sec. V).

(xi) The ratio R of e^+e^- interactions is predicted to increase with energy to an asymptotic value $\sim 10^3$ in the one-photon-exchange approximation.

In general, the SM is uncomplicated and based on physical principles. It accounts qualitatively for the general behavior of hadrons and leptons. Whether or not it, or some modification of it, can account for the data quantitatively is an open question at this time.

III. WEAK INTERACTIONS IN THE SUBNUCLEON MODEL

In Ref. 11 a scheme for weak interactions was proposed within the framework of the SM. Here that scheme is modified somewhat, for reasons given below. We use the method, notation, and hadron classification of Ref. 11, and assume for the weak interactions a "Puppi triangle" of high charge as shown in Fig. 1(a), a "Puppi–Marshak–Dallaporta–Gell-Mann tetrahedron" of charge e as shown in Fig. 1(b), and a "Puppi octahedron" of charge zero as shown in Fig. 1(c). The motivation for proposing this scheme is, of course, twofold. It is reasonably simple and symmetric, and it is possibly consistent with presently available data, as is argued below.

A fit to available data may be attempted by ad-

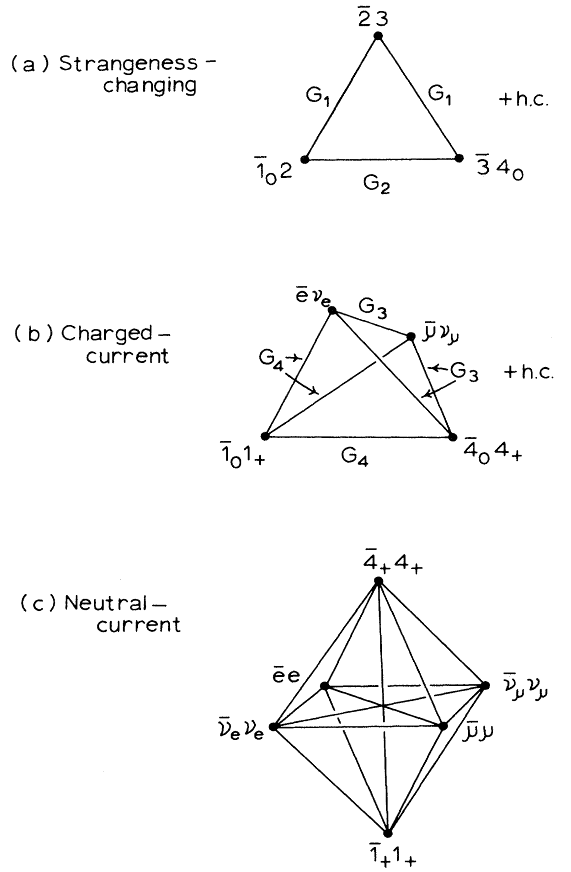

FIG. 1. (a) Proposed scheme for strangeness-changing weak interactions. The couplings are assumed to be point or contact four-fermion $(V-A)_\mu (V-A)_\mu$ interactions. G_1 and G_2 are the coupling constants. (b) Proposal for charged-current weak interactions. $(V-A)_\mu (V-A)_\mu$ point interactions are assumed, with coupling constants G_3 and G_4 as indicated. (c) Proposal for neutral-current weak interactions. The various possible coupling constants have not been inserted. Note that "elastic" weak interactions (e.g., $\bar{2}2 \to \bar{2}2$) could possibly be added to the above scheme, but are not, *a priori*, required.

justing the coupling constants G_i appropriately. Clearly, G_3 must be set equal to the muon-decay coupling constant. Reference to the particle classification of Ref. 11 or to Eq. (1) indicates that G_1 must be set equal to the coupling constant for strangeness-changing nonleptonic decays. Setting $G_2 = 0$ (or $\ll G_1$) yields the $\Delta S \neq 2$ and $\Delta I = \frac{1}{2}$ rules. The precise value of G_1 is not presently calculable because of effects of strong interactions. Likewise, the magnitude of G_4 may not be calculated precisely, at present. In Ref. 11 it was argued that it was moderately strong. Here, to avoid a prediction of moderately strong parity violations, we assume it is weak but postpone its precise evaluation at this stage. The couplings and coupling constants (or constant) for the neutral-current octahedron shown in Fig. 1(c) are not considered here in detail, since information on these reactions is sparse, and also because the discussion which follows below on new particles does not involve neutral-current weak interactions. Evidently, the available data on neutral currents may be fitted with coupling constants of the order of the muon-decay coupling constant.

The possible significance, if any, of the numerics and geometries of the triangle, tetrahedron, and octahedron is, of course, difficult to assess. We note that each fermion in the model appears the same number of times (i.e., twice). If the neutral-current octahedron is enlarged to include the remaining possible pairs (viz., $\bar{1}_0 1_0$, $\bar{2}2$, $\bar{3}3$, and $\bar{4}_0 4_0$) this symmetry is broken. The neutral-current scheme implied by the octahedron is, however, proposed here on a more tentative basis than those implied by the triangle and tetrahedron for strangeness-changing and charged-current interactions, respectively.

The present scheme for weak interactions differs from the earlier one of Ref. 11 in three ways. First, G_4 has been assumed to be weak. Second, the charge e loop has been replaced by a (more symmetrical) tetrahedron. Third, neutral-current weak interactions have been included in a symmetric and consistent manner. We note here that the interactions contained in the tetrahedron are obviously consistent with available data on $\pi \to \mu\nu$ and $\pi \to e\nu$ decays, in contrast to the original scheme proposed in Ref. 11 for these decays. In the present scheme decay processes for particles other than the π are either unaltered from those listed in Ref. 11 or are mentioned below.

The above scheme for weak interactions may not be a firmly founded quantum field theory. However conventional weak-interaction theory is not[11] without its problems (e.g., the Λ, $\Sigma^\pm$, Ξ, Ω^-, and K_S^0 lifetimes) and alternate schemes may be considered. In what follows we proceed by considering the implications of the above scheme for the new particles discussed in Sec. I under the supposition that the model is valid.

It is noteworthy that, although antisubnucleons are contained in the nucleon in the SM, the above scheme for weak interactions obviously predicts $\sigma(\bar{\nu}N)/\sigma(\nu N) \approx 1/3$ for charged-current interactions. Also, the above scheme for neutral-current interactions obviously forbids $K_L^0 \to \mu^+\mu^-$ in lowest order.

IV. NEW WEAKLY DECAYING PARTICLES

A. The $\bar{1}1$ ground state with $B=S=0$ and $(I,J^P)=(1,1^-)$

The hadron spectrum predicted by the SM was listed in Ref. 11, which listing included some previously unobserved or unidentified states. All of these, except one, would be very strange and/or massive, and would not be expected to be produced frequently in relation to other particles, or would definitely be resonances. The exception is the $\bar{1}1$ configuration. This is a predicted nonstrange meson configuration containing heavy $I=0$ and $I=1$ multiplets. The charged members of the $I=1$ ground-state multiplet would decay via the G_4 interaction, which we have here assumed (see above) is weak. If they are pseudoscalar particles (i.e., $J^P=0^-$) the dominant decay modes would be

$$(\bar{1}1)^{\pm}\to\pi^{\pm}\pi^0,\ \pi^{\pm}\eta,\ \mu\nu_{\mu}\,. \tag{2}$$

If they are vector particles (i.e., $J^P=1^-$) the dominant decay modes would be

$$(\bar{1}1)^{\pm}\to\pi^{\pm}\pi^0,\ \pi^{\pm}\eta,\ \mu\nu_{\mu},\ e\nu_e\,. \tag{3}$$

Irrespective of their spins, the hadron classification of Ref. 11 implies that they would be pair produced (or singly in association with a $\bar{K}K$ pair) in πN, NN, νN, $\bar{\nu}N$, and e^+e^- interactions. Also, in νN interactions the $(\bar{1}1)^+$ state would be singly produced, and in $\bar{\nu}N$ and K^-p interactions the $(\bar{1}1)^-$ state would be singly produced.

The above remarks suggest that the data of Refs. 1, 2, and 4–8 may possibly be accounted for in terms of the above $\bar{1}1$ state with $J^P=1^-$. This may be seen as follows. Clearly the data of Ref. 1 are consistent with pair production followed by decays to $\pi^{\pm}\pi^0$ and $\mu\nu$. Event AJ-20 of Ref. 2 is consistent with single-particle production and decay to $\mu\nu$. The event of Ref. 4 is consistent with pair production and decays to $\pi^{\pm}\pi^0$ and $\pi^{\pm}\eta$. The events of Refs. 5 and 8 are consistent with pair production and decays to $\mu\nu$ and $e\nu$ with equal probability. The $\mu^-\mu^+$ events reported in Ref. 6 are consistent with single-particle production and decay to $\mu^+\nu_{\mu}$ and $\mu^-\bar{\nu}_{\mu}$ in νN and $\bar{\nu}N$ interactions, respectively. And the $\mu^-\mu^-$ and $\mu^+\mu^+$ events are consistent with pair production in $\nu_{\mu}N$ and $\bar{\nu}_{\mu}N$ interactions, respectively, with appropriate decay modes. In fact, as may easily be checked, pair production in $\nu_{\mu}N$ and $\bar{\nu}_{\mu}N$ interactions may lead to final states containing from 0 to 3 prompt muons with total charge from $-2e$ to $+2e$. Finally, we note here that the event of Ref. 7 is consistent with single-particle production and decay to $e^+\nu_e$.

If we assume that the above described $\bar{1}1$ state of the SM is indeed being seen in the above experiments, then its short lifetime may easily be accounted for by assuming that the coupling responsible for its decay, i.e., G_4, is somewhat greater in magnitude than the muon-decay coupling constant G_3.

The above possible explanation of the data would imply an upper limit on the mass of the particle in question. According to the classification of Ref. 11 it would decay strongly to $K\bar{K}$ if kinematically allowed. This yields a predicted upper limit of 990 MeV for the mass which may be compared with available data. This is provided, unambiguously, by the individual nuclear emulsion events of Refs. 1, 2, and 4. Assuming that the decay scheme (3) applies, the measured masses for the individual events are 1.78, 1.0 ± 0.2, 1.55 ± 0.38, and 1.59 ± 0.40 GeV, respectively. Here the first, third, and fourth measurements are from cosmic-ray data. These data may or may not be consistent with the upper limit of 990 MeV set by the SM. Further experimental work of the type reported in Ref. 2 could elucidate this question.

The available data certainly imply that the mass of the particle in question is not much less than 990 MeV. This suggests a tentative identification of this particle as the $\eta\pi^-$ bump seen at 970 MeV in K^-p interactions (i.e., the δ^-). The observation[5] of prompt lepton production in pp collisions at $\sqrt{s}=4.5$ GeV is, of course, consistent with the predicted upper limit of 990 MeV for the mass of the source particle.

B. The $2\bar{1}\bar{1}$ ground state with $B=1$, $S=-3$ and $(I,J^P)=(1,\frac{1}{2}^+)$

The second least complicated and most prominent of the unidentified states listed in Ref. 11 would be the isovector $2\bar{1}\bar{1}$ state. The ground state of this configuration is a predicted $I=1$ partner to the Ω^-. It has $B=1$, $S=-3$, and charge states 0, −, and − −. The Pauli principle strongly suggests that it has $J^P=\frac{1}{2}^+$. (Note that no such suggestion for the Ω^- is made in the SM, as may easily be checked.) Its mass would be comparable to that of the Ω^-. Prominent weak decay modes, assuming they are kinematically allowed, of the $I_3=\pm1$ states would be

$$(2\bar{1}\bar{1})^0\to\Omega^-l^+\nu,\ \Sigma\bar{K},\ \Xi^0\pi^0\,, \tag{4}$$

$$(2\bar{1}\bar{1})^{--}\to\Omega^-l^-\nu,\ \Xi^-\pi^-,\ \Sigma^-K^-\,. \tag{5}$$

The 3-body and 2-body decays could have comparable rates if the coupling responsible for the former, i.e., G_4, is somewhat greater (as was suggested above) than that for the latter, i.e., G_1. The corresponding $(2\bar{1}\bar{1})^-$ state with $I_3=0$ would decay electromagnetically into $\Omega^-\gamma$ (cf. the $\omega\to\pi^0\gamma$ decay). If the mass of this state is >1815 MeV then it would decay strongly to $\Xi\bar{K}$ and the weak decay modes listed above unseen.

The above remarks suggest a possible identification of the neutral particles reported in Refs. 2 and 3 as candidates for the $(2\bar{1}\bar{1})^0$ state. The data are consistent with decays into Σ^+K^- and $\Omega^- e^+\nu_e$. Also, the upper limit of 1815 MeV predicted above for the mass may not be inconsistent with the data. In Ref. 2 a mass of 2.39 ± 0.11 or 2.04 ± 0.12 GeV is quoted for the Σ^+K^- decay mode, and in Ref. 3 the reported data imply a mass of 1.86 GeV assuming an $\Omega^- e^+\nu_e$ decay mode in which the positron and neutrino had equal longitudinal components of momentum. Further experiments like those of Refs. 2 and 3 could be helpful.

It is noteworthy that helicity effects in the 3-body decays in (4) and (5) would be different from those in the decays $\Sigma^\pm \rightarrow \Lambda e^\pm \nu$ assuming the Ω^- has spin $\frac{3}{2}$.

It is also noteworthy that the interpretations suggested above for the observations reported in Refs. 1–8 are not the only possible ones, even within the framework of the SM. Reference 11 lists some other unidentified states besides the isovector $\bar{1}1$ and $2\bar{1}\bar{1}$ states, but these are more complicated states, and they would seem less likely candidates for the observed particles. Another complicated and presumably unlikely possibility was also given previously.[14,15]

V. SUMMARY, DISCUSSION, AND SEARCHES FOR SUBNUCLEONS

A possible interpretation of the data on new weakly decaying particles reported in Refs. 1–8 has been proposed. This involves a charged meson with a mass predicted to be slightly below 990 MeV and decay modes (3), and a neutral baryon with mass less than 1815 MeV and decay modes (4). Associated with the latter particle the model predicts a doubly charged partner with decay modes (5). The above interpretation is based on a model of hadron constituents which are assumed to be heavy and highly electrically charged.

The latter assumption is, of course, at complete variance with presently conventional ideas on nucleon structure as determined by analysis of (so-called) deep-inelastic lepton-nucleon scattering. However, that analysis (i.e., the quark-parton model) treats permanently bound quarks as free particles and is illogically founded. Not surprisingly, it fails as often as it possibly succeeds.[15]

The present model suggests a picture of the nucleon as consisting mostly of a cloud $\sim 10^{-13}$ cm of "bare" pions in which a "bare" nucleon moves. By "bare" particles we mean here tightly bound subnucleonic configurations such as those listed in Eq. (1). These bare particles would be characterized by sizes ~ inverse subnucleon mass $\sim 10^{-16}$ cm. Such a picture was suggested previously.[11] If the individual bare pions which comprise the cloud are considerably lighter than the bare nucleon, then deep-inelastic lepton-nucleon scattering would be dominated by interactions with the bare spin-$\frac{1}{2}$ nucleon. It is conjectured here that such a picture may account for the data. Related models have, of course, been proposed by other authors.[16] In such models the parity of a particle may not coincide with the parity of its associated bare particle.

The above picture has possible implications for the J and ψ resonances. It suggests the existence of two types of resonances, viz., those in which the cloud is excited and those in which a bare particle is excited. The latter would include radial and other excitations. The lightest of the radial excitations would clearly be the $n=2$ states of the $\bar{1}1$ configuration, and these could differ qualitatively from normal resonances. This suggests a possible identification of the J and ψ resonances as $\bar{1}1$ states with $n=2$. This idea is experimentally testable because it requires the existence of charged partners to the J and ψ resonances.

Independent of all details of the model, the most direct experimental test of the SM involves searching for highly electrically charged subnucleons. Recently, the calibration data for the quark search of the CERN-Munich group[17] was examined for evidence of particles with charges $>\pm 3e$. No candidates were detected, and consequently an upper limit of $\sim 10^{-31}$ cm^2 may be placed on the subnucleon pair-production cross section in pp collisions at $\sqrt{s}\approx 53$ GeV. This limit refers to highly charged subnucleons being produced with ranges >25 g/cm^2 plastic. The unsuccessful search for monopoles of Giacomelli *et al.*[18] at the CERN ISR sets an upper limit $\sim 10^{-35}$ cm^2 for pair production of subnucleons with charges between about $27e$ and $170e$ in pp collisions at similar energies.

The feasibility of searching for highly electrically charged subnucleons in cosmic radiation was noted previously.[14] Also, a preliminary search was made.[15] We now consider the highly charged particle recently observed by the Berkeley-Houston group.[12] They have reported the observation of a slow, very highly ionizing, primary particle of cosmic radiation with unusual characteristics. They concluded that the data for the event may be fitted by a magnetic momopole or a particle with electric charge $\approx 70e$ and mass $>10\,000 m_p$. The observation corresponds to a flux $\sim 10^{-13}$ cm^{-2} sec^{-1} sr^{-1}. This is several orders of magnitude greater than upper limits for the flux of slow magnetic monopoles that have been set by other authors.[19,20]

For this reason alone it seems most unlikely that the particle was a monopole. If the reported data are reasonably accurate, this strongly suggests that the particle was very heavy and highly electrically charged. The "4_0" variety of subnucleon, which would be stable, was estimated to have a charge of the order of $40e$ and mass approximately in the range $200-2\,000 m_p$ (see Sec. II or Ref. 15). The reported data, provided they are reasonably accurate, may therefore be interpreted as possible evidence of a subnucleon. When further details on this event become available, especially on the accuracy of the reported speed measurement, the probability of this interpretation may be compared with probabilities for other possible interpretations (e.g., a nucleus which interacted in the detector).

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