deny the existence of a μ^0 meson of about this mass value or lower. However, there is no compelling reason to postulate such a particle at this time.

We are pleased to acknowledge the help and advice received from Dr. Katharine Way in several phases of our tabulation.

† This work has been supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission, and also by the National Academy of Sciences—National Research Council.

* Present address: Department of Physics, Brown University, Providence 12, Rhode Island.

[1] R. E. Marshak and E. C. G. Sudarshan, Nuovo cimento **6**, 1335 (1957).
[2] Revs. Modern Phys. (to be published).
[3] Birge, Perkins, Peterson, Stork, and Whitehead, Nuovo cimento **4**, 834 (1956).
[4] G-Stack Collaboration, Nuovo cimento **2**, 1063 (1955).
[5] Ritson, Pevsner, Fung, Widgoff, Zorn, Goldhaber, and Goldhaber, Phys. Rev. **101**, 1085 (1956).
[6] Crussard, Fouché, Hennessy, Kayas, Leprince-Ringuet, Morellet, and Renard, Nuovo cimento **3**, 731 (1956).
[7] W. H. Barkas, University of California Radiation Laboratory Report UCRL-3769, April 9, 1957 (unpublished).
[8] Barkas, Barrett, Cüer, Heckman, Smith, and Ticho, University of California Radiation Laboratory Report UCRL-3768, April 9, 1957 (unpublished).
[9] Alexander, Johnston, and O'Ceallaigh, Nuovo cimento **6**, 478 (1957).

Fundamental Interactions and Hyperfragments

H. WEITZNER*

Harvard University, Cambridge, Massachusetts

(Received December 2, 1957)

WITH the presently existing data on hyperfragments it is possible to make preliminary tests of specific elementary-particle schemes. The scheme described in detail elsewhere by Schwinger,[1] postulating in part a universal pion-baryon coupling and fundamental equivalence of baryons in the absence of K-meson interactions, is that to be considered here. The work on hyperfragments of Lichtenberg and Ross[2] and Dallaporta and Ferrari[3] is based on similar interactions without any underlying symmetry considerations, but they appear to have neglected the effect of three-body forces to be described.

Just as pion exchange is considered to generate nuclear forces, so would one also assume the same origin for nucleon-hyperon forces binding the lambda to nuclei. From the usual invariance considerations, the simplest effective pion-lambda interaction must be of the form $\varphi_\pi(r)\varphi_\pi(r)\bar{\psi}_\Lambda(r)\psi_\Lambda(r)$. With two pions available at each effective vertex, exchange with two different nucleons or with the same nucleon will both occur. Thus a three-body term should appear in any potential based on a pion exchange with simple symmetry properties.

With the given specific interactions taken in the nonrelativistic limit, the potential was calculated in the static limit in the lowest nonvanishing order of the perturbation expansion. The lambda-sigma mass difference was largely ignored, as its effect seems to be a change in the range of the potential of $\sim 10\%$, scarcely noticeable among all the other approximations. With tensor forces omitted, the asymptotic form of the potential for two nucleons and a lambda is

$$V\{F^2(|\mathbf{r}_1-\mathbf{r}_\Lambda|)(1+a\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_\Lambda)+F^2(|\mathbf{r}_2-\mathbf{r}_\Lambda|)(1+a\boldsymbol{\sigma}_2\cdot\boldsymbol{\sigma}_\Lambda)\} + V^1\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2F(|\mathbf{r}_1-\mathbf{r}_\Lambda|)F(|\mathbf{r}_2-\mathbf{r}_\Lambda|),$$

where $F(r)=[\exp(-m_\pi r)]/m_\pi r$. The amount of dependence on the lambda spin in the two-body force cannot be reasonably determined from such a treatment, although the potential appears to be stronger in the singlet state ($a<0$). The potential formed in a similar manner from the phenomenological interaction differs primarily in the absence of lambda spin dependence ($a=0$). Either form seems consistent with the work to be described, but accepting the specific interactions one can make the estimate that $g_{\Sigma\Lambda\pi}^2/g_{N\pi}^2\sim 1$.

The binding energies of the lightest possible hyperfragments, ${}_\Lambda H^2$, ${}_\Lambda H^3$, ${}_\Lambda He^4$, and ${}_\Lambda H^4$, were examined by variational techniques. To facilitate computation the function $F(r)$ was replaced by $\exp(-\frac{1}{2}\lambda r^2)$. Although there seem to be no studies of the equivalence of various potential forms for three-body interactions, the equivalence of potential forms in the description of very low-energy nuclear phenomena suggests that one might attempt to extend it to this case. As the potential supposedly is generated by two-pion exchange, λ was taken to correspond to a range of $1/2m_\pi$, or $\lambda=1.05\times 10^{26}$ cm^{-2}. The lambda spin dependence in the potential was suppressed, as within the limitations of the work herein described there is not sufficient theoretical or experimental evidence to include it meaningfully. Trial functions with spatial coordinate dependence of the form

$$\exp\{-\alpha\sum_{i>j}|\mathbf{r}_i-\mathbf{r}_j|^2-\beta\sum_i|\mathbf{r}_i-\mathbf{r}_\Lambda|^2\},$$

where i, j refer to nuclear coordinates and Λ to the lambda coordinate, were used. By variation of both α and β it was found that the binding energies of ${}_\Lambda H^3$, ${}_\Lambda He^4$, and ${}_\Lambda H^4$, and the nonexistence of ${}_\Lambda H^2$ could be reproduced with $V=107$ Mev and $V^1=0.35V$. As a partial check on the procedure, the binding energies of the deuteron and the triton were computed with the same nuclear potentials and the same form of wave function. The binding energy of the deuteron was 58% of the actual value and of tritium 102% of the actual value. The excess binding in the latter case results in part from the form of the nuclear potential used, in which singlet and triplet potential ranges (but not strengths) were taken equal, and to a lesser degree from the omission of tensor forces. When information appears on the limiting value of the binding energy of a lambda in a large nucleus, it will be possible to test the validity of the omission of lambda spin dependence in this potential, as further variational calculations with Slater determinants of plane waves as trial functions indicate that without such dependence the binding energy should be extremely large, 30 Mev or more, while with it the energy could be much lower.

To estimate $g_{\Sigma\Lambda\pi}^2/g_{N\pi}^2$, the property of the potential that the hyperdeuteron has zero energy was used. By use of baryon equivalence[1] and the resulting interpretation of the operators $\boldsymbol{\tau}_\Lambda$, the static nucleon-nucleon potential may be interpreted as a nucleon-lambda-sigma potential. In the singlet state, it is readily shown that with the chosen ratio the hyperdeuteron is just unbound. The extension to other hyperfragments of this procedure at present seems unfeasible. Relations between V, V^1 and the masses and coupling constants are of questionable accuracy considering the changes the explicit form of the potential has undergone. These relations give roughly the same ratio.

Hyperfragments also give information on the scalar meson introduced by Schwinger[1] to produce further symmetries among the elementary particles. This meson also has a universal baryon interaction. Provided all other interactions between a nucleon and a lambda are attractive, the nonexistence of $_\Lambda H^2$ restricts the mass and coupling constant of the meson so that $m/m_N > 0.65(g^2/4\pi)$. If the contribution of this meson to the limiting value of the lambda heavy-nucleus binding energy is denoted by B, then further $B \cong 6.5 \times (g^2/4\pi)(m_N/m)^2$.

These restrictions are valid only as long as the meson mass is not so large that the nonrelativistic static limit ceases to apply. Since the masses and coupling constants are renormalized, initially equal constants may now differ as a result of the breaking of symmetries by the interactions.

* National Science Foundation Predoctoral Fellow.
[1] J. Schwinger, Ann. Phys. 2, 407, (1957).
[2] D. B. Lichtenberg and M. Ross, Phys. Rev. **107**, 1714 (1957); **103**, 1131 (1957); Bull. Am. Phys. Soc. Ser. II, 1, 337 (1956).
[3] N. Dallaporta and F. Ferrari, Nuovo cimento **5**, 111 (1957).

Neutron Spectrum from $p+d$ Reaction*

M. P. Nakada, J. D. Anderson, C. C. Gardner, J. McClure' and C. Wong

University of California Radiation Laboratory, Livermore, California

(Received February 19, 1958)

OBSERVATION of the neutron spectrum when deuterons are disintegrated through proton bombardment might give information on nucleon interactions.[1,2]

Neutrons produced when 8.9-Mev protons bombard deuterium in a gas cell were observed by time-of-flight techniques[3] on the Livermore variable-energy cyclotron. Figure 1 shows a time spectrum that was obtained.

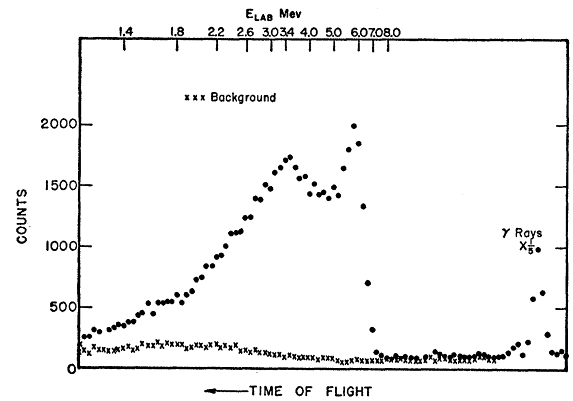

FIG. 1. Typical time-of-flight neutron spectrum for $p+d \rightarrow p+p+n$ reaction at 0°. The time scale is 1.012 mμsec per channel. The gamma rays are produced by protons striking the beam stopper in the gas target. The background run is taken on an evacuated target and also shows a gamma peak. The neutron energy scale is indicated above.

The peak near 6-Mev neutron energy is surprising when compared to the unstructured time spectrum that is obtained in d-d breakup; a previous observation[4] of d-d breakup at 6.3 Mev and our observations at 11.75 Mev show unstructured time distributions. To check the reality of the peak, the possibility of contaminants in the beam and gas cell was examined by checking on purity and by making observations on possible contaminants. Although such parameters as

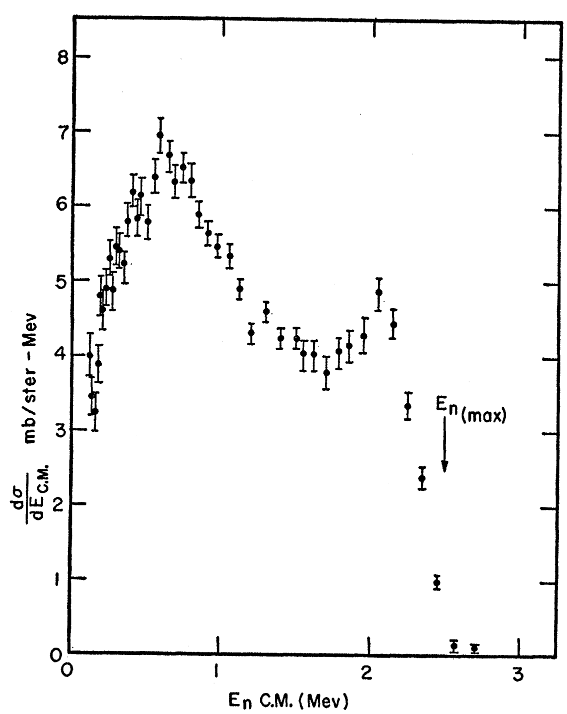

FIG. 2. Differential cross sections in the center-of-mass coordinate system for neutrons from the $p+d \rightarrow p+p+n$ reaction at 0°. E_n(max) is the calculated, maximum possible neutron energy from the breakup reaction.