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AN EXPERIMENTAL SEARCH FOR THE DINEUTRON

Part I:

SEARCH FOR A STABLE DINEUTRON

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ABSTRACT

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, it is greater than the upper limit of the observed activity by a factor of 10^5 The uncertainties in estimating the cross sections are discussed, and they appear to be far too small to explain the discrepancy It is thus concluded that it is extremely unlikely that a dineutron can exist as a stable entity Other experiments of this type reported in the literature are analyzed and found to be much less sensitive

The fact that the dineutron does not have a bound state indicates that the product of the well depth and the square of the range of the neutron-neutron potential cannot be more than 10% greater than for the singlet neutron-proton potential

A INTRODUCTION

The neutron-neutron force problem is one of the most important in nuclear physics but, at the same time, one of the most difficult to investigate While neutron-proton and proton-proton forces have been exhaustively studied through scattering experiments, the problem of the neutron-neutron force has so far been attacked only indirectly through the principle of charge symmetry of nuclear forces This principle was held in high regard for many years because of the remarkably accurate way in which the difference in binding energies of mirror nuclei can be accounted for by coulomb forces alone[(1)] However, recent experiments on neutron-proton and proton-proton scattering at high energy have shown that the principle of charge symmetry may be open to very serious question

An important piece of information on neutron-neutron forces would be a definite answer to the question as to whether or not a system of two neutrons possesses a bound state To show this, consider the singlet n-n force to be represented by a potential well of depth V_o and range a It may be shown quite simply that the condition for existence of a bound state is $V_o a^2 \geqslant 1\ 02 \times 10^{-24}$ Mev-cm^2 The experimental results for n-p and p-p singlet potentials are $V_o a^2 = 93 \times 10^{-24}$ and 82×10^{-24} Mev-cm^2 respectively For the triplet n-p potential, $V_o a^2 = 1\ 67 \times 10^{-24}$ Mev cm^2, thus allowing the existence of the bound state of the deuteron According to the charge symmetry principle, $V_o a^2$ should be identical for the n-n and n-p systems However, a difference of only 10% in $V_o a^2$ between the two would result in the existence of a bound state of the n-n system known as the dineutron Feather[(2)] has shown that if such a bound state exists it must be β-active with a half life of 1 to 5 seconds

The question of the existence of the dineutron (hereafter designated by δ) has been raised several times in the past few years. Feather[2] 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 (Sec. C) indicates that their methods were somewhat insensitive.

Kundu and Pool[5] have reported evidence for at least a quasi-stable dineutron from their experiments on (t,p) reactions. Taschek[6] reported preliminary evidence for this in the reaction $t+t \rightarrow He_4+2n$, but a later paper[7] makes no mention of it.

Phillips[12], from measurements of the γ-ray spectrum emitted in the reaction $\pi^- + d \rightarrow 2n + \gamma$, calculated that the dineutron should be unbound by about 260 KV, however, a bound state would result if their determination of the scattering length were changed by one probable error.

In this paper (I), we describe a search for dineutrons emitted in (p,δ) reactions, attempting to detect them by the radioactivity of the end product of (δ,p) reactions. Estimates of the cross sections of (p,δ) and (δ,p) reactions from the statistical theory of nuclear reactions(8) (assuming δ stable) give an expected activity larger than the upper limit of the observed activity by a factor of 10^5. The uncertainties in estimating the cross sections are discussed and it is concluded that it would be almost impossible to account for such a large discrepancy. It is thus concluded that it is extremely unlikely that a dineutron can exist as a stable entity.

A second paper to follow shortly, Part II*, will report on experiments now in progress on (t,p) and (p,t) reactions which should determine whether the dineutron has transitory existence as reported in Ref 6 and 7

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B EXPERIMENTAL DETAILS

The detecting reaction used was

$$Cu^{65}(\delta, p)\ Ni^{66} \rightarrow \beta^{-}(56\,hr) + \beta^{-}(50\,min) + Zn^{66}$$

Several plates of electrolytic copper weighing a total of 3,000 grams were placed immediately behind a target of a heavy element which was then bombarded with 1,000 micro-amperes of 23 Mev protons for 125 hours

Following the bombardment, the copper was dissolved in concentrated nitric acid Ni carrier was added, then the nitric acid was removed by repeated boiling to dryness with hydrochloric acid The solution was finally made approximately 1N in hydrochloric acid and divided into portions of convenient volume Each of these portions in turn was saturated with hydrogen sulfide, centrifuged, and the copper sulfide precipitate rejected The combined supernate was boiled down to approximately 200 ml, scavengered twice with CuS and $Fe(OH)_3$, Co holdback carrier added, and the Ni precipitated as Ni DMG The precipitate was filtered, washed with water and alcohol, dried at 110° C , and weighed as Ni DMG

The quantity of nickel impurity was determined by activation analysis and spectragraphic analysis to be 0 04% Based on this and the weight of the recovered precipitate, the chemical yield was determined to be 11%

The nickel sample was counted under an end window geiger counter with a 70 mg/cm^2 aluminum absorber interposed Since Ni 66 would be in equilibrium with Cu 66 which decays with a 2 8 Mev beta, the absorber has far less effect on this acitvity than on other long-lived activities (e g Ni 57) which generally decay with soft betas

Table I shows the counting data from the best run When plotted, it resolves into a very long half life ($\gtrsim$5 years) and a 36-hour activity due to Ni 57 from (n,2n) reactions in the nickel impurity in the copper The maximum possible 56-hour activity extrapolated to the end of bombardment and taking into account the chemical yield and the 40% counting geometry, was determined to be 2 5 dis/sec

TABLE I Counting Data For Run 4

Table shows counts per 12 hours (± 64) End of bombardment was July 8, 1952, 1 00 p m Background is 209

DATE		A M	P M	DATE		A M	P M
July	14	-	271	Aug	4	-	235
	15	266	262		5	232	230
	17	-	246		6	226	225
	18	244	245		7	225	235
	19	248	240		8	240	243
	20	248	244		9	240	241
	21	236	238		10	241	238
	22	236	235		11	241	237
	23	239	241		12	233	232
	24	237	237		13	236	240
	25	234	-		14	239	243
Aug	1	-	236		15	240	240
	2	237	235		16	241	241
	3	238	237				

C ESTIMATION OF CROSS SECTIONS

Weisskopf[8] has shown that the probability per unit time for a particle with energy E to be emitted by a compound nucleus with excitation energy E_o is

$$P(E) = C E \sigma \omega(E_o - B - E) \tag{1}$$

where C is a combination of universal constants,

σ is the cross section for the inverse reaction, that is, capture of the emitted particle with energy E by the residual nucleus

$\omega(E_o - B - E)$ is the density of states of the final nucleus at an excitation energy $(E_o - B - E)$

B is the binding energy of the emitted particle

The quantity ω appears in the expressions for the emission of neutrons, protons, alphas, etc , so that there is a considerable amount of experimental data on it

Weisskopf[8] has shown that

$$\sigma = \sum_{l=0}^{\infty} (2l+1)\pi \lambda\!\!\!^{-2} P_l \eta_l \tag{2}$$

where $\lambda\!\!\!^{-}$ is the wave length of the incident particle,

P_l are the penetration factors through the angular momentum barriers

η_l are the "sticking factors"

If we define an average sticking probability, ξ , (2) may be expressed in terms of the nuclear radius, r , as

$$\sigma = \pi r^2 \xi \tag{3}$$

where $\xi = 1$ if all η_l in (2) are unity This is commonly assumed to be the case for energies above about 1 Mev

Integrating (1) over the energy of the emitted particles (and using the notation of Ref 8, p 58), we find

$$\sigma(p,\delta) = \sigma_p \, f_\delta/f_n = \sigma_p \frac{f_n(E_0 - B_\delta)}{f_n(E_0 - B_n)} \tag{4a}$$

$$\sigma(\delta,p) = \sigma_\delta \, f_p/f_n = \sigma_n \frac{f_p(E_0 - B_p)}{f_n(E_0 - B_n)} \tag{4b}$$

since, if we assume $\xi = 1$ for dineutrons, there is no difference between σ_n and σ_δ and thus no difference (except for energy balance considerations) between f_n and f_δ (Factors of 2 and 1/2 from the difference in momentum—at a given energy—and spin degeneracies cancel) From the measured threshold for the (p,2n) reaction in the target, $B_\delta = B_n + 8\ 0$ Mev in (4a) Since the target is thick, $\sigma(p,\delta)$ must be integrated over the decreasing proton energy to obtain yields From the fact that Ni 66 decays to Cu 66 with a 56-hour half life, we may assume that in (4b), $B_p - B_n \approx 1$ Mev Since even a thermal dineutron would give $E_0 - B_n \approx 8$ Mev, we may choose $E_0 - B_n \approx 10$ Mev as an average We assume that level densities in even-even nuclei are smaller than those in odd-odd nuclei by a factor of four[10] Curves for f_n and f_p are given in Ref 11 They are calculated from a level density formula fitted to several experimental results

Using these curves and the above assumptions, calculations reveal that at the end of bombardment, the Ni 66 (and thus also the Cu 66) activity should be 3×10^5 disintegrations per second Comparing this with the experimental result of Sec B, there is a discrepancy of more than 10^5

In this calculation, we have made two assumptions, we have assumed unit sticking probability, and have adopted the expressions for energy level densities from Ref 11 It is important before drawing conclusions, to consider how far they may be trusted

According to Weisskopf's theory, sticking probabilities[8] differ from unity only by a quantity which takes into account reflection of the incident wave by the sudden change in wave length at the nuclear surface For incident energies such as those in this experiment, this effect is negligible

Experimentally, sticking probabilities have been found to be approximately unity for neutrons, protons, deuterons, alphas, and π mesons, that is, all experimentally available particles which interact with nuclear forces There thus seems to be little reason to suspect that it should be otherwise for dineutrons if they exist

Since ξ enters in both the (p,γ) and (γ,p) cross sections, to explain our discrepancy would require $\xi \lesssim 1/300$

The assumptions about level densities in calculating the (γ,p) cross section are exactly the same as those used in calculating (n,p) cross sections Measurements of (n,p) cross sections indicate that in general, the theory predicts too small a value However, there are a very few cases where the deviations run counter to this general trend, the largest discrepancy in this direction is less than an order of magnitude In the case of the (γ,p) reactions in copper, there is some uncertainty in $B_p - B_n$ In the calculation this was assumed to be 1 Mev If it were 4 Mev, which is just about as large as possible for a 56-hour half life, this would reduce the cross section by a factor of 10 Thus, the most extreme errors in the estimate of $\sigma(\gamma,p)$ would reduce the discrepancy in the experiment by a factor of 100 This leaves a factor of at least a thousand to be accounted for by errors in $\sigma(p,\gamma)$

To obtain a feeling for the errors that might be possible in the calculation of $\sigma(p,\delta)$, consider the neutron energy distribution to be given by the usual approximation $N(E) \propto E e^{-E/T}$ This implies $\omega(E_0 - B_n - E) = Ce^{-E/T}$, which in turn implies $\omega(E_0 - B_\delta - E) = Ce^{-\left(\frac{E+B_\delta-B_n}{T}\right)}$, when integrated over the energy distributions, the ratio of dineutrons to neutrons emitted is

$$\frac{\delta}{n} = \exp\left(-\frac{B_\delta - B_n}{T}\right) \approx \exp\left(-\frac{8\,Mev}{T}\right) \qquad (5)$$

In our calculation, we found from the curves of Ref 11, $\delta/n \approx 2 \times 10^{-4}$ which corresponds to T = 1 0 Mev in (5) To reduce the discrepancy in our result by a factor of a thousand would require that T = 0 55 Mev A survey of all work on nuclear temperatures reveals that so low a temperature has never been found for excitation energies as high as those in this experiment In fact, there is considerable evidence from (n,p) and (n,α) cross section measurements on heavy elements that the curves of Ref 11 give too small a value for the ratio δ/n

It thus seems that a discrepancy as large as 10^5 between the theoretically expected and experimentally observed counting rates cannot reasonably be explained by inaccuracies in the statistical theory of nuclear reactions The only alternative is that the dineutron does not possess a stable state

It is interesting here to apply a similar analysis to the experiments of Fenning and Holt[3] and Ferguson and Montague[4] Their results from a search for (δ,γ) reactions in the Harwell and Chalk River reactors, may be expressed as

Bismuth Detector [3] $\quad \delta/n\, \sigma(\delta,\gamma) \lesssim 2\times10^{-33}\,cm^2$

Helium Detector [4] $\quad \delta/n\, \sigma(\delta,\gamma) \lesssim 10^{-31}\,cm^2$

The ratio δ/n in fission may be estimated as above Since the neutron spectrum has a temperature of about 1 Mev, $\delta/n \approx 2 \times 10^{-4}$ On this basis, the above results are

For bismuth $\quad \sigma(\delta,\gamma) \lesssim 10^{-29} cm^2$

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

Since (δ,γ) reactions complete with (δ,n) reactions in which neutron emission is energetically possible by at least 7 Mev, these cross sections are not unreasonably small When the possible errors in the determination of δ/n are considered, the experiments from Ref 3 and 4 appear to be very insensitive indeed The major improvement in the experiment reported here is detecting by a (δ,p) instead of a (δ,γ) reaction This is favorable because the former has a larger cross section and, more importantly, because the product can be refined from the target by radiochemical techniques thus allowing good beta counting efficiency while still using a large detecting sample By use of these techniques in reactors, the search for the dineutron in fission could be extended to almost any desired sensitivity by using a sufficiently large quantity of copper

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