is such that even with a crude measurement such as the one described here, worthwhile information can be obtained on the parameters of many individual states just above the photoneutron threshold and on several statistical properties of these states. Bertozzi, Sargent, and Turchinetz,[6] who performed measurements at higher energies, and Bollinger,[11] who has considered the application of this technique to the problems now studied primarily by neutron resonance spectroscopy, have pointed out that nuclei in any mass region can be investigated with adequate precision by using a high-current pulsed electrostatic accelerator operating in the 5- to 8-MeV range as the source of electrons. For light nuclei, however, for which the spacing between the levels near the ground state is large, the poorer electron energy resolution of a linear accelerator is a less stringent restriction on the application of the technique.

We should like to acknowledge helpful discussions with Dr. S. C. Fultz and Dr. W. C. Dickinson. We also wish to thank E. M. Lent for calculations of the bremsstrahlung energy dependence and intensity; D. E. Petrich and the mechanical technicians for construction and assembly of the equipment required for this experiment; and E. Dante, Jr., and the accelerator operators for the good performance of the machine under unusual operating conditions.

---

*Work performed under the auspices of the U. S. Atomic Energy Commission.

[1]For example, see R. T. Carpenter, Argonne National Laboratory Report ANL-6589, 1962 (unpublished).

[2]P. Axel, K. Min, N. Stein, and D. C. Sutton, Phys. Rev. Letters 10, 299 (1963).

[3]For example, see F. D. Seward, Phys. Rev. 125, 335 (1962).

[4]J. A. McIntyre and J. C. Randall, Phys. Letters 17, 137 (1965).

[5]G. Ben-David, B. Arad, and I. Pelah, Nucl. Instr. Methods 26, 209 (1964).

[6]W. Bertozzi, C. P. Sargent, and W. Turchinetz, Phys. Letters 6, 108 (1963).

[7]K. K. Seth, R. H. Tabony, E. G. Bilpuch, and H. W. Newson, Phys. Letters 13, 70 (1964).

[8]S. A. Moszkowski in Alpha-, Beta-, and Gamma-Ray Spectroscopy, edited by Kai Siegbahn (North-Holland Publishing Company, Amsterdam, 1965), p. 881.

[9]L. M. Bollinger and G. E. Thomas, Rev. Sci. Instr. 28, 489 (1957).

[10]C. D. Bowman, G. S. Sidhu, and B. L. Berman, University of California Lawrence Radiation Laboratory Report No. UCRL-14942, 1966 (unpublished).

[11]L. M. Bollinger, in Proceedings of the Conference on Neutron Cross-Section Technology, Washington, D. C., 1966, edited by P. B. Hemmig, Atomic Energy Commission Report No. CONF 660303 (U. S. Government Printing Office, Washington, D. C., 1966), Books 1 and 2.

COUPLED-CHANNEL, SEVERAL-FORCE MODEL FOR A BARYON ANTIDECUPLET*

J. J. Brehm† and G. L. Kane‡
Summer Institute for Theoretical Physics, Seattle, Washington
(Received 15 August 1966)

Recent experiments[1] showing structure in K^+p and K^+d total cross sections have led us to examine in some detail the predictions of dynamical calculations for these systems. We find that two of the usual resonance mechanisms (baryon exchange and inelastic coupling) must be considered and yield a resonant $\underline{10}^*$ SU(3) multiplet with $J^P = \frac{1}{2}^+$ in the mass range 1.5 to 2 BeV.[2]

Baryon (B) and decuplet (D) exchanges in pseudoscalar meson-baryon (PB) scattering were studied by Martin and Wali,[3] who obtained a consistent set of particles, with a limited range of d/f ratios, comprised of the B octet ($\frac{1}{2}^+$), the D decuplet ($\frac{3}{2}^+$), and two unitary singlets, $\frac{1}{2}^-$ and $\frac{3}{2}^-$, all of which can be identified with observed particles. Their forces were attractive in the $\underline{10}^*$ states with $\frac{1}{2}^+$, but a resonant multiplet could not be conclusively established. The phase-shift analysis of Frye and Warnock,[4] based on the KN data of Stenger et al.,[5] allow for a $T=0$, $\frac{1}{2}^+$ phase shift ≈40° around 800 MeV/c. Lovelace[6] suggested that this system should resonate around 1300 MeV/c, and that the associated antidecuplet should include the Roper resonance[7] as well. Lovelace,[6] and others,[8] noted the importance of inelastic effects (notably, production involving a strongly interacting s-wave pion pair) in connection with the Roper resonance.

Cook and Lee,[9] and Auvil and Brehm[10] have proposed various inelastic models of various higher πN resonances. These are based on the effect of strong absorption when the quantum numbers of interest allow an s-wave inelastic state. Accordingly, we consider the effects of coupling to a scalar meson-baryon channel, where the scalar meson (S) is an octet.[11] Here it makes no significant difference whether we view S as a resonance or as a large scattering-length effect in a PP octet. Absorption through the SB channel should be important only for $J^P=\frac{1}{2}^+$, where it can have an s-wave component. Thus we consider coupled channels PB and SB with SU(3)-symmetric forces due to elastic B and D exchange, and P exchange coupling PB to SB. All the forces are significant in the $J^P=\frac{1}{2}^+$ channel. The elastic forces alone give the bound octet and a resonant $\underline{10}^*$. The inelastic forces are strongest in the singlet and $\underline{10}^*$ channels, because of the D-type coupling at the SPP vertex. Taken together, the singlet is eliminated by repulsive elastic forces, and a resonant $\underline{10}^*$ results.

The partial-wave scattering matrix satisfies an equation of the form

$$F(W)=B(W)+\int_{\text{right-hand cut}} F(x)\rho(x)F^+(x)dx/(W-x). \quad (1)$$

We construct an N/D solution to (1) using the method of Pagels,[12] which incorporates the desirable properties of symmetry of ND^{-1} and independence of the subtraction point. Moreover, no approximation is made to the input matrix $B(W)$, and no integration over $B(W)$ is called for (thus, no cutoff is needed). We assume that $B(W)$ in perturbation theory is an adequate approximation to the force that a complete theory, with consistent high-energy behavior, would give for those values of $W\lesssim 3M_B$ where we use $B(W)$. We have chosen to treat S as a resonant particle coupled to PP in $B(W)$. An alternative interpretation in terms of a scattering length would not affect our results qualitatively. There is also the usual ambiguity in defining exchanges of spin ≥ 1 in the elastic forces, because of the presence of nonresonant contributions in the exchange. Recent arguments,[13] based on analyticity in angular momentum, indicate that these contributions should be retained, and we have done so by calculating $B(W)$ in perturbation theory.

The couplings BBP, DBP, and SPP are taken SU(3) symmetric, and, where it is relevant, we take $f=0.4$.[3] The over-all coupling scale for BBP is given by $g^2/4\pi=15$. We choose the DPB coupling to yield the bound octet at the B mass,[14] giving $g'^2/4\pi\approx 0.04$. The masses of P, B, and D are obtained by averaging over the multiplets. For S we choose a mass in the region 600-800 MeV. (The results are not sensitive to this choice.) An upper limit of the scale of the SPP coupling may be obtained by assuming the decay width of the isoscalar member of S to be typically 100 MeV.

For resonances with $J^P\neq\frac{1}{2}^+$, the inelastic effect is not s wave and contributes little to other states treated in previous calculations.[3,9,10] In the $J^P=\frac{1}{2}^+$ channel, we could have SU(3) multiplets $\underline{1}, \underline{8}, \underline{10}, \underline{10}^*, \underline{27}$. In the $\underline{10}$ and the $\underline{27}$, neither the elastic nor the inelastic forces are strong enough to give any structure. In the singlet, both the elastic and inelastic forces have their strongest effect, repulsive from D and B exchange and attractive from the inelastic mechanism. D exchange easily dominates, and we find no enhancement. The octet channel is quite complicated, because the elastic forces alone give the baryon octet, and the effect of absorption is not negligible. We approximate the 4×4 octet problem by rotating the $(\underline{8}, \underline{8}')$ subspace to the basis in which the strongest exchange (D exchange) is diagonal, and then by neglecting all of the other (smaller) octet components. We then find only the baryon bound state, with no hint of higher energy structure.

In the $\underline{10}^*$ channel, we find the following results: The inelastic forces alone do not give a resonant $\underline{10}^*$, though for values of the PPS coupling constant near the limit mentioned above, they are strong enough to bring $\det D$ some distance toward zero. Their main effect is to require a modification of the mass splitting within the $\underline{10}^*$ (see below), so that it is not linear, as it might be expected to be, in a model based only on elastic forces.[15] The main result, we find, is that decuplet exchange alone will always give a resonant $\underline{10}^*$ when it gives a bound octet, with the $\underline{10}^*$ average mass about $4m_\pi$ above the octet average mass. This difference varies by about $\pm\frac{1}{3}m_\pi$, depending on the inelastic forces and the precise choice for the DBP coupling. The results for the problem with all forces differ only a little from the results for decuplet exchange alone; this is to some extent because strong forces tend to saturate using a realistic ND^{-1} solution such as Pagels's, and it is not easy to separate the effect of various forces. The $\underline{10}^*$ width comes out to be in the range $0.7m_\pi$-$0.9m_\pi$.

To see what mass splitting we expect in the $\underline{10}^*$, we can give the following argument: Consider the imaginary part of the elastic amplitude. Through unitarity it involves the square of the amplitude for $PB \to SB$. This latter amplitude is driven by single-particle exchange; and Wali, Warnock, and Ernst[15] have made it plausible that such amplitudes will lead to mass splittings consistent with an assumption of octet-symmetry breaking. Then its square will contain all the symmetry-breaking effects in $\underline{8}\times\underline{8}$, with contributions from $\underline{1}$, $\underline{8}$, and $\underline{27}$-type terms in the mass formula. For the $\underline{10}^*$ amplitude in the elastic channel, this then leads[16] to a mass formula $M = M_0 + M_1 Y + M_2 Y^2$; so the particle masses satisfy the relations $\Xi_{3/2} = Z_0 + 3(Y_1 - N_{1/2})$. From the model we are using, heavier physical input masses will in general lead to heavier resonance masses. Suppose we identify $N_{1/2}$ with the Roper resonance, at about 1450 MeV, and Z_0 with a $T = 0$ resonance at 1865 MeV. We would expect Y_1 to be no heavier than Z_0 (the particles coupled to Y_1 are of mass equal to those coupled to Z_0, but there is more absorption to pull down the Y_1). If we guess, for example, that $Y_1 = 1750$ MeV, we get $\Xi_{3/2} \approx 2750$ MeV. Since the Roper resonance has not yet been seen in total-cross-section measurements or bubble-chamber experiments, we have no reason to expect that the Y_1 has, and we are not aware of any existing $Y_1{}^*$ which we would want to assign to the $\underline{10}^*$.

We would like to thank the computation center of the University of Washington for subsidized computer time, and Professor E. M. Henley and Professor B. A. Jacobsohn for their hospitality at the Summer Institute.

---

*Research supported by the U. S. Atomic Energy Commission and by the National Science Foundation.

†Permanent address: Physics Department, Northwestern University, Evanston, Illinois.

‡Permanent address: Physics Department, University of Michigan, Ann Arbor, Michigan.

[1]R. L. Cool, G. Giacomelli, T. F. Kycia, B. A. Leontić, K. K. Li, A. Lundby, and J. Teiger, Phys. Rev. Letters 17, 102 (1966).

[2]This multiplet is among those in Goebel's strong-coupling theory, a different model. C. J. Goebel, Phys. Rev. Letters 16, 1130 (1966).

[3]A. Martin and K. C. Wali, Nuovo Cimento 31, 1324 (1964).

[4]R. Warnock and G. Frye, Phys. Rev. 138, B947 (1965).

[5]V. J. Stenger, W. E. Slater, D. H. Stork, H. K. Ticho, G. Goldhaber, and S. Goldhaber, Phys. Rev. 134, B1111 (1964).

[6]C. Lovelace, CERN Report No. CERN-TH628, 1956 (unpublished).

[7]L. D. Roper, Phys. Rev. Letters 12, 340 (1964).

[8]P. Carruthers, private communication. G. L. Shaw, private communication.

[9]L. F. Cook and B. W. Lee, Phys. Rev. 127, 283, 297 (1962).

[10]P. R. Auvil and J. J. Brehm, Phys. Rev. 138, B458 (1965); 140, B135 (1965). We have used the conventions and notation given in these papers.

[11]Though we know of no compelling experimental evidence for such an octet, there is a great deal of experimental evidence for a strong $J = T = 0$ $\pi\pi$ interaction, and it is well known [see, for example, Chan Hong-Mo, J. E. Paton, and P. de Celles, Nuovo Cimento 33, 70 (1964); R. Capps, Phys. Rev. Letters 16, 673 (1966)] that the single-particle-exchange forces in PP scattering give appreciable attraction in the scalar channel. Thus the dynamical assumptions we use also guarantee us the strong scalar interaction we are using.

[12]H. Pagels, Phys. Rev. 140, B1599 (1965). We adopt his notation for the parameters of the solution. A single term is kept in Pagels's approximation to his kernel function. The point a is chosen so that $N(a) \approx B(a)$. Interpretation of the solution is greatly simplified by this choice. Pagels's parameter matrix c is determined by matching at the elastic threshold, so that the formulas for $\det D(W)$, appropriate to the regions above and below threshold, will be continuous there.

[13]G. F. Chew, quoted in the following references: E. Abers and V. Teplitz, Nuovo Cimento 39, 739 (1965); Y. N. Srivastava and P. Nath, Phys. Rev. 142, 982 (1966).

[14]It has been known for some time that the forces generated by baryon exchange in the reciprocal bootstrap were in some sense too strong [see A. Martin and J. L. Uretsky, Phys. Rev. 135, B803 (1964), and references in their paper to other comments on this question]. Ordinarily some cutoff procedure has been used to reduce the forces such that a bound octet and a resonant decuplet result. In our calculation we have the advantage that we do not need to integrate over the baryon-exchange input; but the decuplet exchange force is indeed too strong, and we cannot suppress it by cutting off an integration. We use instead a DPB coupling constant chosen to give a bound octet around the average B mass we are using, and then we use this coupling constant in all channels. An interesting by-product of this procedure is that we have a simpler measure of the amount of suppression needed than that implied by a cutoff mass. The value given in the text for the coupling constant corresponds to about $\frac{1}{10}$ that we would obtain from the decuplet width.

[15]K. C. Wali and R. L. Warnock, Phys. Rev. 135, B1358 (1964); F. J. Ernst, K. C. Wali, and R. L. Warnock, ibid. 141, 1354 (1966).

[16]S. Okubo, Phys. Letters 4, 14 (1963).