The possibility that the Fermi scale is the only fundamental energy scale of Nature is under serious consideration at present, yet cosmic rays may already have provided direct evidence of new physics at a much higher scale. The recent detection of very high energy particles with no plausible astrophysical sources suggests that these originate from the slow decays of massive particles clustered in the halo of our Galaxy. Such particles had in fact been predicted to exist beforehand with mass and lifetime in the range required to explain the observations. I discuss recent work focussing on experimental tests of this speculative but exciting idea.

1 Introduction

The only massive particles in the Standard Model to have survived from the Big Bang are nucleons — protons and (bound) neutrons — along with a commensurate number of electrons to yield the observed charge neutrality of the universe. Considerations of primordial nucleosynthesis restrict the nucleonic contribution to the density parameter to $\Omega_N \lesssim 0.1$ and it is widely accepted that the dark matter in galaxies and clusters which contributes $\Omega_{\text{DM}} \gtrsim 0.3$ is non-nucleonic and probably composed of a new stable relic particle. There are many candidates for the identity of this particle but the most popular notion is that it is associated with the new physics beyond the Standard Model necessary to stabilize the hierarchy between the Fermi scale, $G_F^{-1/2} \simeq 300 \text{ GeV}$, and the Planck scale, $G_N^{-1/2} \simeq 10^{19} \text{ GeV}$. In particular theories of (softly broken) low energy supersymmetry (SUSY) typically imply that the lightest SUSY partner is a neutralino with mass of order the Fermi scale, which is absolutely stable if the discrete symmetry termed $R$-parity is exactly conserved. Interestingly enough the relic abundance of such a weakly interacting particle which was in thermal equilibrium in the early universe can account for the dark matter.

In supergravity theories, there is a new energy scale of $\mathcal{O}(10^{11}) \text{ GeV}$ — the geometric mean of the Fermi and Planck scales. This is the scale of the ‘hidden sector’ in which SUSY is broken through gaugino condensation induced by a new strong interaction, and communicated to the visible sector through gravitational interactions. Following the emergence of superstrings (for which

\footnote{We know now that massive relic neutrinos contribute at least as much as the luminous component of nucleons to the present energy density. However they are unlikely to be the dominant component of the dark matter, based on arguments concerning structure formation.}
$N = 1$ supergravity is the effective field theory) it was realised that the hidden sector can also serve to confine fractionally charged states which are a generic prediction of string theory. This avoids a serious conflict with the unsuccessful experimental searches for fractional charges but necessarily implies the existence of (integrated charged) bound states with mass of $\mathcal{O}(10^{11})$ GeV. In a specific construction with $SU(5) \otimes U(1)$ unification, it was noted that most such states would be short-lived but that the lightest such state would only decay through non-renormalizable operators of dimension $\geq 8$ and thus have a lifetime exceeding the age of the universe. This introduces a new candidate for the constituent of the dark matter — named “cryptons” — interestingly similar to nucleons which too are bound states of fractional charges and can only decay through non-renormalizable operators.

However, just as with nucleons, their cosmological origin is a puzzle. If such particles were ever in thermal equilibrium their relic abundance would have been excessive since their self-annihilations are rather inefficient. For nucleons the problem is just the opposite and their very existence today requires an out-of-equilibrium origin. If the same were true of cryptons, their relic abundance may well have a cosmologically interesting value. It is then interesting to ask what the observational signatures of such particles might be.

Reviving an old suggestion, we recognised that the most sensitive probe would be in extremely high energy cosmic rays (EHECR), specifically in the flux of high energy neutrinos which would necessarily be created by crypton decays. The best constraint we obtained followed from the upper limit on deeply penetrating air showers set by the Fly’s Eye atmospheric fluorescence experiment; this implied that such particles must have a lifetime exceeding $\sim 10^{18}$ yr if they are an important constituent of the dark matter. As this was close to the theoretically expected lifetime in the “flipped” $SU(5)$ model, I was optimistic enough to suggest in a conference talk that “…some improvement of these experimental sensitivities can rule out (or detect!) such particles”.

Just a few months later the Fly’s Eye array detected an event, consistent with a proton primary, but with an energy of $(3.0 \pm 0.9) \times 10^{11}$ GeV. This was well above the Greisen-Zatsepin-Kuzmin (GZK) cutoff energy of $\sim 5 \times 10^{10}$ GeV, beyond which resonant photopion production losses on the cosmic microwave background should limit the propagation distance of any such strongly interacting particle to less than about a hundred Mpc. Over a dozen such events have been detected subsequently by the Akeno airshower array (AGASA) as well as HiRes, the successor to Fly’s Eye, so the absence of

\[ \text{It has recently been noted that particles with mass of } \mathcal{O}(H_{\text{inf}}) \sim 10^{13} \text{ GeV — also dubbed “wimpzillas” — can be created with a cosmologically interesting abundance through quantum vacuum fluctuations during inflation or during the subsequent (re)heating process.} \]
the GZK cutoff\footnote{This was independently proposed by Berezinsky, Kachelriess and Vilenkin\cite{Berezinsky}, without, however, a specific particle candidate in mind. Kuzmin and Rubakov\cite{Kuzmin} also made a qualitative suggestion that EHECR may originate from relic particle decays, however they did not make the crucial observation that such particles would be highly concentrated in our Galactic halo.} is now well established. However contrary to the expectation that such high energy particles, being essentially undeflected by the weak intergalactic magnetic fields, should point back to their sources, the observed distribution on the sky\footnote{This was independently proposed by Berezinsky, Kachelriess and Vilenkin\cite{Berezinsky}, without, however, a specific particle candidate in mind. Kuzmin and Rubakov\cite{Kuzmin} also made a qualitative suggestion that EHECR may originate from relic particle decays, however they did not make the crucial observation that such particles would be highly concentrated in our Galactic halo.} is consistent with isotropy. This is quite baffling given that only a few astrophysical sites (active galactic nuclei or the extended lobes of radio galaxies) are capable of accelerating such particles, even in principle, and there are none\footnote{This was independently proposed by Berezinsky, Kachelriess and Vilenkin\cite{Berezinsky}, without, however, a specific particle candidate in mind. Kuzmin and Rubakov\cite{Kuzmin} also made a qualitative suggestion that EHECR may originate from relic particle decays, however they did not make the crucial observation that such particles would be highly concentrated in our Galactic halo.} along the arrival directions within the propagation range. Hence it is generally acknowledged\footnote{This was independently proposed by Berezinsky, Kachelriess and Vilenkin\cite{Berezinsky}, without, however, a specific particle candidate in mind. Kuzmin and Rubakov\cite{Kuzmin} also made a qualitative suggestion that EHECR may originate from relic particle decays, however they did not make the crucial observation that such particles would be highly concentrated in our Galactic halo.} that there is no “conventional” astrophysical explanation for the observed EHECR.

2 EHECR from decaying dark matter

Faced with the above conundrum, some authors have resorted to desperate measures, e.g. postulating that the intergalactic magnetic field may be a thousand times stronger than usually believed, so capable of isotropising particles from a nearby active galaxy. However, following from our previous discussion, there is a natural explanation\footnote{This was independently proposed by Berezinsky, Kachelriess and Vilenkin\cite{Berezinsky}, without, however, a specific particle candidate in mind. Kuzmin and Rubakov\cite{Kuzmin} also made a qualitative suggestion that EHECR may originate from relic particle decays, however they did not make the crucial observation that such particles would be highly concentrated in our Galactic halo.} for both the observed isotropy and absence of the GZK cutoff if the EHECR originate from the decays of metastable cryptons which are part of the dark matter\footnote{This was independently proposed by Berezinsky, Kachelriess and Vilenkin\cite{Berezinsky}, without, however, a specific particle candidate in mind. Kuzmin and Rubakov\cite{Kuzmin} also made a qualitative suggestion that EHECR may originate from relic particle decays, however they did not make the crucial observation that such particles would be highly concentrated in our Galactic halo.} This is because such particles will behave as cold dark matter (CDM) and hence cluster in the halo of the Milky Way with a concentration $\sim 10^4$ times higher than the cosmic average. The local flux of EHECR will thus be dominated by decays of cryptons in the halo, implying two distinct observational tests of the hypothesis. First, the energy spectrum and composition (nucleons, gammas, neutrinos) beyond the GZK cutoff will be determined essentially by the physics of crypton decays. Second, there will be a small anisotropy\footnote{This was independently proposed by Berezinsky, Kachelriess and Vilenkin\cite{Berezinsky}, without, however, a specific particle candidate in mind. Kuzmin and Rubakov\cite{Kuzmin} also made a qualitative suggestion that EHECR may originate from relic particle decays, however they did not make the crucial observation that such particles would be highly concentrated in our Galactic halo.} in the arrival directions of EHECR since we are located $\sim 8$ kpc away from the centre of the Galaxy and should therefore observe more particles arriving from that direction than from the anticentre. There may also be measurable correlations between arrival times of high energy nucleons, gammas and neutrinos.

2.1 Particle candidates

As noted above, the possibility of metastable relic particles with mass of $\mathcal{O}(10^{11})$ GeV had been proposed\footnote{This was independently proposed by Berezinsky, Kachelriess and Vilenkin\cite{Berezinsky}, without, however, a specific particle candidate in mind. Kuzmin and Rubakov\cite{Kuzmin} also made a qualitative suggestion that EHECR may originate from relic particle decays, however they did not make the crucial observation that such particles would be highly concentrated in our Galactic halo.} before the observations of EHECR beyond the GZK cutoff. An updated discussion\footnote{This was independently proposed by Berezinsky, Kachelriess and Vilenkin\cite{Berezinsky}, without, however, a specific particle candidate in mind. Kuzmin and Rubakov\cite{Kuzmin} also made a qualitative suggestion that EHECR may originate from relic particle decays, however they did not make the crucial observation that such particles would be highly concentrated in our Galactic halo.} of such particles in string/M-theory confirms that cryptons are indeed favoured over other possibilities such as

\begin{itemize}
  \item[]...
the Kaluza-Klein states associated with new compact dimensions (which are too short-lived). The most likely candidate is still a neutral pion-like ‘tetron’ composed of four constituents, with a minimum lifetime of

\[ \tau_X \simeq \frac{1}{m_X} \left( \frac{M}{m_X} \right)^{10}, \]

where \( m_X \sim 10^{12-13} \text{ GeV} \), and the scale \( M \) of suppression of non-renormalizable terms is of \( \mathcal{O}(10^{18}) \) GeV. Thus both the mass and lifetime of the candidate particle are motivated by topical physical considerations. This is in contrast to other proposals \(^{15,16}\) where the mass scale is not given any physical motivation and the decays are presumed to be mediated by unspecified instanton or quantum gravity effects so as to yield a suitably long lifetime.

2.2 Calculation of decay spectrum

Nevertheless all such proposals have a common phenomenology in that regardless of the decay mechanism, the spectra of the decay products is essentially determined by the physics of QCD fragmentation \(^{21}\) and has no major astrophysical uncertainties. In particular given that the propagation distance in the halo is \( \lesssim 100 \text{ kpc} \), much shorter than the GZK range of \( \sim 100 \text{ Mpc} \), the EHECR spectrum at Earth will be the same as the decay spectrum (apart from the decay photons which will be degraded through scattering on background photon fields). Of course the decay mode (e.g. 2-body vs many-body) may well play an important role. However in our picture the decaying particle is a singlet under Standard Model interactions and has a mass which significantly exceeds the Fermi scale so the inclusive spectra of final state nucleons, photons and neutrinos should be relatively insensitive to the precise decay channel.

We can thus imagine that we have say a \( e^+e^- \) collider at our disposal with a centre-of-mass energy \( \sqrt{s} \) sufficient to create a supermassive particle such as a crypton, rather than just a \( Z^0 \) as at LEP (Figure 1). This then decays into quarks and gluons which initiate multi-parton cascades through gluon bremsstrahlung. These finally hadronize to yield high multiplicity jets when the momentum scale of the process drops below \( \Lambda_{\text{QCD}} \). In the present context we are only interested in the final yields of nucleons, photons and neutrinos into which all the produced hadrons will decay. The production of different hadron species is quantified by their respective ‘total fragmentation functions’ \( F^h(x, s) = \sigma_{\text{tot}}^{-1}d\sigma/dx \), viz. the probability distributions for their

\(^d\) Other authors \(^{19}\) have also considered string candidates for superheavy dark matter, and discussed \(^{20}\) the confinement of fractionally charged particles into baryon-like states in the hidden sector and the discrete symmetries required to ensure their longevity.
inclusive production as a function of the scaled hadron energy \( x = 2E_h/\sqrt{s} \). These can be factorized as the sum of contributions from different primary partons \( i = u, d, \ldots, g \):

\[
P^h(x, s) = \sum_i \int \frac{dz}{z} C_i(s; z, \alpha_s(s)) D^h_{i}(x/z, s),
\]

(2)

where \( C_i \) are the ‘coefficient functions’ dependent on the production process, and \( D^h_i \) is the ‘universal fragmentation function’ for parton \( i \to \) hadron \( j \). The essential physics in the hard parton cascade is the logarithmic evolution of the strong coupling \( \alpha_s \) with energy and sophisticated techniques have been developed to handle divergences associated with collinear and soft gluon emission.

The formation of the final hadrons is however an inherently non-perturbative process and can only be described at present by empirical models encoded in Monte Carlo event generators, e.g. JETSET\textsuperscript{24} based on the ‘string fragmentation’ model, or HERWIG\textsuperscript{25} based on the ‘cluster hadronization’ model. These also account for the subsequent decay of the hadrons into the observed particles, taking into account all experimentally measured branching ratios, resonances etc, so can make detailed predictions of measurable quantities.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{hadronization_process}
\caption{The hadronization process\textsuperscript{21} in the decay of a massive particle.}
\end{figure}

Although the fragmentation functions are not perturbatively calculable, their evolution as a function of the momentum scale is governed by the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equation\textsuperscript{22}

\[
s \frac{\partial}{\partial s} D^h_i(x, s) = \sum_j \int_x^1 \frac{dz}{z} P_{ji}(z, \alpha_s(s)) D^h_{j}(x/z, s),
\]

(3)
where \( P_{ji} \) are the ‘splitting functions’ for the process parton \( i \to j \). Thus by measuring the fragmentation functions at one momentum scale, one can evaluate them at another scale. As seen in Figure 2, the DGLAP equations predict violations of ‘Feynmann scaling’ — a softening of the spectrum with increasing energy — in good agreement with data, in this case measured at PETRA (\( \sqrt{s} = 22 \text{ GeV} \)) and LEP (\( \sqrt{s} = 91.2 \text{ GeV} \)).

![Figure 2: Scale dependence of fragmentation functions in e^+e^- experiments.](image)

At small values of \( x \), multiple soft gluon emission gives rise to higher-order corrections, which turn out to be resummable by altering the scale in the DGLAP equation (3) from \( s \to z^2 s \); this yields a simple Gaussian function in the variable \( \xi \equiv \ln(1/x) \):

\[
x F^h(x, s) \propto \exp \left[ -\frac{1}{2\sigma^2} (\xi - \xi_p)^2 \right],
\]

which has a characteristic peak at \( \xi_p \sim \ln s/4 \), with width \( \sigma \sim (\ln s)^{3/4} \). Including ‘next-to-leading’ corrections to these predictions yields the ‘modified leading log approximation’ (MLLA) which accounts very well for the shape of the observed fragmentation functions at small \( x \). In comparing with data one has to further assume ‘local parton hadron duality’ (LPHD), viz.
that the hadron distribution is simply proportional to the parton distribution. Thus the prediction cannot distinguish between the individual hadronic species. Moreover although this kinematic region dominates the total multiplicity, it accounts for only a small fraction of the energy in the cascade, hence the MLLA spectrum cannot be correctly normalized.

With this background, we can review what has been done so far to explain the EHECR data in terms of decaying halo particles. Berezinsky et al. adopted the gaussian approximation \((\text{LLA})\) to MLLA to infer the spectrum of nucleons from the decay of a particle of mass \(m_X\). Although this approximation is only valid for small \(x (\ll 0.1)\), these authors nevertheless normalized it by requiring that \(\int_0^1 dx \, x F^h(x) = f_N \) where \(f_N \sim 0.05\) is the assumed fraction of the decaying particle mass transferred to nucleons (on the basis of \(Z\) decay data). The rest is assumed to go into pions which decay to yield photons and neutrinos, with neutral pions taking a third of the total energy. Figure 3 shows their fit to the EHECR data (multiplied by \(E^3\) for clarity) with decaying particles of mass \(m_X = 10^{13} \text{ GeV}\) which contribute a fraction \(\xi_X\) of the CDM density in our halo (taken to have a radius of 100 kpc). Their adopted normalization then implies a particle lifetime \(\tau_x/t_0 = 2 \times 10^{10} \xi_X\), where \(t_0 \simeq 12 \times 10^9 \text{ yr}\) is the age of the universe. Note that the constant suppression with energy of the nucleon flux with respect to photons (and neutrinos) follows from the assumed proportionality of the nucleon and pion fragmentation functions.

Figure 3: Predicted fluxes from decaying dark matter particles of mass \(10^{13} \text{ GeV}\) according to Berezinsky et al.\(^2\) the GZK-suppressed extragalactic proton flux is also shown.
Because of the above problems with the MLLA spectrum, we had already considered and rejected this convenient approximation and chosen instead to embark on a time-consuming calculation of the fragmentation functions in the kinematic region of relevance to the data, using the HERWIG event generator. In doing so we were initially motivated to test an argument due to Hill that the fragmentation spectrum at large $x$ should be $\propto (1 - x)^2$. By normalizing to the total multiplicity and demanding energy conservation Hill was then able to obtain an empirical fragmentation function which could be fitted to extant data. Assuming the multiplicity to be $\propto s^{1/4}$ as in the naive statistical model of jet fragmentation, this was

$$F_h = \frac{15}{16} x^{-3/2} (1 - x)^2,$$

(5)

while by adopting the leading-log QCD prediction for the multiplicity ($\propto \exp \sqrt{\ln(s/\Lambda^2)}$), he obtained

$$F_h = N(b) \exp\left[ b \sqrt{\ln(1/x)} (1 - x)^2 \right] / x \sqrt{\ln(1/x)}.$$

(6)

By fitting this form to PETRA data, Hill found $N(b) = 0.08$ and $b = 2.6$. On the basis of the same data he assumed that 3% of the hadronic jets form nucleons and the other 97% are pions which decay into photons and neutrinos.

![Figure 4: Comparison of the nucleon fragmentation functions for decaying particles of mass $10^{11}$ GeV (lower curve) and $10^{13}$ GeV (upper curve), calculated using HERWIG. The Hill approximation is also shown (dotted line). Note the significant scaling violation.](image-url)
Many authors who have investigated the annihilation of GUT-scale relic topological defects (TD) as the source of EHECR have used these expressions to estimate the fluxes. However this is clearly inaccurate since there would be large scaling violations (see Figure 2) in going from the PETRA energy scale of 22 GeV up to the very much higher GUT energy scale. This is just what our calculations using HERWIG demonstrate.  The functional form (6) continues to provide a good fit to the fragmentation function of nucleons but as shown in Figure 4 the spectrum becomes significantly softer with increasing particle mass, e.g. for $m_X = 10^{13}$ GeV, the normalization $N(b)$ drops to 0.0078 (with $b = 2.8$). Thus TD models of EHECR which use the fragmentation functions (5,6) overestimate nucleon production by a factor of $\sim 10$ at high energies.

The EHECR spectrum in the energy range $10^{9-11}$ GeV is well fitted as the sum of two power-laws — the extrapolation of the $E^{-3.3}$ spectrum from lower energies and a new flatter component $\propto E^{-2.7}$ which dominates above $10^{10}$ GeV. (The AGASA data gives the slope of the new component as $-2.78^{+0.25}_{-0.33}$.) There is some indication that the composition also changes from iron-group nuclei to protons at this energy. In Figure 5 we see that the HERWIG generated spectrum for a decaying particle mass of $10^{12}$ GeV is indeed in reasonable agreement with this new component of cosmic rays. Our normalization requires a lifetime $\tau_X/t_0 = 3 \times 10^9 \xi_X$ in the notation of Berezinsky et al., i.e. a factor of $\sim 6$ smaller. (This is because they seem to have normalized to photons rather than nucleons at $10^{10}$ GeV; see Figure 3).

![Figure 5: Expected nucleon flux for decaying halo particle masses of order the hidden sector scale compared with data (multiplied by $E^3$ for clarity). The spectra are normalized at $10^{10}$ GeV to the new component (dashed line) suggested by the observations.](image)
However our own calculations suffer from two problems. The first, which we were initially unaware of, is that HERWIG has a known tendency to overproduce baryons at large $x$ (essentially due to the fragmentation of the leading quark from the initial hard process, viz. particle decay in the present case). Although the overall multiplicity is correctly predicted at LEP energies (e.g. 0.953 protons per event vs $0.98 \pm 0.09$ observed in $Z^0$ decay), HERWIG overproduces nucleons at $x \gtrsim 0.3$ by a factor of $\sim 2-3$. Secondly, in studying the evolution of the fragmentation function to very high energies we should take into account that the running of the strong coupling $\alpha_s$ would be altered above $\sim 10^3$ GeV when SUSY particles begin to be excited from the vacuum.

![Graph](image)

Figure 6: Effect of ad hoc baryon suppression factor on HERWIG default (top) and isodipole (bottom) baryon cluster decays.
Both these issues have been addressed recently in unpublished work\textsuperscript{[2]} by Rubin. As shown in Figure 6 he finds that agreement of HERWIG with LEP data\textsuperscript{[3]} on baryon production is significantly improved by isotropizing the decay of the hadron cluster formed from the hard process (rather than have the hadron leave the cluster along the direction of the initial quark). An additional suppression of the probability for cluster decay by $\sim 20\%$ improves the fit further. To take SUSY particles into account, he evolves the DGLAP equation\textsuperscript{[4]} from LEP energies upwards (with the initial sparton fragmentation functions calculated with the PYTHIA\textsuperscript{[24]} event generator). The SUSY $\beta$ function for $\alpha_s$ is used, with the flavour thresholds corresponding to the sparticle spectrum of a typical minimal supergravity model (with parameters $M_0 = 800$ GeV, $m_{1/2} = 200$ GeV, $A_0 = 0$, $\tan \beta = 10$, $\text{sgn}(\mu) = +$).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure7.png}
\caption{Comparison of data with spectra predicted using coherent branching: $M_X = 10^{15}$ GeV without SUSY (top); $M_X = 10^{17}$ GeV with SUSY (bottom).}
\end{figure}
Figure 7 shows his results for both the non-SUSY and SUSY cases. The high energy “bump” in our proton spectrum (see Figure 4) has been erased but the non-SUSY spectrum continues to reproduce the shape of the data for a decaying halo particle mass of $O(10^{12})$ GeV. The effect of including the effects of SUSY on the evolution of the parton cascade is to flatten the spectrum further so that a $\sim 10$ times larger mass is still acceptable. We note that the spectral shape differs considerably from the “SUSY-QCD” spectrum calculated by Berezinsky and Kachelrieß using MLLA. This is not unexpected since as emphasized earlier, this approximation is unjustified at large $x$ so cannot be normalized (as these authors do) to the energy released in the decay. Moreover their assumption of an energy-independent ratio between nucleons and pions is invalid; as is evident from Figure 7 this ratio increases with energy.

3 Conclusions

Although some progress has been made in sharpening the spectral predictions of the decaying halo particle model for EHECR, much work still needs to be done. The calculations so far have assumed the simplest decay channel — into two partons. However non-renormalizable operators are in fact likely to induce many-body decays. The effects of supersymmetry also need to be investigated more carefully, e.g. the effects of varying the SUSY parameters and inclusion of sparticle decay channels. Nevertheless it is already clear that the general trend in the EHECR data can be accounted for by this hypothesis, if the particle mass is $m_X \sim 10^{12-13}$ GeV and its lifetime is $\tau_X \sim 10^{16}$ yr($\xi_X/3 \times 10^{-4}$), so that even with a very long lifetime such particles need constitute only a tiny fraction $\xi_X$ of the halo CDM. It is also clear that TD models in which $m_X$ corresponds to the GUT-scale, are already ruled out by the spectral data.

The next generation of large area cosmic ray, gamma-ray and neutrino observatories (Auger, Amanda, Antares, . . . ) is now under construction so it is important to refine these calculations in order to make specific predictions for the expected fluxes. We emphasize that previous estimates of high energy gamma-ray and neutrino fluxes from TD models are based on the Hill fragmentation functions (5,6), while other work use the (M)LLA spectrum (4) or its SUSY variant. Blasi has calculated in detail the flux of $\gamma$-rays in the decaying halo particle model but he too uses the Hill and the MLLA spectra. All these approximations are inapplicable at the high energies of interest as explained earlier, and moreover the spectra of pions are not simply proportional to that of nucleons as assumed. Hence it is clear that all these estimates are unreliable.

*However it never exceeds unity as in our previous work using HERWIG which suffered from overproduction of hard baryons and gave an incorrect prediction of the $p/\nu$ ratio.*
It is essential that further work use the physically more realistic approach to calculating fragmentation spectra outlined above in order to devise definitive experimental tests of the decaying particle hypothesis.

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