PHYSICAL REVIEW VOLUME 92, NUMBER 1 OCTOBER 1, 1953

An Experimental Search for a Stable Dineutron

B. L. COHEN and T. H. HANDLEY
Oak Ridge National Laboratory, Oak Ridge, Tennessee

(Received June 25, 1953)

An attempt is made to detect dineutrons (δ) emitted from hypothetical (p,δ) reactions by observing the activity of the end product of (δ,p) reactions. The activity expected, assuming the dineutron to be stable, is calculated from the statistical theory of nuclear reactions and found to be greater than the maximum observed activity by a factor of 10^5. The acceptance of this result as conclusive would indicate that V_0a^2 for the neutron-neutron interaction cannot be more than 10 percent larger than for the neutron-proton interaction.

A DEFINITE answer to the question of whether or not a system of two neutrons possesses a bound state would be a significant contribution to the important nuclear physics problem of the neutron-neutron force. To show this, consider the singlet n-n force to be represented by a potential well of depth V_0 and range a; it may be shown[1] that the condition for existence of a bound state is $V_0a^2 \gtrsim 1.02\times10^{-24}$ Mev cm^2. The experimental results for n-p and p-p singlet potentials are $V_0a^2=0.93\times10^{-24}$ and 0.82×10^{-24} Mev cm^2, respectively. For the triplet n-p potential, $V_0a^2=1.67\times10^{-24}$ Mev cm^2, thus allowing the bound state of the deuteron. According to the principle of charge symmetry of nuclear forces, n-p and n-n forces should be identical; however, a difference of only 10 percent between the two would result in the existence of a bound state of the n-n system known as the dineutron.

The question of the existence of the dineutron (hereafter designated by δ) has been raised several times in the past few years. Feather[2] discussed the possibility of its existence and suggested several methods by which it might be detected. Fenning and Holt[3] attempted to detect its presence in fission by the activity that would be produced in bismuth by a (δ,γ) reaction. Ferguson and Montague[4] performed a similar experiment with helium. In both cases negative results were reported, but a quantitative analysis of their data (see below) indicates that their methods were somewhat insensitive.

Phillips,[5] from measurements of the γ-ray spectrum emitted in the reaction $\pi^-+d\rightarrow 2n+\gamma$, calculates that the dineutron should be unstable by about 260 kev; however, a bound state would be indicated if his results were changed by less than one probable error.

Kundu and Pool[6] and Taschek[7] have reported evidence for at least a quasi-stable dineutron, but their results can be explained equally well by a virtual state.

To throw additional light on this problem, a search was made for dineutrons emitted from (p,δ) reactions, with an attempt to detect them by (δ,p) reactions. This method of detection has two very distinct advantages over the methods of Fenning and Holt[3] and of Ferguson and Montague;[4] firstly, the cross section for (δ,p) would be expected to be much larger than for (δ,γ); and secondly, the radioactive end product may be extracted by radiochemical processing, which makes it possible to use a large detecting sample and still obtain good counting efficiency.

The detecting reaction used was

$$\mathrm{Cu}^{65}(\delta,p)\mathrm{Ni}^{66}\rightarrow\beta^-(56\text{ hr})+\beta^-(5\text{ min})+\mathrm{Zn}^{66}.$$

Several plates of electrolytic copper weighing a total of 3000 grams were placed in the ORNL 86-inch cyclotron immediately behind a thick bismuth target which was then bombarded with 1000 microamperes of 23-Mev protons for 125 hours. After the bombardment, the copper was chemically processed to remove the nickel which was then counted for 35 days under an end-window Geiger counter with an absorber interposed (since the 5-min daughter of Ni^{66} decays with a 2.6-Mev beta). The data resolved into a very long half-life ($\gtrsim 5$ years) and the 36-hour activity due to Ni^{57} from the $(n,2n)$ reaction in the nickel impurity. The maximum possible 56-hour activity, extrapolated to the end of the bombardment and taking into account the 11 percent chemical yield (determined from both spectrographic and activation analyses of the nickel impurity in the copper) and the 40 percent counting efficiency, was determined to be 2.5 disintegrations per second.

The expected yield, assuming the dineutron to be stable, was calculated from the statistical theory of nuclear reactions[8] in a straightforward way.[9] It was found to be larger than the maximum observed activity by a factor of 10^5. An analysis of the uncertainties in-

---

[1] H. A. Bethe, Revs. Modern Phys. **9**, 71 (1937).

[2] N. Feather, Nature **162**, 213 (1948).

[3] F. W. Fenning and F. R. Holt, Nature **165**, 722 (1950).

[4] A. J. Ferguson and J. H. Montague, Phys. Rev. **87**, 215 (1952).

[5] R. H. Phillips, University of California Radiation Laboratory Report UCRL-1895, 1952 (unpublished).

[6] D. N. Kundu and M. L. Pool, Phys. Rev. **73**, 22 (1948).

[7] R. F. Taschek, Phys. Rev. **79**, 238 (1950).

[8] J. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, New York, 1952).

[9] B. L. Cohen, Oak Ridge National Laboratory Report 1382 (unpublished). The calculation assumes that sticking probabilities for dineutrons are unity, so that $F_\delta=F_n$ (except, of course, for energetic differences) in reference 8, p. 373. The threshold for $(p,2n)$, and therefore for (p,δ), in bismuth has been measured as about 8 Mev. The maximum beta energy of Ni^{66} was taken as 1.7 Mev which is as large as can be expected for a 56-hr activity. The level density of the odd-odd nucleus Cu^{66} was assumed four times larger than that of the even-even nucleus Ni^{66}.

volved in the calculation reveals that while they are large, they could not, without the greatest difficulty, be stretched to explain so large a discrepancy.[9a]

A similar calculation on the data from references 3 and 4 indicates that, if a dineutron were stable,[10]

$$\text{for bismuth, } \sigma(\delta,\gamma) \lesssim 10^{-29}\ \text{cm}^2;$$

$$\text{for helium, } \sigma(\delta,\gamma) \lesssim 5\times 10^{-28}\ \text{cm}^2.$$

Since (δ,γ) reactions compete with (δ,n) reactions in which neutron emission is energetically possible by at least 7 Mev, these cross sections are not unreasonably small. In addition, there is greater uncertainty in the application of the statistical theory of nuclear reactions to fission than to simpler reactions such as (p,δ). By use of (δ,p) detection, the sensitivity of the search for the dineutron in fission could be extended to almost any desired sensitivity by using a sufficiently large quantity of copper.

The authors wish to acknowledge the many helpful comments and suggestions of J. L. Fowler and T. A. Welton. The activation analysis was performed by G. W. Leddicotte, and J. A. Martin helped with the cyclotron bombardments.

[9a] *Note added in proof:*—It has recently been found [B. L. Cohen and T. H. Handley, "Experimental Studies of (p,t) Reactions," Phys. Rev. (to be published)] that the statistical theory successfully predicts the cross sections for (p,t) reactions occurring by compound nucleus interaction in iron and palladium. Since the uncertainties in these calculations are very similar to those in the dineutron calculation (the thresholds are about the same), the dineutron calculation is probably not in error by as much as a factor of ten.

[10] The statistical theory does not predict (δ,γ) cross sections, so the results of the calculation are given in terms of $\sigma(\delta,\gamma)$ necessary to explain the experimental results.

PHYSICAL REVIEW VOLUME 92, NUMBER 1 OCTOBER 1, 1953

Magnetic Analysis of the $V^{51}(d,p)V^{52}$ Reaction*†

J. E. SCHWAGER‡ AND L. A. COX‡
Physics Department and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received June 23, 1953)

The proton groups from vanadium targets bombarded with 6-Mev deuterons from an electrostatic generator have been analyzed with a 180-degree magnetic spectrograph. The ground-state Q value for the $V^{51}(d,p)V^{52}$ reaction was found to be 5.072 ± 0.008 Mev. Of the proton groups observed, twenty-three have been ascribed to vanadium and correspond to excited states in V^{52} between the ground state and an excitation energy of 3.30 Mev.

I. INTRODUCTION

INFORMATION regarding the excited states of V^{52} has been derived principally from studies of the $V^{51}(d,p)V^{52}$ reaction[1–4] and from the study of the gamma rays from the $V^{51}(n,\gamma)V^{52}$ reaction.[5] The results of these various investigations are not in good agreement. The Q value for the ground-state transition of the (d,p) reaction has been reported to be 7.80 Mev by Davidson[1] and 5.53 ± 0.15 Mev by Abramov.[2] Harvey's value[3] of 5.02 ± 0.05 Mev is in better agreement with the value of 5.079 ± 0.008 Mev which is deduced from the gamma-ray measurements.[5] The discrepancy between these various values is somewhat reduced if one assumes that a second group of protons of Q value 5.33 Mev, as measured by Davidson,[1] is the ground-state group and that the higher Q value is due to some other process. There is similar disagreement regarding the positions of the excited states of V^{52}, the gamma-ray measurements showing a considerably more complicated spectrum than would be expected from the results of the (d,p) reaction studies.

Recently, King and Parkinson[4] have reported angular distribution studies of two proton groups from the (d,p) reaction, the groups being assigned to the ground state and first excited state. Such a study was proposed by Bethe and Butler[6] as a test of the nuclear-shell model. There is some doubt regarding the interpretation of these experiments, since the gamma-ray measurements indicate that several different groups may have been involved in the measurements.

In view of these discrepancies, the measurements to be reported in this paper were undertaken in order to study the (d,p) reaction with higher-resolution apparatus than has been available to other workers.

---

* This work has been supported in part by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.

† These results are taken from a thesis submitted by the authors to the Massachusetts Institute of Technology in partial fulfillment of the requirements for the degree of Master of Science in Physics under the Naval Postgraduate Training Program.

‡ Lieutenant, United States Navy.

[1] W. L. Davidson, Phys. Rev. **56**, 1061 (1939).

[2] A. Y. Abramov, Doklady Akad. Nauk. (U.S.S.R.) **73**, No. 5, 923 (1951).

[3] J. A. Harvey, Phys. Rev. **81**, 353 (1951).

[4] J. S. King and W. C. Parkinson, Phys. Rev. **89**, 1080 (1953).

[5] G. A. Bartholomew and B. B. Kinsey, Phys. Rev. **89**, 386 (1953).

[6] H. A. Bethe and S. T. Butler, Phys. Rev. **85**, 1045 (1952).