were measured at dry ice temperatures while Logan's were measured at room temperature. Furthermore, Logan's points scatter as much as 100% from the line drawn through them, while my data when plotted yielded a rather good straight line. It therefore seems to me that, within the possible experimental errors inherent in this kind of experiment, Logan's and my results agree for the number of acceptors quenched into Ge. Furthermore, we both find the same activation energy of 2 ev.

Logan's method of quenching is to drop his samples into an oil bath. His quench time is clearly faster than the quench time used in my experiments where the sample cools by its own radiation. On the other hand, this is not to say that one can conclude from Logan's data that I could not possibly have quenched fast enough to trap these defects. Logan's shortest annealing time is of the order of one minute; in order to conduct annealing experiments to determine whether a given quench is fast enough, he would need to control anneals for periods of only a few seconds. My quenching rate was 100°C/sec initially and 5 seconds were required for the sample to cool to 500°C.

Logan has provided an interesting new fact on the quenching problem when he studied the effect of dislocations on the annealing rate. Logan found that in a sample with a dislocation density of $10^6/\text{cm}^2$ (measured by etch pits) he could not quench in any acceptors. Clearly, this is an indication that dislocations influence the speed of annealing of the defects produced by the heat treatment. In the process of dropping samples into the oil bath, it would be quite likely that some dislocations were introduced through plastic flow during the thermal shock associated with the quench. Possibly for this reason Logan's samples anneal much faster than my sample. On the other hand, the nature of his annealing curves is very similar to the annealing I observed.

Because of the obvious importance of dislocations on the annealing rate which Logan has shown, I have had the dislocation density measured in the sample which I used for my annealing experiments. We[4] found a dislocation density of $10^4/\text{cm}^2$ by counting CP4 etch pits on the (111) surface. This density is typical of the dislocation density for crystals pulled from the melt, indicating no noticeable production of dislocations during my heat treatment. I, therefore, would like to suggest that the apparent differences between the annealing rates in Logan's experiments and in mine arises from different dislocation densities.

As far as the experiments of Hopkins and Clarke are concerned, it is conceivable that no quenched defects were observed because the dislocation density in their samples might have been too high for their quench rate. It seems clear from the importance of the dislocations on the annealing process that any future experiments in this field should include measurements of dislocation density.

[1] R. A. Logan, Phys. Rev. **101**, 1455 (1956).
[2] R. L. Hopkins and E. N. Clarke, Phys. Rev. **100**, 1786 (1955).
[3] S. Mayburg, Phys. Rev. **95**, 38 (1954).
[4] S. A. Kulin and M. Dumais of the Lincoln Laboratories were kind enough to check our measurement of etch pit density.

Λ^0-Nucleon Forces*

DON B. LICHTENBERG AND MARC ROSS
Department of Physics, Indiana University, Bloomington, Indiana
(Received June 29, 1956)

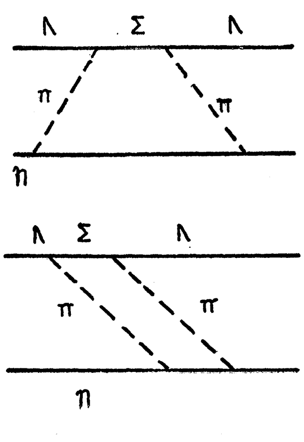
An analysis of the binding of Λ^0 hyperons in nuclei by Dalitz[1] has produced some definite information on the Λ-nucleon force. In particular the forces are strong and highly spin-dependent. It is the purpose of this note to show how this result may be predicted by a simple field-theoretic model, assuming the forces are due only to exchange of pions.[2] We assume spin $\frac{1}{2}$ for the Λ and Σ and give them the same parity. The form of the fixed-source Hamiltonian is then prescribed for processes

$$\Lambda\rightleftarrows\Sigma+\pi. \tag{1}$$

Instead of writing this directly, the interaction is more conveniently expressed in terms of a model of some intrinsic interest,[3] i.e., consider the Λ and Σ as corresponding singlet and triplet isotopic spin states of a bound nucleon and some other isotopic spin $\frac{1}{2}$ particle (such as the $\bar{\theta}$ meson). This picture, coupled with the assumption that the $\bar{\theta}$, say, does not interact with pions and so plays only a geometrical role, is equivalent to the assumption above. Now the Λ-nucleon potential is expressed in terms of the usual fixed-source pion-nucleon Hamiltonian

$$H=\sum_{k,\alpha}(a_{k\alpha}V_{k\alpha}+a_{k\alpha}^*V_{k\alpha}^*),$$
$$V_{k\alpha}=(ih/\mu)[\boldsymbol{\sigma}\cdot\mathbf{k}/(2\omega_k)^{\frac{1}{2}}]\tau_\alpha. \tag{2}$$

We must, of course, consider that the coupling constant h may be different from the usual constant f. We shall consider only fourth order diagrams. All crossed diagrams plus diagram (b) of Fig. 1, are those usually



(a)

(b)

FIG 1. Some processes considered in the Λ-nucleon potential.

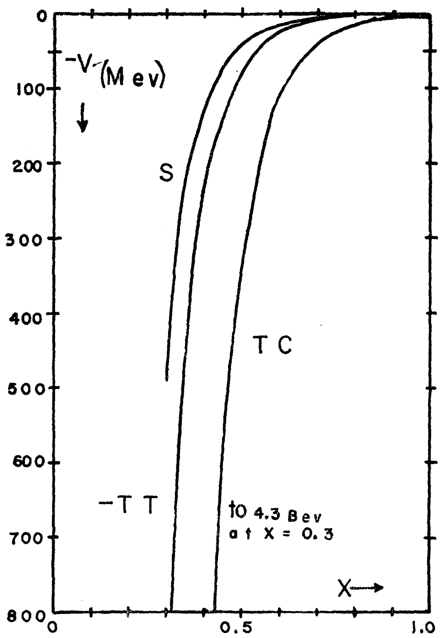


FIG. 2. The calculated Λ-nucleon potential for $h^2=0.14f^2$, $f^2=0.08$. The three curves are the singlet potential (S), the triplet central potential (TC), and minus the triplet tensor potential ($-TT$).

summed to obtain the fourth order of the two-nucleon potential. The uncrossed diagrams such as (a) of Fig. 1, with no mesons present in one intermediate state, are different from those usually considered in the two-nucleon problem.[4] The energy denominator in the zero-meson intermediate state is just $\Delta\equiv M_\Sigma-M_\Lambda=80$ Mev.

The evaluation of the potentials is straightforward. The integrals are easily performed in closed form if we neglect Δ compared to ω in the energy denominators. Noting that the expectation value of $\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2$ in the Λ-nucleon system vanishes, we obtain for the uncrossed diagrams such as that of Fig. 1(a):

$$V^{(a)}=-3[h^2f^2/(4\pi)^2](\mu^2/\Delta)(e^{-2x}/x^2)\times\left\{\left(1+\frac{4}{x}+\frac{10}{x^2}+\frac{12}{x^3}+\frac{6}{x^4}\right)+\tfrac{2}{3}\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\left(\frac{2}{x}+\frac{5}{x^2}+\frac{6}{x^3}+\frac{3}{x^4}\right)-\tfrac{1}{3}S_{12}\left(\frac{2}{x}+\frac{8}{x^2}+\frac{12}{x^3}+\frac{6}{x^4}\right)\right\},$$

where $x=\mu r$ and $\hbar=c=1$. For the remaining contributions, merely set $\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2=0$ and let $f^4\rightarrow f^2h^2$ in the expression given, for example, by Brueckner and Watson.[4] As might be expected, the $V^{(a)}$ is about five times as large as the latter potential except in the singlet state where $V^{(a)}$ is very small.

The total potential (see Fig. 2) is very singular near the origin as in the two-nucleon case. Since the static model fails for small x, these potentials are not valid there, and we therefore adopt repulsive cores for $x<x_0$, in analogy with the two-nucleon case. The quantitative results are sensitive to the core, so we will just illustrate the situation roughly with two examples. In the following the relatively weak tensor force has been neglected and distances are expressed in meson Compton wavelengths. There is a strong attraction in the triplet state which we know experimentally should not bind the Λ-nucleon system (at least, not strongly). Then let us ask: (A) what core radius corresponds to a just unbound state using $h^2/4\pi=f^2/4\pi=0.08$; and (B) what coupling constant h^2 corresponds to a just unbound state using the Brueckner-Watson two-nucleon radius $x_0=0.3$.[5] The results are approximately:

$$\text{(A)}: x_0=0.49,\qquad r_0=1.35,$$
$$\text{(B)}: h^2=0.14f^2,\quad r_0=1.04,$$

where the r_0's are the corresponding triplet effective ranges. Equivalent square-well potentials[6] have ranges equal to r_0. Their depths and volume integrals, $U=-\int V_0d^3r$ in Mev $\text{cm}^3\times10^{-39}$, are:

$$\text{(A)}: V_0=26 \text{ Mev},\qquad U=710,$$
$$\text{(B)}: V_0=44 \text{ Mev},\qquad U_t=570.$$

These results compare with the empirical value of Dalitz (assuming that the spin of the Λ is $\frac{1}{2}$ and its parity is +): $U_t=380$. In the singlet state the attraction is too weak to dominate the repulsive core and a discussion of the volume integral of the equivalent square well is not meaningful. However, a crude estimate of the role of such a hard core potential in a nucleus, assuming the nucleon-nuclear forces are relatively long-ranged, indicates that $U_s\approx -U_t$, a result which agrees to an order of magnitude with Dalitz' finding: $U_s=-480$. Thus this model is qualitatively in agreement with the highly spin-dependent Λ-nucleon force.

The authors would like to thank Dr. J. S. Kovacs for helpful discussions.

* Supported in part by the National Science Foundation.

[1] R. H. Dalitz, *Proceedings of the Sixth Annual Rochester Conference on High Energy Physics, Rochester, 1956* (Interscience Publishers, Inc., New York, to be published).

[2] Forces due to exchange of K mesons have received special attention up to the present. See, for example, K. Nishijima, Progr. Theoret. Phys. **14**, 527 (1955) and G. Wentzel, Phys. Rev. **101**, 835 (1956).

[3] M. Goldhaber, Phys. Rev. **101**, 433 (1956).

[4] We follow the procedure of K. A. Brueckner and K. M. Watson [Phys. Rev. **92**, 1023 (1953)] in making this statement about the two-nucleon potential. Fukuda, Sawada, and Taketani [Progr. Theoret. Phys. **12**, 156 (1954)] have shown that the omission of those diagrams corresponding to repetition of the second-order potential is not quite correct. This omission seems reasonable, however, if the potential is used only in a low-energy region. Of course, there is no ambiguity in deciding which fourth order diagrams to evaluate in the Λ-nucleon potential, since second-order diagrams are absent.

[5] The authors would like to thank Dr. M. Sugawara for information about the repulsive core in the two-nucleon potentials. See also, Brueckner, Levinson, and Mahmoud, Phys. Rev. **95**, 217 (1954).

[6] A proper investigation should of course be made of such hard-core potential in Λ-nucleus systems. This difficult task is not undertaken here; instead we feel that it is reasonable to consider the Λ-nucleon square-well potential yielding the same low-energy scattering results.