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De Rújula A, Georgi H & Glashow S L. Hadron masses in a gauge theory.
Phys. Rev. D—Part. Fields **12**:147-62, 1975.
[Lyman Laboratory, Dept. Physics, Harvard Univ., Cambridge, MA]

We explored the implications for hadron spectroscopy of the 'standard' gauge model of weak, electromagnetic, and strong interactions. We obtained many old and several new well-satisfied mass relations. Interpreting the newly discovered particles as 'charmonium,' we predicted the masses of charmed particles. [The *SCI*® indicates that this paper has been cited in over 725 publications since 1975.]

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"Heavily quoted papers are not necessarily the authors' very best. My coauthor, S.L. Glashow, shared the 1979 Nobel prize for earlier work.[1] H. Georgi may win the same prize for work on proton decay,[2-4] should protons decay. Perhaps the most striking feature of our paper is that its opening line, 'Once upon a time...' somehow escaped the strict editorial scissors of the *Physical Review*, devised to make 'scientific' English as colourless as possible. But I ought to find other redeeming values to this article.

"Hadrons (protons, neutrons, pions, and their 'strange' partners) are not elementary; they are bound states of quarks. The proton is two 'up' and one 'down' quarks; to 'obtain' the neutron, change up for down. The imperative 'change' can be extended, and expressed mathematically, as an 'SU(2) rotation' in an abstract space where 'up' and 'down' are basic directions. Strange particles require the introduction of a third 'strange quark' and the generalization of SU(2) to SU(3). To the extent that the distinctions between quarks (their different masses and charges) can be treated as a small correction, SU(3) is a good symmetry: it correctly predicts relations between particle masses. Up to the mid-1970s, quarks were generally thought to be a mere mathematical trick, the more abstract SU(3) symmetry being the only 'truth.' Theorists, mainly Glashow, had since 1964 advocated the existence of a fourth 'charmed' quark. A new particle, now known to be 'charmonium'—a bound state of a charmed quark and an anticharmed antiquark, was experimentally found in 1974. Its total charm was rather discreet: zero! This did not deter the Nobel Committee from awarding the 1976 prize to the leaders of the experimental groups: S. Ting[5] and B. Richter.[6] Did particles with net charm (only one charmed constituent) exist? In 1976 the answer was established to be affirmative. Could theorists correctly predict the masses of charmed particles? This is a point at hand.

"Infatuation with abstract mathematics is not uncommon in our field. Many authors exploited the 'obvious' SU(4) symmetry of a four-quark world to predict properties of its charmed sector. But the mass excess of the fourth quark was too large to be treated as a perturbation. Nature punished the culprits by proving them wrong. For chaotic reasons that completely escape my recollection, we explored a more committed approach. We took constituent quarks very seriously, and treated their bound states much as an 'unsophisticated' atomic physicist would. Quarks are bound by 'chromodynamic' forces, analogous in many respects to atomic electrodynamics. We used chromodynamics, then an infant, to estimate the mass splittings between particles having the same constituents, but different spin arrangements. Our approach, though not a complete theory, simply explained many properties of the 'old' particles, and correctly predicted the masses of the charmed ones. I hope that is why we are quoted.

"It is with great pride that I must admit that a single man, Andrei Sakharov,[7,8] independently reached conclusions very similar to ours."

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4. **Georgi H, Quinn H R & Weinberg S.** Hierarchy of interactions in unified gauge theories. *Phys. Rev. Lett.* **33**:451-4, 1974. (Cited 575 times.)
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8. **....................** Mass formula for mesons and baryons with alowance for charm. *JETP Lett.—Engl. Tr.* **21**:258-9, 1975.

