is not so, and measurement errors of ±1 $\mu$ have been used for the $Li^7$ track (13.4 $\mu$ long), and for the $_{\Lambda\Lambda}He^6$ track, which is 30.0 $\mu$ long.

The decay event gives somewhat better accuracy for the interaction energy as there are fewer mass errors contributing. The visible energy in the decay is $30.0 \pm 0.5$ MeV. Most of this error is due to the pion range straggling. The $\Lambda$-hyperon $Q$ value adds an error of 0.1 MeV. The total error on the value of 4.5 is thus 0.6 MeV. Combining the two independent determinations, $4.7 \pm 1.0$ MeV from production and $4.5 \pm 0.6$ MeV, we get a final result of $4.6 \pm 0.5$ MeV. As the $_{\Lambda\Lambda}He^6$ core has no spin, the question of the hyperon-core spin interaction does not arise. This value then is the true binding between the two $\Lambda$ hyperons in $_{\Lambda\Lambda}He^6$.

We are most indebted to the Brookhaven National Laboratory and to the groups involved in the $\Omega^-$ experiment for their kindness in allowing us to expose our stack behind their apparatus. We also wish to thank Dr. Hornbostel for making the emulsion facilities available to us, and Mr. Charles Walker, Dr. B. Bhowmik, and Dr. Jere Lord for help with the exposure.

---

*Partially supported by the National Science Foundation.

[1]M. Danysz et al., Nucl. Phys. 49, 121 (1963).

[2]European collaboration, Université Libre de Bruxelles, Institut de Physique, Bulletin No. 24 (unpublished).

[3]J. Pniewski and M. Danysz, Phys. Letters 1, 142 (1962).

[4]A. H. Rosenfeld et al., Rev. Mod. Phys. 37, 633 (1965).

[5]L. A. König et al., Nucl. Phys. 31, 1 (1962).

[6]A. Lou et al., "Range-Momentum Relationship for Heavy Low Velocity Ions" (to be published).

[7]R. P. Henke and E. V. Benton, Phys. Rev. 139, A2017 (1965).

[8]M. Danysz and J. Zakrzewski, Nucl. Phys. 74, 572 (1965).

[9]H. H. Heckman et al., Phys. Rev. 117, 544 (1960).

[10]J. H. Atkinson and B. H. Willis, University of California Radiation Laboratory Report No. UCRL-2426 (revised), 1957 (unpublished), Vol. II.

---

# SEARCH FOR QUARKS IN THE FAR ULTRAVIOLET SOLAR SPECTRUM*

O. Sinanoğlu† and B. Skutnik
Yale University, New Haven, Connecticut

and

R. Tousey
Naval Research Laboratory, Washington, D. C.
(Received 9 August 1966)

The sharp emission lines in the range 200 to 1700 Å originate from regions of the sun where quarks may be found mainly as bound to the nuclei of carbon, nitrogen, and oxygen. Electronic transitions of such species are predicted and a search is carried out in the far uv solar spectrum.

As a possible explanation of the approximate SU(3) symmetry and the meson and baryon multiplets, Gell-Mann[1] and Zweig[2] have proposed a fundamental triplet of constituents, the fractionally charged "quarks" ($Q_{p'} = +\frac{2}{3}e$; $Q_{n'} = Q_{\Lambda'} = -\frac{1}{3}e$). The SU(6) classification[3] acquires a particularly simple interpretation in terms of the generalized Pauli principle in this model, although its predictions may be obtained with or without models. The higher meson and baryon resonances so far seem to fit quite well into the quark model with the introduction of orbital angular momentum,[4] $\vec{L}$, though here again many of the predictions seem to follow quite equally either from abstract group-theoretic[5] or Lie-algebraic methods or from specific dynamical models.[6,7] The question of whether such triplets do actually exist and are not just mathematical artifacts seems to acquire further significance as the dimension of the unitary irreducible representations of the groups grow, whereas models though crude retain a certain amount of specific calculational features.

A number of other integrally charged triplets have also been proposed[8,9] to get around the antisymmetric spatial wave-function difficulty of the ground-state baryon quark model. This involves a large number of constituent species which would also be much more difficult to detect.[10]

Quarks have been searched for in high-energy experiments[11] and in cosmic rays.[12] They have not been found for masses, $M_q$, up to 7 BeV. A number of physico-chemical means for looking for stable quarks have been proposed.[13] Searches in meteorites and on earth have not revealed them.[14,15]

Zel'dovich, Okun', and Pikel'ner's cosmological estimates[13] indicate that $+\frac{2}{3}$ quarks would be less abundant and remain in interstellar space, whereas $-\frac{1}{3}$ quarks would attach themselves mainly to carbon, nitrogen, and oxygen and stay in stellar objects. Such "quarked atoms" and ions (C′, N′, O′) should exhibit distinct electronic spectra.

In this note, we propose and carry out a preliminary search for quarks in solar extreme uv spectra in the range $\lambda < 2000$ Å, obtained from above the atmosphere.[16] Below about 1900 Å, the spectra yield well-defined emission lines, many of which have been identified with the laboratory lines of various multiply ionized atoms. They originate from the low chromosphere to the corona, where the temperatures range from $5\times10^3$ to $2\times10^6$ °K and where carbon, nitrogen, and oxygen are the most abundant elements next to hydrogen and helium. According to a recent estimate[13] based on Coulombic forces alone, $-\frac{1}{3}$ quarks would remain preferentially attached to the C, N, and O nuclei up to a temperature of $10^7$ °K.

The resolution of the spectra is ca 0.2 Å for

Table I. Predicted "quarked atom" transitions.

| Species[a] | Transition | λ (Å) | $\lvert f_{ki}\rvert$ | Relative intensity |
|---|---|---|---|---|
| C′ IV (1) | $^2P_{3/2}\to{}^2S_{1/2}$ | 1691.2 ±0.2 | 0.102 | 2 |
| | $^2P_{1/2}\to{}^2S_{1/2}$ | 1689.0 ±0.2 | 0.102 | 1 |
| C′ III (1) | $^1P_1\to{}^1S_0$ | 1077.93 ±0.1 | 0.29 | |
| O′ VI (1) | $^2P_{3/2}\to{}^2S_{1/2}$ | 1097.77 ±0.08 | 0.065 | 2 |
| | $^2P_{1/2}\to{}^2S_{1/2}$ | 1092.6 ±0.1 | 0.069 | 1 |
| O′ VI (4) | $^2S_{1/2}\to{}^2P_{3/2}$ | 206.667 ±0.008 | 0.060 | 2 |
| | $^2S_{1/2}\to{}^2P_{1/2}$ | 206.483 ±0.008 | 0.030 | 1 |
| O′ V (1) | $^1P_1\to{}^1S_0$ | 668.84 ±0.08 | 0.19 | |
| O′ IV (1) | $^2D_{5/2}\to{}^2P_{3/2}$ | 846.24 ±0.04 | 0.093 | 9 |
| | $^2D_{3/2}\to{}^2P_{1/2}$ | 845.06 ±0.04 | 0.080 | 5 |
| | $^2D_{3/2}\to{}^2P_{3/2}$ | 846.17 ±0.04 | 0.015 | 1 |
| O′ IV (2) | $^2S_{1/2}\to{}^2P_{3/2}$ | 653.27 ±0.08 | 0.20 | 2 |
| | $^2S_{1/2}\to{}^2P_{1/2}$ | 651.99 ±0.08 | 0.10 | 1 |
| O′ III (1) | $^3D_3\to{}^3P_2$ | 904.34 ±0.05 | 0.090 | 84 |
| | $^3D_2\to{}^3P_1$ | 902.91 ±0.05 | 0.072 | 45 |
| | $^3D_1\to{}^3P_0$ | 902.16 ±0.05 | 0.053 | 20 |
| | $^3D_2\to{}^3P_2$ | 904.15 ±0.05 | 0.023 | 15 |
| | $^3D_1\to{}^3P_1$ | 902.90 ±0.05 | 0.039 | 15 |
| | $^3D_1\to{}^3P_2$ | 904.14 ±0.05 | 0.0026 | 1 |
| N′ V (1) | $^2P_{3/2}\to{}^2S_{1/2}$ | 1330.7 ±0.3 | 0.084 | 2 |
| | $^2P_{1/2}\to{}^2S_{1/2}$ | 1327.3 ±0.3 | 0.084 | 1 |
| N′ IV (1) | $^1P_1\to{}^1S_0$ | 824.6 ±0.2 | 0.23 | |
| N′ III (1) | $^2D_{5/2}\to{}^2P_{3/2}$ | 1084.65 ±0.05 | 0.12 | 9 |
| | $^2D_{3/2}\to{}^2P_{1/2}$ | 1082.76 ±0.05 | 0.10 | 5 |
| | $^2D_{3/2}\to{}^2P_{3/2}$ | 1084.58 ±0.05 | 0.021 | 1 |
| N′ II (1) | $^3D_3\to{}^3P_2$ | 1207.6 ±0.2 | 0.087 | 84 |
| | $^3D_2\to{}^3P_1$ | 1206.5 ±0.2 | 0.072 | 45 |
| | $^3D_1\to{}^3P_0$ | 1206.0 ±0.2 | 0.047 | 20 |
| | $^3D_2\to{}^3P_2$ | 1207.4 ±0.2 | 0.021 | 15 |
| | $^3D_1\to{}^3P_2$ | 1207.4 ±0.2 | 0.0023 | 1 |
| | $^3D_1\to{}^3P_1$ | 1206.5 ±0.2 | 0.036 | 15 |

[a]$A'$ is atom $A$ with one $-\frac{1}{3}$ quark associated with its nucleus. The number in parentheses after the species designation is the multiplet number as in C. E. Moore's Ultraviolet Multiplet Tables, National Bureau of Standards, Circular 488 (U. S. Government Printing Office, Washington, D. C., 1950), Sec. 1. It specifies the electron configurations involved.

1200 to 2000 Å, and ca 0.1 Å for $\lambda < 1200$ Å. At $\lambda > 2100$ Å the spectra are photospheric, containing closely packed absorption lines on a continuum. Since so large a fraction is unidentified, a search for quark lines here was not worthwhile. Gaseous nebulas also produce well-defined lines, but faint "forbidden" ones; where, also, the quark concentrations are expected to be much smaller.

We have predicted a number of strongest transitions of the species C′, N′, O′ in various stages of ionization for 200 Å $< \lambda <$ 1800 Å. Interpolation techniques similar to Edlén's[17] along isoelectronic series are used. The accuracy of the values are checked by test predictions of known members of the appropriate series. The accuracy of the predictions and that of the solar wavelengths are about equal. Oscillator strengths are also interpolated.[18] Relative intensity ratios of different $\Delta J$ transitions within the same multiplet are calculated in the usual way.[19] The species, transition involved, predicted $\lambda$'s, and error estimates are shown in Table I.[20]

In the photographic spectra, the lowest detectable intensity increment for an emission line above the chromospheric continuum is ca $5\times10^{-6}$ erg/cm$^2$ sec in the range 1000 Å $< \lambda <$ 1200 Å and $1.2\times10^{-4}$ for 1300 Å $< \lambda <$ 1800 Å. Comparing this with the intensity of a strong line of a normal species of known abundance, one sets upper limits to the corresponding "quarked-atom" abundances.

Table II shows the outcome of the search. Three coincidences with unidentified solar lines were found and 11 lines were masked. Where a predicted line was not detected an upper limit on the abundance is given.

In the present search, the observed intensity of the line at 1689.0 Å, which is the most probable quark line, leads to an abundance for quarked carbon of $10^{-3}$ the value of ordinary carbon.[21] The masking by Fe II of the other line of the multiplet prevents obtaining a check on this identification. In this region the probability of a wavelength to fall on an unidentified line is 7% as obtained from the number of lines within decreasing intervals. The probability of masking by some already identified line is 20%. The observed 1207.77-Å line, if identified with the 1207.6 ∓ 0.2 Å of N′ II (1), would lead to an abundance ratio $5\times10^{-4}$ N′/N. The probability of hitting an unidentified line here is 11%, and that of masking, 30%. Though the first few lines in Table II are quite favorable, their significance is diminished in view of the lines missing for related transitions or ions. The normal C III (1) line is especially strong in the spectrum, yet it is missing for C′ III (1). All "quarked-oxygen" lines are missing. Thus the over-all outcome is negative though for unobserved lines the upper limits that can be set at present are not very low. More restrictive upper limits to quark abun-

Table II. Comparison of predictions with the solar spectrum.

| Species | Predicted (Å) | Remarks |
|---|---|---|
| C′ IV (1) | 1689.0 ∓ 0.2 | A faint line is present and is otherwise unidentified |
| | 1691.2 ± 0.2 | Blends with Fe II (40), 1691.28 Å |
| N′ II (1) | 1207.6 ± 0.2 | A line at 1207.77 is present and is otherwise unidentified |
| | 1206.5 ± 0.2 | Masked by Si III (2), 1206.52 Å |
| | 1206.0 ± 0.2 | Not present |
| | 1207.4 ± 0.2 | A line at 1207.25 is present and is otherwise unidentified |
| N′ III (1) | 1084.65 ± 0.05 | Blended with N II (1), 1084.568 Å |
| | 1082.76 ± 0.05 | Not present |
| | 1084.58 ± 0.05 | Blended with N II (1), 1084.568 Å |
| O′ III (1) | 902-904 | Masked completely by C II (3) 903-904 Å |
| C′ III (1) | 1077.93 ± 0.1 | Not present; upper limit to abundance ratio $10^{-4}$ C′/C |
| O′ VI (1) | 1092.6-1097.8 | Neither present; abundance ratio $<10^{-4}$ O′/O |
| (4) | 206.5-206.7 | Neither present; abundance ratio $<10^{-4.5}$ O′/O |
| O′ V (1) | 668.84 ± 0.08 | Not present; abundance ratio $<10^{-4}$ O′/O |
| O′ IV (1) | 845-846 | Neither present; abundance ratio $<10^{-4}$ O′/O |
| (2) | 652-653 | Neither present; abundance ratio $<10^{-4}$ O′/O |
| N′ V (1) | 1327-1330 | Neither present; abundance ratio $<10^{-3}$ N′/N |
| N′ IV (1) | 824.6 ± 0.2 | Not present; abundance ratio $<10^{-3}$ N′/N |

dance would be set (or more of the predicted lines may become detectable) if larger spectrographs are flown with greater resolving power and larger exposures.

We thank Professor F. Gürsey and Mr. N. P. Patterson for stimulating and helpful discussions and Dr. J. D. Purcell for technical assistance.

---

*Work supported in part by a grant from the National Science Foundation.

†Alfred P. Sloan Fellow.

[1]M. Gell-Mann, Phys. Letters 8, 214 (1964).

[2]G. Zweig, CERN Report, 1964 (unpublished).

[3]F. Gürsey and L. A. Radicati, Phys. Rev. Letters 13, 173 (1964); B. Sakita, Phys. Rev. 136, B1756 (1964).

[4]M. Gell-Mann, Phys. Rev. Letters 14, 77 (1965).

[5]R. Gatto, L. Maiani, and G. Preparata, Phys. Rev. 140, B1579 (1965).

[6]R. H. Dalitz, in High Energy Physics; Lectures Delivered During the 1965 Session of the Summer School of Theoretical Physics, University of Grenoble, edited by C. De Witt and M. Jacob (Gordon and Breach Publishers, New York, 1966).

[7]O. Sinanoğlu, Phys. Rev. 145, 1205 (1966).

[8]Y. Nambu, in Proceedings of the Second Coral Gables Conference on Symmetry Principles at High Energies, University of Miami, January, 1965, edited by B. Kurşunoğlu, A. Perlmutter, and I. Sakmar (W. H. Freeman & Company, San Francisco, California, 1965), pp. 274-283.

[9]See, e.g., L. Van Hove, in Preludes in Theoretical Physics, edited by A. De Shalit, L. Van Hove, and H. Feshbach (North-Holland Publishing Company, Amsterdam, 1966).

[10]Electromagnetic properties of hadrons seem to favor quarks over integral charge triplets. M. P. Khanna and S. Okubo, International Centre for Theoretical Physics, Trieste, Report No. IC 66/28, 1966 (unpublished).

[11]L. B. Leipuner, W. T. Chu, R. S. Larsen, and R. K. Adair, Phys. Rev. Letters 12, 423 (1964); V. Hagopian, W. Selove, R. Ehrlich, E. Leboy, R. Lanza, D. Rahm, and M. Webster, Phys. Rev. Letters 13, 280 (1964); W. Blum, S. Brandt, V. T. Cocconi, O. Czyzewsky, J. Danysz, M. Tobes, G. Kellner, D. Miller, D. R. O. Morrison, W. Neale, and T. G. Rushbrooke, Phys. Rev. Letters 13, 353a (1964).

[12]A. W. Sunyar, A. Z. Schwarzchild, and P. I. Connors, Phys. Rev. 136, B1157 (1964); T. Bowen, D. A. DeLise, R. M. Kalbach, and L. B. Mortara, Phys. Rev. Letters 13, 778 (1964).

[13]Y. B. Zel'dovich, L. B. Okun', and S. B. Pikel'ner, Usp. Fiz. Nauk 87, 113 (1965) [translation: Soviet Phys.—Usp. 8, 702 (1966)].

[14]J. C. Barton and C. T. Stockel, Phys. Letters 21, 360 (1966).

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

[16]R. Tousey, Space Sci. Rev. 2, 3 (1963); S. R. Pottasch, ibid. 3, 816 (1964); H. Hinteregger, ibid. 4, 461 (1965).

[17]B. Edlén, in Handbuch der Physik, edited by S. Flügge (Springer-Verlag, Berlin, 1964), Vol. 27, p. 80.

[18]W. L. Weise, M. W. Smith, and B. M. Glennon, Atomic Transition Probabilities (National Bureau of Standards, Washington, D. C., 1966), Vol. I; C. W. Allen, Astrophysical Quantities (The Athlone Press, The University of London, London, England, 1963), pp. 53-76.

[19]E. U. Condon and G. H. Shortley, The Theory of Atomic Spectra (Cambridge University Press, Cambridge, England, 1963), pp. 237-239.

[20]The transitions selected and looked for are those where the corresponding normal atom lines appear strongly in the solar spectrum. Many other lines have been predicted which, however, already occur very weakly for normal atoms. The larger table available may be useful for laboratory spectroscopic searches in the C, N, and O of Earth. It may be argued that if quarks existed in the sun, they would have also shown up in the searches on Earth. It is also possible, however, that upon further fractionation, the earth quarks may have remained mostly in inaccessible layers, e.g., in the iron rich core.

[21]This is obtained by comparing the intensity with that of the corresponding transition of the normal atom [0.11 erg/cm$^2$ sec for 1548.2 Å of C IV (1)].