GEOPHYSICAL ASPECTS OF THE SEARCH FOR THE QUARK

A. Nir
The Weizmann Institute of Science, Rehovoth, Israel
(Received 19 April 1967)

We discuss the suitability of natural media to serve as objects of analysis for quark abundance, including the effects of momentum distribution at production, concentration or dilution in collection, effective length of irradiation by cosmic radiation, and target shape. The resulting concentrations may vary by ten orders of magnitude, the lowest being for sea water, the highest for stratospheric aerosols and selected iron meteorites.

The present experimental methods of search for the quark can be divided into static and dynamic methods. The static methods are mass spectrometry, charge determination (Millikan type), and spectral observations in stars. The dynamic method is based on observation of characteristic energy loss of high-energy particles of fractional charge. Extensive mass-spectrometric investigations were reported by Chupka, Schiffer, and Stevens[1] who performed also preliminary charge determination experiments. Sensitive charge-determination experiments were initiated by Becchi, Gallinaro, and Morpurgo[2] and Gallinaro and Morpurgo,[3] while spectral observations for the uv solar spectrum were reported by Sinanoğlu, Skutnik, and Tousey.[4] All these methods provide upper limits for quark/atom ratio in their respective media of observation.

The numerous experiments based on the dynamic method were summarized by Massam, Muller, and Zichichi,[5] with more recent experiments being performed by Kasha, Leipuner, and Adair,[6] Buhler-Broglin et al.,[7] and Lamb et al.[8] These provided an upper limit for quark flux in nature or in high-energy accelerator beams.

The static concentration can be related to the flux measurement if we know the range or momentum distribution of the produced quarks and the dynamics of the medium in which they come to rest. The first factor is of purely physical nature, the second is geophysical. Knowledge of the two can enable us to determine the suitability of a medium as a target of research for the quarks, as the resulting concentration of quarks will vary greatly in various targets. The relative concentration in a target can be evaluated with the aid of the following five criteria: (1) length of irradiation time (T), (2) enrichment in collection (E), (3) dilution by nonirradiated matter (D), (4) relative accumulation rate due to the dynamics of the production process (A), and (5) geometrical factors in cases of small targets. Primordial abundance of quarks is neglected here. The nature of these factors will be made clearer in the discussion of specific examples. The first three factors are usually of primary importance and their combined effect is used here to define a merit number, $M = TE/D$. The last two factors should not normally change the result by more than one order of magnitude.

As this discussion is concerned with the relative merits of the various media, it does not depend on the assumptions about the actual cross section for quark production. The momentum distribution as derived by Adair and Price,[9] and the consequent concentration distribution of the stable quarks or quark-nucleus systems, is accepted here as a basis for calculation. The distribution of quarks of mass 9 BeV/c^2 as given in Fig. 6 of Adair and Price was taken as a representative case. While the actual distribution should change with different assumptions about quark mass, the detailed structure of the quark-producing interactions, and the subsequent quark-nucleon interactions, it is assumed that the general nature of the arguments will not be radically influenced by this modification.

The concentration distribution of Adair and Price was here modified only to correct for isotropy of primary flux. No corrections were made for specific energy loss of the different quark species in these media, as this would not materially change the resulting distribution, and in view of the other approximations.

This modified distribution (Fig. 1) gives here the relative accumulation rate as function of depth. The actual concentration will depend on the effective irradiation time, and the other factors mentioned above, which are different for each of the media under consideration.

The following discussion will be concerned now with estimates of the factors (1) to (5) in

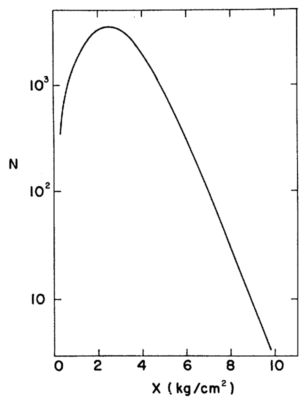

FIG. 1. Accumulation rate of quarks, N, as a function of depth of the target, X.

the most obvious targets of the search for the quark: sea water, air, rock, marine sediments, and meteorites.

Sea water.—The residence time of quarks in the oceans may be discussed in analogy to the common considerations in marine geochemistry. The extreme variability of the residence times of various elements is indicated by Mason[10] and Goldberg.[11] Residence times of Al and Fe are of the order of few hundred years, while that of Na, 10^8 y.

The uncertainties about the nuclear and chemical interactions of quarks prevent definite predictions, but some possibilities, based on evaluation of thermodynamic equilibria of quarks and quark atoms in sea water,[12] may be indicated. The positive presumably stable quark with charge $+\frac{2}{3}e$ after coming to rest would reside in its equivalent of water molecule $(\mathrm{H}Q\mathrm{O})^{-1/3}$. This would be preferentially adsorbed by trivalent ions of Al and Fe, as compared with neutral water molecules. The negative quark, with charge $-\frac{1}{3}e$, if it escaped decay before coming to rest, would be absorbed into an atomic orbit and finally absorbed into a nucleus. In analogy to the π^- (Petrukhin and Prokoshkin[13]) it could be preferentially absorbed by the oxygen nucleus. The resulting water molecule $(\mathrm{H_2O}_Q)^{-1/3}$ would be similarly adsorbed by polyvalent ions. The oxygen-quark nucleus may, however, undergo β decay and produce a higher-Z nucleus of fractional charge. Essentially similar results are obtained for antiquarks or under assumption that the negative quark is the stable one. The foregoing arguments leave a wide range of the residence times, 10^2-10^9 y, with a probable value of 10^3 y, that of trivalent ions.

We have to consider also the dilution effect in the oceans. The initial distribution of quarks at creation is in the upper 4 kg/cm^2, but within the residence time they are mixed throughout the average depth of the oceans—380 kg/cm^2. The dilution factor is therefore ~100.

We obtain, therefore, for sea water $T = 10^3$ and $D = 100$. The factors which were not mentioned in the discussion do not contribute, and in the following calculation of the merit number will be assumed to be unity. We obtain, therefore, $M_\mathrm{S} = 10$ and the range of values 1-10^7.

Air.—The earth's atmosphere is subdivided in this discussion into stratosphere and troposphere, the stratosphere being defined for simplicity as the upper 200 g/cm^2 of the atmosphere.

We shall calculate first the stratospheric merit number, M_AS. Stratospheric residence time for aerosol particles is assumed to be 1 y.[14] We have to consider in this case also the enrichment factor. The air-sample-collection method concentrates the sample by the ratio of air mass to its aerosol content, as all nonvolatile, charged species would be collected on aerosol particles within minutes to hours.[15] Air density for lower stratosphere is 2.5×10^{-4} g/cm^3, and its aerosol content 8×10^{-15} g/cm^3.[15] The enrichment factor E is therefore 3×10^{10}. Accumulation rate correction should be applied to the stratosphere. Integration of the curve of Fig. 1 yields average values for the top 200 g/cm^2 one order of magnitude lower than for the peak of the distribution. We obtain therefore $M_\mathrm{AS} = 3\times10^9$.

Calculation of contribution of micrometeorites to stratospheric aerosols, considering recent data on their flux[16] and irradiation time[17] indicates that their effect can be neglected.

Similar considerations can be made with respect to the troposphere. However, aerosol residence time is only 0.03 y. Tropospheric aerosol content is 10^{-10} g/cm^3,[15] while air density is 1.28×10^{-3} g/cm^3. The enrichment ratio is therefore 10^7. Consequently, we obtain for the tropospheric merit number, M_AT, the value 3×10^5. It can be readily shown that the cosmic-dust contribution is even less important than in the stratosphere, and so is the contribution of the stratospheric aerosols.

Rock.—The irradiation time of the earth's surface rocks is limited by its erosion rate, which can be estimated from total influx of soil matter into the oceans.[10] The estimate is 0.2

kg/cm^2 per million years, possibly varying within factor of 10 for various rock types and climates. The maximum irradiation time is defined here as the ratio of the width of the maximum concentration (at half intensity) divided by the erosion rate. Using 3 kg/cm^2 as peak width (Fig. 1) we obtain irradiation times of 10^7 y, with a range of 2×10^6-2×10^8 y. The accumulation-rate factor is 1 at ground level if it could be assumed that the rock surface was completely exposed throughout that period. The merit number would therefore be $M_{\rm R}=10^7$ with a range of 10^6-10^8.

Considerations of similar nature with respect to marine sediments based on average sedimentation rates,[18] give merit numbers $M_{\rm Sed}=2\times10^7$, with a probable range of 10^6-10^8 y.

Meteorites.—Meteorites record the longest irradiation times, of over 10^9 y. The effect of space erosion, atmospheric ablation, and finite size have to be considered, however. For iron meteorites having the longest measured exposure ages, space erosion is considerably smaller than for chondrites. Its upper limit is set at 3.7×10^{-8} cm/y,[17] or 300 g/cm^2 10^9 y. The ablation is harder to evaluate, typical values for stone meteorites being 70-90%.[19] Consideration of the concentration dependence with depth leads to the exclusion of small meteorites. A preatmospheric diameter of 4-5 m (i.e., 270-530 ton) should provide an optimum size. Of the available meteorites, Sikhote-Alin (irradiation age 2.2×10^8) may be closest to this requirement.[19] Its preatmospheric size was probably 270 tons of which 70 survived the ablation while 200 tons were evaporated.[20] The merit number would therefore be $M_{\rm M}=2.2\times10^8$.

The Henbury meteorite was probably much larger,[20] and its radiation age estimate is 1200 my. It might therefore increase $M_{\rm M}$ by factor of 5 if location of sample with respect to the surface could be determined with the aid of the radioisotope ratio method.[21,22] The practical difficulty is due to the fact that meteorites of this size arrive at an energy which "explodes" their entire mass, and only early-breakup samples may be available.

The upper limit for M for iron meteorites, if we add also the effect of focusing due to radial irradiation, could possibly be 5×10^9.

Discussion.—Table I sums up the merit numbers of the various media, and the available experimental results.

Stratospheric aerosols and iron meteorites of relatively large size and long irradiation age constitute therefore an optimum search medium according to our present knowledge. More selective sampling of aerosols could still improve their merits, if the stratosphere could be sampled in defined regions of relatively longer residence times[14] and low aerosol content, so as to maximize the product TE. However, efficient methods of sampling of gram quantities of material in the stratosphere are not yet available.

Iron meteorites may have an experimental advantage in availability of large samples, possibility of determining irradiation time and location, and lower background in a mass spectrometric search because of its well defined

Table I. Values of merit numbers, M.

Medium	Typical value	Range	Upper limit of quark/nucleon concentration (experimental)
Sea water	10	$1-10^7$	5×10^{-27}
Stratospheric aerosol	3×10^9	10^9-10^{10}	
Tropospheric aerosol	3×10^5	10^5-10^6	$3\times10^{-27}-10^{-33}$ [a]
Rock	10^7	10^6-10^8	
Marine sediments	2×10^7	10^6-10^8	
Meteorite	2×10^8	$10^8-5\times10^9$	10^{-17} [a]
Graphite			10^{-16} [b]
"Ideal" medium	3×10^9		10^{-18} [c]

[a]Chupka, Schiffer, and Stevens, Ref. 1.
[b]Gallinaro and Morpurgo, Ref. 3.
[c]"Ideal" medium is defined as one that integrates the quark flux for 3×10^9 y without enrichment and dilution effects ($E=D=1$). Upper limit of the flux is that given by the dynamic experiments (i.e., Lamb et al. [Ref. 8]). The limiting concentration is calculated at the peak of the distribution given in Fig. 1.

composition, peaked at the iron group.

It is hard to justify graphite as a suitable medium of search[3] without detailed investigation of its geological origin and chemical processing.

The experimental results can now be reviewed in light of the foregoing considerations. The limits imposed by the dynamic experiments indicate that a useful search method should be more sensitive than 10^{-20} quark/nucleon. The differences in limiting concentrations of 10^{-17} quark/nucleon for meteorites and 10^{-27} for sea water do not seem really significant in view of the possible difference of 10 orders of magnitude in their M values of Table I. The tropospheric value may be more significant, but requires more detailed knowledge of the collection efficiency in the sampling procedure. A careful consideration of geophysical aspects is obviously justified before significant additional effort is spent in quark search.

I would like to thank Professor G. Alexander, Professor M. Anbar, and Dr. A. Lerman for helpful discussion, and Mr. Gershon for computation programs.

[1]W. A. Chupka, J. P. Schiffer, and C. M. Stevens, Phys. Rev. Letters 17, 60 (1966).

[2]C. Becchi, G. Gallinaro, and G. Morpurgo, Nuovo Cimento 39, 409 (1965).

[3]G. Gallinaro and G. Morpurgo, Phys. Letters 23, 609 (1966).

[4]O. Sinanoǧlu, B. Skutnik, and R. Tousey, Phys. Rev. Letters 17, 785 (1966).

[5]T. Massam, Th. Muller, and A. Zichichi, Nuovo Cimento 40A, 589 (1965).

[6]H. Kasha, L. B. Leipuner, and R. K. Adair, Phys. Rev. 150, 1140 (1966).

[7]A. Buhler-Broglin, G. Fortunato, T. Massam, Th. Muller, and A. Zichichi, in Proceedings of the Thirteenth International Conference on High Energy Physics, Berkeley, 1966 (University of California Press, Berkeley, California, 1967).

[8]R. C. Lamb, R. A. Lundy, T. B. Novey, and D. D. Yovanovitch, Phys. Rev. Letters 17, 1068 (1966).

[9]R. K. Adair and J. Price, Phys. Rev. 142, 844 (1966).

[10]B. Mason, Principles of Geochemistry (John Wiley & Sons, Inc., New York, 1962), 2nd ed., Chap. 6.

[11]E. D. Goldberg, in The Sea, edited by M. N. Hill (Interscience Publishers, Inc., New York, 1963), Vol. II, Table I, p. 4.

[12]M. Anbar, private communication.

[13]V. I. Petrukhin and Yu. D. Prokoshkin, Nuovo Cimento 28, 99 (1963).

[14]H. Bhandri, D. Lal, and Rama, Tellus 18, 391 (1966).

[15]C. E. Junge, Air Chemistry and Radioactivity (Academic Press, Inc., New York, 1963), Chap. 2.

[16]R. K. Soberman, Proceedings of the Summer School on Space Physics., University of Tel Aviv, 1966 (to be published).

[17]D. E. Fisher, J. Geophys. Res. 71, 3251 (1966).

[18]E. D. Goldberg and M. Koide, Geochim. Cosmochim. Acta 26, 417 (1962).

[19]E. Anders, Rev. Mod. Phys. 34, 287 (1962).

[20]E. L. Krinov, in The Moon, Meteorites, and Comets, edited by B. M. Middlehurst and G. P. Kuiper (University of Chicago Press, Chicago, Illinois, 1963), p. 183.

[21]P. Eberhardt, J. Geiss, and H. Lutz, in Earth Science and Meteorites, edited by J. Geiss and E. D. Goldberg (North-Holland Publishing Company, Amsterdam, 1963), p. 143.

[22]A. K. Lavrukhina, Dokl. Akad. Nauk SSSR 168, 1275 (1966) [translation: Soviet Phys.—Doklady 11, 471 (1966)].

REGGEIZATION OF INTERNAL SYMMETRIES

Abdus Salam and J. Strathdee*
International Atomic Energy Agency, International Centre for Theoretical Physics, Trieste, Italy
(Received 19 June 1967)

A new approach to higher symmetries is suggested, particularly to the particle spectrum associated with them, based on a generalized partial-wave analysis of the conventional S matrix.

In this note we suggest a new approach to higher symmetries, and particularly to the particle spectrum associated with them, based on a generalized partial-wave analysis of the conventional S matrix. We exploit the fact that partial-wave analyses can be effected using (almost) any complete set of orthogonal functions and in particular (for certain classes of S-matrix elements) using orthogonal sets defined on the higher symmetry groups. The partial-wave amplitudes turn out in such a scheme to depend on the Casimir invariants (C) of the symmetry group in question. An assumption of meromorphy of the amplitudes for complex C then leads to the following results:

(1) Reggeization of ordinary spin gives rise also to recurrences in internal symmetries.