Aust. J. Phys., 1983, **36**, 717–23

An Estimate of the Flux of Free Quarks in High Energy Cosmic Radiation*

C. B. A. McCusker

Falkiner Nuclear Department, School of Physics,
University of Sydney, Sydney, N.S.W. 2006.

Abstract

The flux of quarks in air shower cores at sea level is estimated from four different types of experiments. All four estimates agree and yield a quark flux of $8\times10^{-12}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$. The calculated concentration of quarks in the Earth's crust resulting from this flux is compared with that found in niobium in the Stanford quark search.

1. Introduction

In 1968 the Sydney Air Shower Group began a search for quarks in the central region of extensive air showers (EASs) of cosmic radiation. These showers were mostly due to primary cosmic ray particles of energy between 10^{15} and 10^{17} eV. In 1969 we found a track in event 66240 with all the expected characteristics of a quark track and no contra-indications (McCusker and Cairns 1969). This event led to other searches in air shower cores and it also led to some criticisms and suggestions for other explanations of the event. In the last 13 years we have been able to answer the various criticisms. It is now possible to use results from our own and other experiments to estimate the flux of free quarks in high energy cosmic radiation. In this paper, I summarize our rebuttal evidence (most of which has only appeared in theses or in-house reports) and make and compare estimates of the flux from various experiments.

2. Event 66240

Details

The Sydney quark candidate was found in a Wilson cloud chamber close to the core of an EAS of size 8×10^5 particles. The particle may well have been the central particle of the shower. The shower size gives the primary particle energy at around 2×10^{15} eV. The particle density at the cloud chamber was about 2000 particles per m^2. Many of the tracks were approximately parallel to the quark track; its projected zenith angle was $9\cdot0°$ and the mean projected zenith angle of ten other straight tracks was $9\cdot1°$ (varying from $7\cdot5°$ to 12°). This helped to identify it as part of the air shower. An even better criterion is its width. The tracks were allowed to diffuse

* Dedicated to the memory of Professor S. T. Butler who died on 15 May 1982.

0004-9506/83/050717$02.00

for 100 ms before expanding the chamber to improve the ionization measurement. The width of the tracks is proportional to the square root of the diffusion time. The width of the quark track was 143 ± 2 micrometer units, while the widths of the four nearest parallel tracks were 142 ± 4, 144 ± 3, 143 ± 3 and 144 ± 4 micrometer units.

It was possible to measure the drop count along $0 \cdot 103$ m of the quark track giving a drop count of $16 \cdot 2 \pm 2 \cdot 5$ drops per cm. The mean for three parallel tracks in the same section of the chamber was $40 \cdot 7 \pm 1 \cdot 0$ drops per cm^2, a value within one standard deviation for the overall mean of many tracks in many photographs.

Criticisms

Frauenfelder *et al.* (1970) and Rahm and Louttit (1970) suggested that the measured ionization of the track could be due to either a fluctuation in the ionization of a singly charged fast track or, alternatively, it could be due to a single charged particle at the minimum of the ionization versus energy curve.

At first sight, the first explanation seems very unlikely. For the quark track we counted 168 drops in a length where 430 were expected for a normally charged fast particle. However, the statistical problem is not quite straightforward. The ionization process is complicated by the fact that some of the electrons freed by the primary particle are themselves sufficiently energetic to produce further ions. This means that if we count N drops, the relevant standard deviation is not $\sqrt{N}$ but $a\sqrt{N}$, where $a > 1$. The constant a depends on the experimental set up. We found its value by counting a large number of tracks of normal shower particles; it was $1 \cdot 5$ for this experiment. Thus the expected number of drops in a $0 \cdot 103$ m length for a normal track is 430 ± 31. It is obvious that even this increased value of the standard deviation makes this a very unlikely explanation. The probability of a normal track producing such a deviation once in the whole of the experiment is $< 6 \times 10^{-8}$ (Cairns 1971).

The second explanation also seems rather unlikely. Most of the particles in air shower cores are electrons of high energy ($> 10^9$ eV). Thus their relativistic factor γ is ~ 2000 and they are well past the minimum of the ionization curve. However, some theoretical estimates had given an increase of ionization in argon from the minimum to the plateau as high as 60%. This seemed to us, from experience, to be a considerable overestimate. The matter was settled by the Livermore group (Clark *et al.* 1974) who compared shower tracks directly with low energy electrons at the ionization minimum and found an 18% rise, rather than 60%. With their figure, the probability of a single charged particle producing a track at the ionization observed is $< 2 \times 10^{-7}$ in the course of the whole experiment.

A third suggestion made by Adair and Kasha (1969) was that if quarks are produced in collisions in the atmosphere there should be equal numbers (on average) produced in the forward and backward directions in the centre-of-mass system. When transformed to the lab system the quarks in the forward direction will indeed be in the air shower core, but the quarks in the backward direction will be comparatively low energy particles in the outskirts of the shower. In this backward region the particle density is so low that they would (to a small area detector) appear as single particles. Many searches have been made for single quarks in the cosmic radiation and none have been found. Hence, Adair and Kasha suggested that our track must have some other explanation.

This is obviously a serious criticism and remained so until the paper by Bjorken and McLerran in 1979. For a different reason, these authors suggested that globs of quark matter are a component of high energy cosmic radiation (see Section 4). If the quarks enter the atmosphere as part of the cosmic radiation, rather than being produced in the atmosphere, then the Adair–Kasha objection collapses. It also turned out, as a result of further experiments, that the estimated flux of quarks in air shower cores at sea level is a factor of ten less than the best lower limit from single particle searches (Jones 1977).

3. Other Quark Searches in EAS Cores

Cloud Chamber Searches

Groups at Michigan, Edinburgh, Leeds and Livermore carried out searches in EAS cores using cloud chambers. Two of these at Michigan and Edinburgh (Hazen 1971; Evans *et al.* 1971) had only a limited exposure. The Leeds experiment used a very large cloud chamber but, as it was then used, could not detect quarks within a few metres of the air shower core (Hazen *et al.* 1975). The Livermore experiment used eleven cloud chambers each somewhat bigger than the Sydney chambers and their total exposure (area by time) was about four times longer than the Sydney exposure ($0 \cdot 8$ compared with $0 \cdot 2\ \mathrm{m}^2$ yr). None of these other experiments detected quarks.

Durham Search

The Durham group used a lead shielded neon hodoscope as their quark detector (Ashton *et al.* 1973; Ashton and Saleh 1975), which gave a large exposure of $2 \cdot 8\ \mathrm{m}^2$ yr. They found two tracks with all the expected characteristics of air shower $\frac{1}{3}e$ quark tracks. The tracks were parallel to the air shower muons, lightly ionizing, and without any knock-on electrons. There is a $<8\%$ probability that they could be due to single muons, arriving 103–144 μs before the air shower, being parallel to the air shower tracks by chance, and having a downward fluctuation in the number of knock-on electrons produced. Such an explanation cannot account for the Sydney track.

Overall Result of Core Searches

The result of the core searches is that three tracks, with all the expected characteristics of quark tracks and no contra-indications, have been found in an exposure of $5 \cdot 2\ \mathrm{m}^2$ yr if we include the Leeds experiment, and $3 \cdot 8\ \mathrm{m}^2$ yr if not. With a flux of this size, the Michigan, Edinburgh, Livermore and Sydney experiments expected to see one quark between all of them, which they did, while the Durham group expected to see two, which it did.

4. Centauro

Details

This event was found in 1973 in emulsion chamber 15 of the Brazilian–Japanese Emulsion Collaboration (Lattes *et al.* 1980). The chamber with the large area of $\sim 40\ \mathrm{m}^2$ was exposed for one year at an altitude of 5200 m on Mount Chacaltaya in Bolivia. The event occurred in the atmosphere, about 50 m above the chamber, and resulted in the production of a beam of ~ 75 hadrons, *but no pions*. At first glance the event was somewhat similar to the total break up of an energetic iron nucleus (McCusker 1975) but many details were different, for example, the number of hadrons and the unusually high transverse momenta of these hadrons. Above all, the event occurred at a depth of $\sim 500\ \mathrm{g\,cm^{-2}}$ in the atmosphere. The interaction mean free path of an energetic iron nucleus in emulsion is $25\cdot 7^{+1\cdot 7}_{-1\cdot 5}\ \mathrm{g\,cm^{-2}}$ (McCusker 1980), giving a mean free path in air of $17\cdot 7\ \mathrm{g\,cm^{-2}}$. This, in turn, gives the probability of an iron nucleus surviving to a depth of $500\ \mathrm{g\,cm^{-2}}$ of only $\exp(-500/17\cdot 7)$, which is negligible. Attempts to simulate this event using the Monte Carlo technique and proton (Acharya *et al.* 1981) or iron (Goodman *et al.* 1979) primaries have failed.

Bjorken–McLerran Hypothesis

No explanation of the Centauro event consistent with our wealth of information on high energy physics was found until the Bjorken–McLerran (1979) suggestion. They accounted for the event by supposing it was due to a glob of quark matter, incident on the atmosphere, as part of the cosmic radiation: because of the very strong binding force between quarks this glob would be superdense and so have a sufficiently small interaction cross section to reach to a depth of $500\ \mathrm{g\,cm^{-2}}$; because it is made of quarks it can, on break up, only form baryons and not mesons; and again because of the strong quark–quark force, on break up it should give a high mean transverse momentum to its fragments.

A further consequence of the hypothesis is that if the number of quarks in the glob is not exactly divisible by three then one or two free quarks should remain close to the centre of the resulting air shower. Thus, the hypothesis can be used also to explain the features of the Sydney and Durham events. It also explains a number of other previously inexplicable results in high energy cosmic radiation (see next section), so that estimates from a number of very different experiments can be made of the flux of quark globs. If this hypothesis is incorrect we would expect these estimates to differ very considerably—even by orders of magnitude—however, the opposite turns out to be the case and they agree within the errors.

5. Flux of 'Free Quarks'

EAS Core Searches

The five cloud chamber searches plus the Durham neon hodoscope search have given a total exposure of $5\cdot 2\ \mathrm{m^2\,yr}$. There are two corrections one may make to this exposure. Firstly, the Leeds cloud chamber could not detect quarks very close to the core of the shower (within one or two metres), which is not only where one expects to see them according to the Bjorken–McLerran model, but also where the three candidates to date have actually been seen. Therefore, we may subtract $1\cdot 37\ \mathrm{m^2\,yr}$ from the total.

Secondly, the Durham hodoscope was shielded by $0\cdot 15$ m of lead, which has the effect of removing the electron component and thus making the quark easier to detect. It also gives the high energy hadrons in the core a chance to interact and, if they do so, then the burst of ionization will, in general, make it impossible to see a quark track. It is possible to estimate the frequency of this effect from the results of the Sydney 64 scintillator experiment used in the 'sandwich' mode (Winn *et al.* 1965; McCusker *et al.* 1969). Of 17 events similar to that of 66240 in size and core type, eight were free from noticeable nuclear interaction products under the lead shield. This gives a minimum value for the total exposure of the experiments of $2\cdot 25\ \mathrm{m}^2\,\mathrm{yr}$ and a maximum value of $2\cdot 90\ \mathrm{m}^2\,\mathrm{yr}$. Allowing for the rather large fluctuations possible in the small number of lightly ionizing tracks observed we get a flux of free quarks at sea level of between $0\cdot 5$ and $2\cdot 1\ \mathrm{m}^{-2}\,\mathrm{yr}^{-1}$.

Centauro and Mini-Centauro Events

The Brazilian–Japanese Emulsion collaboration found five events which they claim are of the Centauro type. They also found 13 they call mini-Centauro events—rather similar but producing a much smaller number (~ 12) of baryons. These events do not fit easily into the Bjorken–McLerran picture but do fit naturally into the alternative hypothesis of 'quark globs' due to de Rujula *et al.* (1978).

All of both the later Centauro and the mini-Centauro events occurred at greater distances from the chamber than the event discussed in Section 4. This means that the showers arrived at the chamber with a greater degree of contamination from secondary interactions in the atmosphere, making them harder to distinguish from showers produced by normal nuclei. Goodman *et al.* (1979) found that simulations using normal nuclei could not possibly account for two of the Centauro events and two of the mini-Centauro events. Accordingly, we take four events as establishing the minimum flux and 18 events as establishing the maximum. The exposure was $150\ \mathrm{m}^2\,\mathrm{yr}$.

All the interactions occurred within 500 m of the chamber (at greater distances the events are too contaminated to be distinguishable), representing a slice of atmosphere $37\ \mathrm{g\,cm}^{-2}$ thick. To calculate the overall flux of quark globs we take interaction mean free paths for the globs of 200 or $300\ \mathrm{g\,cm}^{-2}$. To get the flux of showers containing free quarks at sea level we must then multiply by $\frac{2}{3}$, if we assume the Bjorken–McLerran process. This then gives us the value of $0\cdot 7$–$4\cdot 8\ \mathrm{m}^{-2}\,\mathrm{yr}^{-1}$, to compare with that of the previous section.

'Long-flighting' Component

The large air shower array of the P.N. Lebedev Physical Institute at Tien Shan has produced evidence (Aseikin *et al.* 1975) for the occurrence of a component in air showers with a long interaction mean free path (about three times that for protons). The effect begins to be noticeable around a primary energy of 10^{15} eV. For an energy of 5×10^{14} eV in the central hadronic component, half the events show the effect. If we assume that the particles showing this effect are the quarks liberated from a quark glob then we can get an estimate of the flux of these globs from the energy spectrum of the radiation (Antonov and Ivanenko 1975). The value comes out as $\sim 3\ \mathrm{m}^{-2}\,\mathrm{yr}^{-1}$.

Horizontal Air Showers

When one observes the rate of cosmic ray air showers at various zenith angles one finds a rapid decrease in rate as zenith angle increases. This is readily understood as absorption of the showers in the increasingly thick atmosphere. However, at a zenith angle of $\sim 70°$ the situation changes quite dramatically with the rapid decrease of rate with zenith angle changing abruptly to an almost flat curve (Catz *et al.* 1975). Until the Bjorken and McLerran (1979) suggestion that part of the radiation around

10^{15} eV is due to quark globs, these 'horizontal' air showers were not explicable. However, a component with energy around 10^{15} eV, which has a long interaction mean free path and deposits large amounts of energy deep in the atmosphere in the form of numerous comparatively low energy hadrons, as observed in the Centauro events, is an obvious candidate for the causal agency of these showers. Hence, the flux of these showers may be compared with the fluxes derived in the three preceding subsections. This flux can be obtained by combining the results of Catz *et al.* (1975) and those of Nagano *et al.* (1971). For 'horizontal' air showers of size $\geqslant 2200$ particles the rate is $\sim 3\cdot 1\ \mathrm{m}^{-2}\,\mathrm{yr}^{-1}$. (The value of 2200 particles is not entirely arbitrary, the size spectrum of Nagano *et al.* having an inflection at that point.)

Overall Flux

The mean quark flux values for the four methods are $1\cdot 3$, $2\cdot 8$, $3\cdot 0$ and $3\cdot 1\ \mathrm{m}^{-2}\,\mathrm{yr}^{-1}$. Most of the arrays collect over ≈ 1 sr so that, in the units usually used to give quark fluxes in cosmic radiation (Jones 1977), the overall mean flux is $8\times 10^{-12}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$. This is appreciably less than the upper limit for the flux of *single* quarks given by Jones (1977) of $5\times 10^{-11}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ (from Fukushima *et al.* 1969). However, the important point about the four values is their relatively close agreement.

6. Stanford Concentration

In a series of experiments from 1970 to 1981, Fairbank and collaborators (Hebard and Fairbank 1971) at Stanford have repeatedly found evidence for fractional charges of $\pm\frac{1}{3}e$ on small niobium spheres. The frequency with which these fractional charges occur suggests a minimum concentration of one quark per sphere, or one quark per 10^{-4} gm of niobium.

It is possible to estimate the concentration expected from the flux of quarks in cosmic radiation given above. To do so we assume that the radiation has had constant intensity over the age of the Earth and a 'mixing depth', which gives the relationship (Jones 1977)

$$P = 6\times 10^{9}\,\phi\,,$$

where P is the concentration of quarks per gm and ϕ is the cosmic ray flux of quarks per $\mathrm{cm}^2\,\mathrm{s\,sr}$. This gives us an estimated concentration of $4\cdot 8\times 10^{-2}$ quarks per gm, compared with the much larger Stanford value of 10^4 quarks per gm. There are, however, two possible ways in which this discrepancy could be reconciled. The first is that the surface matter of the Earth also contains quarks left over from an early stage of the Universe. The second, which seems more likely since quark searches in materials other than niobium have usually had negative results (Jones 1977), is that the Stanford concentration has arisen as a result of geochemical processes. We note that the ratio of our predicted concentration to the Stanford concentration is 2×10^5, which is the same as the ratio of the concentrations of uranium in the most abundant locations to uranium on average over the Earth's crust.

7. Conclusions

Four different methods of estimating the flux of quarks at sea level from a suggested flux of quark globs in the primary cosmic radiation lead to much the same value (within the rather large uncertainties), with an average of $8\times 10^{-12}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$.

This value leads to a concentration of quarks in the Earth's crust about 10^5 times smaller than that derived from the Stanford results on a quark search in niobium, a factor which is within the possibilities of geochemical concentration.

Acknowledgments

I am very grateful to my colleagues Professors Messel, Peak and Winn for their support, collaboration and help. I acknowledge with deep gratitude the friendship, help and comments of the late Professor Stuart Butler. He displayed a constant interest in problems arising in cosmic ray research and shortly before his untimely death we discussed the matters contained in this paper.

References

Acharya, B. S., Rao, M. V. S., Sivaprasad, K., and Rao, S. (1981). *Lett. Nuovo Cimento* **31**, 149.
Adair, R. K., and Kasha, H. (1969). *Phys. Rev. Lett.* **23**, 1355.
Antonov, R. A., and Ivanenko, I. P. (1975). Proc. 14th Int. Conf. on Cosmic Rays, Munich, Vol. 8, p. 2708 (Max-Planck Institut: Munich).
Aseikin, V. S., Gorjacheva, G. Ja., Nikolskii, S. I., and Yakovlev, V. I. (1975). Proc. 14th Int. Conf. on Cosmic Rays, Munich, Vol. 7, p. 2462 (Max-Planck Institut: Munich).
Ashton, F., Cooper, D. A., Parvaresh, A., and Saleh, A. J. (1973). *J. Phys.* A **6**, 572.
Ashton, F., and Saleh, A. J. (1975). Proc. 14th Int. Conf. on Cosmic Rays, Munich, Vol. 7, p. 2467 (Max-Planck Institut: Munich).
Bjorken, J. D., and McLerran, L. C. (1979). *Phys. Rev.* D **20**, 2353.
Cairns, I. (1971). Ph.D. Thesis, University of Sydney.
Catz, Ph., Hochart, J. P., Milleret, G., Gawin, J., and Wdowczyk, J. (1975). Proc. 14th Int. Conf. on Cosmic Rays, Munich, Vol. 6, p. 2097 (Max-Planck Institut: Munich).
Clark, A. F., Finn, H. F., Hansen, N. E., Smith, D. E., and Powell, W. M. (1974). *Phys. Rev.* D **10**, 2721.
de Rujula, A., Giles, R. C., and Jaffé, R. L. (1978). *Phys. Rev.* D **17**, 285.
Evans, G. R., Fancey, N. E., Muir, J., and Watson, A. A. (1971). *Proc. R. Soc. Edinburgh* A **70**, 13.
Frauenfelder, H., Kruse, U. E., and Sard, R. B. (1970). *Phys. Rev. Lett.* **24**, 33.
Fukushima, Y., *et al.* (1969). *Phys. Rev.* **178**, 2058.
Goodman, J. A., *et al.* (1979). *Phys. Rev.* D **19**, 2572.
Hazen, W. E. (1971). *Phys. Rev. Lett.* **26**, 582.
Hazen, W. E., Hodson, A. L., Winterstein, D. F., Green, B. R., Kass, J. R., and Keller, O. A. (1975). *Nucl. Phys.* B **95**, 189.
Hebard, A. F., and Fairbank, W. M. (1971). Proc. 12th Int. Conf. on Low Temperature Physics, Kyoto, p. 855 (Keigabu: Tokyo).
Jones, L. W. (1977). *Rev. Mod. Phys.* **49**, 717.
Lattes, C. M. G., Fujimoto, Y., and Hasegawa, S. (1980). *Phys. Rep.* **65**, 152.
McCusker, C. B. A. (1975). *Phys. Rep.* C **20**, 230.
McCusker, C. B. A. (1980). *Aust. J. Phys.* **33**, 337.
McCusker, C. B. A., and Cairns, I. (1969). *Phys. Rev. Lett.* **23**, 658.
McCusker, C. B. A., Peak, L. S., and Rathgeber, M. H. (1969). *Phys. Rev.* **177**, 1902.
Nagano, M., *et al.* (1971). *J. Phys. Soc. Jpn* **30**, 33.
Rahm, D. C., and Louttit, R. I. (1970). *Phys. Rev. Lett.* **24**, 279.
Winn, M. M., *et al.* (1965). *Nuovo Cimento* **36**, 701.

Manuscript received 15 November 1982, accepted 27 January 1983