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SYSTEMATICS OF THE LIGHTEST NUCLEI

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MORE than four years ago the journal Uspekhi Fizicheskikh Nauk published our review paper[1] devoted to the properties of new isotopes (mainly isotopes of the light elements) and ways of discovering them. During these years there has been a great increase of interest in this subject. Dozens of papers have appeared devoted to ultraheavy isotopes of hydrogen and helium and to related questions of the systematics of the levels of the α particle and the existence of the tetraneutron. The emission of delayed protons has been discovered and studied in many cases, and the discovery of proton and diproton radioactivity is approaching. In the light of these facts it seems useful to return once more to the properties of the lightest nuclei, mainly those of multineutrons and the isotopes of hydrogen and helium, to analyze the results of the work of the last few years, and to discuss the nature of the problems for further research. After the necessary introductory remarks we deal with the material to be expounded here in the order of increasing mass number: A = 2 (dineutron and diproton), A = 3, A = 4 (He^4, H^4, n^4), A = 5 (H^5), A = 8 (He^8), and finally we touch very briefly on the question of still heavier isotopes. This review article includes all of the material that has come to our knowledge (in the form of publications or of preprints) up to October 1, 1964.

1. INTRODUCTORY REMARKS

In the discussion of the properties of light nuclei we must be especially careful in making use of the concept of "excited state." The point is that the usual concept of the "intermediate nucleus" cannot be applied here. In light nuclei the numbers of nucleons are small, and if the energy of the nucleus is above the threshold for emission of a nucleon or another heavy particle (H^3, He^4, and so on), then as a rule the breakup occurs in times of nuclear order of magnitude—that is, instantaneously. The result is that the levels are smeared out, and their widths are several MeV. Only in those exceptional cases in which the decay is strongly suppressed (for example, by selection rules on the angular momentum or on the isotopic spin, or because of the specific structure of the given state) do we find excited states with small widths.

Apart from these possibilities there remain only levels which decay within nuclear times. Can they be called levels at all? This is not a very simple question, and before answering it we recall the usual classification of the unstable states of nuclei.

There exist three types of instability of nuclear states: Instability against decay with emission of heavy particles (nucleons or nuclei), against emission of γ-ray photons, and against β decay.

It is only in the first of these cases that the decay of the unstable state can occur "instantaneously," even on a time scale measured by the characteristic nuclear time $\sim 10^{-22}$ sec, which is of the order of the period of revolution of a nucleon around the nucleus (speed of the order of 10^9 cm/sec and distance of the order of 10^{-13} cm). The lifetime of an excited nucleus against emission of a γ ray is relatively long: $\tau_\gamma \gtrsim 10^{-18}$ sec. As for β decay, which, as is well known, belongs to the class of weak interactions, the speed of this process is incomparably smaller: for beta-active nuclei $\tau_\beta \gtrsim 10^{-3}$ sec.

Therefore in the absence of any factor which strongly retards decay with the emission of nucleons or γ rays, for a nucleon-unstable state (or a nucleus-unstable state) unstable against all three types of decay it is nucleon emission that predominates.

For nucleon-stable (or nucleus-stable) states, in which decay with nucleon emission is energetically forbidden or for some reason strongly suppressed, and only γ-ray emission or β decay can occur, decay by γ radiation will as a rule predominate.

It is only when the other types of decay are absent (or when their rates are very strongly retarded) that β decay begins to play the main part in the transitions from an unstable nuclear state. We must, of course, keep in mind that only two of the three types of decay that have been mentioned lead to a change of the composition of the nucleus; γ-ray emission involves only a change of the internal energy of the nucleus.

Even when there is instability against nucleon decay it is possible for atomic nuclei to exist for considerable times. As is well known, the presence of a Coulomb barrier causes the occurrence of four types of radioactivity: α decay, spontaneous fission, proton radioactivity, and diproton radioactivity. In all of these cases nuclei which even in the ground state are energetically unstable against the type of decay in question nevertheless exist for an extremely long time not only on the nuclear scale, but also in comparison with the lifetimes of the excited compound nuclei formed in nuclear reactions (the conventional limit of radioactivity, i.e., the minimum lifetime required if we are to speak of the existence of a particular isotope as a radioactive species, is $\tau \gtrsim 10^{-12}$ sec).

Moreover, there are very many isotopes which are energetically unstable against α decay or spontaneous fission, but which owing to the Coulomb barrier are characterized by immeasurably small decay rates, i.e., are practically altogether stable, and accordingly differ in no way from isotopes for which decay with heavy-particle emission is quite impossible from energetic considerations.

On the other hand, cases are also known in which the Coulomb barrier "restrains" a nucleus which is unstable for nucleonic decay only extremely weakly, and the decay is relatively slow only on the nuclear time scale, but is extremely rapid, "instantaneous," in comparison with radioactive decay; examples of such decays are the nucleus B^9, which is proton-unstable in its ground state ($\tau \approx 10^{-18}$ sec), but is not counted among the radioactive species, or the emission of below-barrier protons by excited compound nuclei or by products of β decay.

We shall give the name quasistationary to nuclear states that are energetically unstable against nucleonic decay and have rather long lifetimes on the nuclear scale ($\tau \gg 10^{-22}$ sec), although very short ones on the radioactive scale ($\tau \ll 10^{-12}$ sec).

There are several causes which can lead to a strong retardation of the decay of nucleon-unstable systems and the appearance of quasi-stationary nuclear states. One of them is the isotopic-spin selection rule which applies for strong interactions: $\Delta T = 0$ (cf.[106]).

For example, suppose there exists an excited state of the α particle with isotopic spin $T = 2$ and with energy sufficient for decay into $H^3 + p$ or $He^3 + n$, but not into four nucleons. The final states can have $T = 0$ or $T = 1$, since the isotopic spin of each of the decay products is 1/2. Thus decay from the state with $T = 2$ is forbidden by isotopic invariance; it is possible only owing to small deviations from this invariance, i.e., owing to the electromagnetic interaction of the nucleons in the nucleus. Accordingly the lifetime of such a state would be of the order of 10^{-18} sec, and its width would be $\Gamma = \hbar/\tau \approx 1$ keV.

An example which illustrates another possible cause of the existence of long-lived "quasistationary" states (in what follows we shall often speak of them as "narrow" levels) is the 16.7 MeV excited state of He^5. This state lies much higher than the threshold for the decay $He^5 \rightarrow He^4 + n$, but its width is small. Here the point is that the structure of this state is $He^5\,(1s)^3(1p)^2$, and a transition to $He^4 + n$ is possible only if one nucleon is emitted from the He^5 and at the same instant another one changes from the 1p shell to the 1s shell to form the stable configuration $(1s)^4$ of the α particle. The probability of such a double transition is obviously small, and the lifetime of the 16.7 MeV state of He^5 is rather long on the nuclear scale ($\sim 10^{-20}$ sec).

Finally, a lowered decay rate can be caused by a small phase volume in the final state of the system.

A special case of this mechanism for slowing down decay is due to the necessity of a tunnel-effect penetration of the emerging particle through a centripetal barrier, or through the Coulomb barrier already mentioned. The 16.7 MeV state of He^5 is also an example of this. This state can decay not only into $He^4 + n$, but also into $H^3 + d$; the energy of this decay (70 keV) is much lower than the Coulomb barrier, however, and the result is that this type of decay is also "retarded," and in spite of the existence of two channels for decay into heavy particles the lifetime of the excited state of He^5 is much larger than the characteristic nuclear time.

Smallness of the phase volume also manifests itself strongly in cases in which the decay of the nucleus (even when it is not forbidden owing to the isotopic spin, nor slowed down by any potential barrier) occurs with the simultaneous emission of several particles. For example, when the decay energy E is small, the phase volume for decay into three neutral particles goes to zero like E^2; for comparison we recall that for decay into two particles with orbital angular momentum $l = 1$ the phase volume goes to zero only like $E^{3/2}$.

Besides these sorts of nuclear states which are quasistationary for various reasons, there is another sort of state which is often encountered in the description of systems with small numbers of nucleons: virtual states. Here it is important to emphasize that such states do not have so definite a physical meaning as the quasistationary states, but are essentially a mathematical concept. This is most simply seen from the classic example of two neutrons in a ^1S state. There is no bound state of two neutrons. If, however, the interaction between neutrons were a trifle stronger, a bound state would appear. This closeness to the possibility of having a bound state leads to a number of characteristic features in the interaction of two neutrons at small energies (for example, to an increase of the cross section for scattering of neutrons by neutrons). It is this sort of situation that is described by the term "virtual state."

Quasistationary and virtual states of a system a + b differ decidedly in the nature of the energy dependence of the phase shifts for ab scattering. This difference is illustrated by the examples c) and d) on page 179.

The question of the lifetimes of excited states of nuclei is very important for their classification. Therefore it is interesting to state the problem more generally: suppose a particle is scattered by a center of force of range R. How long a time does the particle spend inside the region of interaction, i.e., in the sphere $r < R$? In other words, what is the lifetime of the intermediate state? The answer to this question is given by the following formula,[2] which was derived by one of the authors of this review (A.I.B.) and connects the lifetime T(E) with the energy dependence of the scattering phase shift:

$$T(E)=\frac{2}{v}\left(R+\frac{d\delta}{dk}\right). \tag{1}$$

Here E, v, and k are respectively the energy, the speed, and the wave vector of the colliding particles. The derivation of this formula is very simple. For a given energy E the wave function $\chi_E(r)$ of the scattered particle for $r > R$ is of the form

$$\chi_E(r)=e^{-\frac{iEt}{\hbar}}\{e^{-ikr}-e^{i[kr+2\delta(k)]}\}.$$

We now form a wave packet which is a superposition of two states with slightly different energies:

$$\chi_E(r)+\chi_{E+dE}(r)=[e^{-ikr-i\frac{Et}{\hbar}}+e^{-i(k+dk)r-\frac{i(E+dE)t}{\hbar}}]$$
$$-[e^{ikr+2i\delta(k)-\frac{iEt}{\hbar}}+e^{i(k+dk)r+2i\delta(k+dk)-\frac{i(E+dE)t}{\hbar}}].$$

The first term describes the incident wave, and the second the scattered wave. The motion of the center of gravity of the packet incident on the scatterer is found from the condition of equality of the phases of the two terms that compose it:

$$-ikr-\frac{iEt}{\hbar}=-i(k+dk)r-\frac{i}{\hbar}(E+dE)t,$$

i.e.,

$$r=-\frac{t}{\hbar}\frac{dE}{dk}=-tv. \tag{2}$$

In a similar way we find the motion of the center of gravity of the scattered packet; we get

$$r=vt-2\frac{d\delta(E)}{dk}. \tag{3}$$

From these formulas we see that the incident packet arrives at the point $r = R$ at the time

$$T_1=-\frac{R}{v},$$

and the scattered packet is at this point at the time

$$T_2=\frac{R}{v}+\frac{2}{v}\frac{d\delta}{dk}.$$

From this we find the time the packet spends inside the scattering center:

$$T(E)=T_2-T_1=\frac{2}{v}\left(R+\frac{d\delta}{dk}\right).$$

Equation (1) has now been proved. Let us consider some special cases.

a) Scattering of a particle by a rigid sphere. In this case the scattering phase shift is $\delta = -kR$. From (1) we find at once that $T(E) = 0$, as must be the case (the particle cannot penetrate inside the rigid sphere, but bounces off from it).

b) The interaction is such that $d\delta/dk = 0$. The lifetime is then the same as the time of free flight through the interaction region, $T = 2R/v$. This result is especially clear in the case in which there is no interaction, $\delta \equiv 0$ and accordingly $d\delta/dk = 0$.

c) Scattering through a resonance of the intermediate nucleus. The phase shift for resonance scattering is

$$\delta=\delta_0+\tan^{-1}\frac{\Gamma}{E_0-E},$$

where E_0 and Γ are the energy and the width of the resonance, and δ_0 is the phase shift of potential scattering, which can be regarded as independent of the energy. The lifetime is given by

$$T(E)=\frac{2\hbar}{\Gamma}\frac{\Gamma^2}{(E-E_0)^2+\Gamma^2}+\frac{2R}{v}$$

and has its maximum at $E = E_0$:

$$T(E_0)=\frac{2\hbar}{\Gamma}+\frac{2R}{v}.$$

It is clear that we can speak of a quasistationary state of the intermediate nucleus only if the first term is the main one: $\hbar/\Gamma \gg R/v$. Under typical conditions with which we are concerned in the case of light nuclei, $R \approx 3 \times 10^{-12}$ cm, $v = 2 \times 10^9$ cm/sec. Accordingly we get as the condition on the width Γ the inequality $\Gamma \ll 0.7 \times 10^{-5}$ erg = 4 MeV. If this condition is not satisfied, it obviously is meaningless to speak of a quasistationary state.

d) Virtual states. In this case the phase shift is $\tan^{-1}|a|k$, where a is the scattering length. We at once get for the lifetime

$$T=\frac{2}{v}\left(R+\frac{|a|}{1+(ak)^2}\right).$$

For small energies ($|a|k \ll 1$) the lifetime is

$$T=\frac{2}{v}(R+|a|),$$

and for $|a| \gg R$ it can be much larger than the time of free flight. Accordingly it is then possible to speak of a comparatively longlived virtual state of the intermediate nucleus. For $R = 3 \times 10^{-13}$ cm the condition for this is $|a| \gg 3 \times 10^{-13}$ cm. It can be seen, however, that such a longlived state can be formed only for extremely small relative energies of the interacting particles: $k \ll 1/|a| \ll 10^{13}/3$ cm^{-1}, i.e., $E \ll \hbar^2/2ma^2 \approx 2$ MeV (here m is the mass of the nucleon).

The main conclusion from these estimates is as follows. We may speak of longlived states of nuclei in only two cases:

1. The intermediate system has a resonance, whose width satisfies the condition $\Gamma \ll 4$ MeV.

2. The scattering length of the intermediate system of particles which is formed is anomalously large ($|a| \gg 3 \times 10^{-13}$ cm); then in a narrow range of energies of the interacting particles ($0 < E \ll 2$ MeV) a comparatively longlived virtual state of the compound system is formed.

The course of many physical processes depends strongly on the length of time that a particular pair of particles is close together. A typical example is a reaction in which three particles are produced, e.g., two

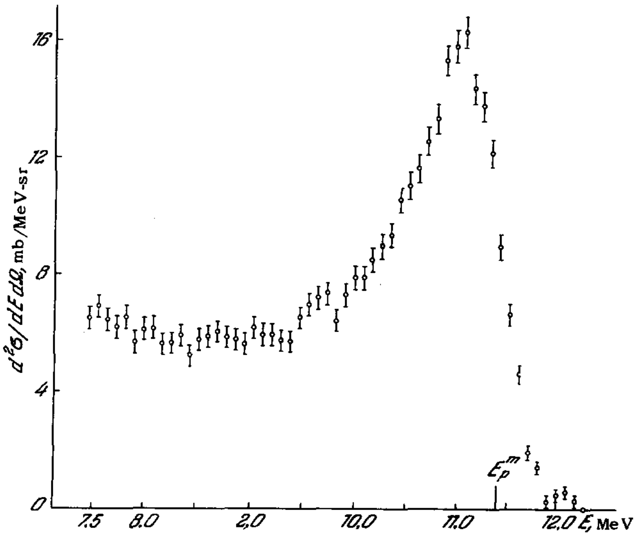

FIG. 1. Spectrum of the protons emitted at the angle 0° in the reaction d + n → p + n + n, from the data of[3]. Energy of the bombarding neutrons, 13.9 MeV. E_p^m is the proton energy corresponding to the calculated upper limit, with allowance for the experimental conditions.

neutrons and some third particle (cf. Fig. 1, taken from[3], which shows the spectrum of protons from the reaction n + d → p + n + n). Because of the existence of a virtual state of the two neutrons the energy spectrum for the third particle—the proton—acquires a characteristic peak at the upper end of the spectrum, since the yield of the reaction is greatly increased, and moreover the neutrons produced in the reaction are strongly correlated both in energy and in angle of emergence.

In such cases one says that the correlation is due to the existence of a virtual state of the two neutrons, or, in other words, to a large interaction between the neutrons in the final state.

If three particles a, b, and c are produced in a reaction, and if in scattering each other at the relative energy ϵ_0 particles a and b form a quasistationary state, then there is a strong increase of the yield of particles a + b with the relative energy ϵ_0, and the energy spectrum of the third particle c has a peak at the energy

$$\varepsilon_c = (\varepsilon - \varepsilon_0)\frac{m_a + m_b}{m_a + m_b + m_c},$$

where m_a, m_b, m_c are the masses of a, b, c, and ϵ is the total energy of all three of the particles in the center-of-mass system.

Thus the study of the energy spectra of particles produced in three-particle interactions gives important information about the nature of the interaction between the particles. It is for this reason that reactions of this type are exceptionally important in the study of the properties of the lightest nuclei.

2. THE DINEUTRON

It has already been known for a long time from the experimental data on pn scattering in the singlet state that in this state the system p + n has no real level, but has a virtual level with energy 70 keV. It then follows from the hypothesis of charge invariance of nuclear forces that neither two protons (He^2 or p^2, the diproton) nor two neutrons (n^2, the dineutron) have a bound state. In the case of He^2 this conclusion is completely confirmed by the data on pp scattering (see below) which, if we take electromagnetic corrections into account, lead to the same energy value 70 keV for the virtual level of two protons in the singlet state.

In the case of two neutrons an experimental check is very difficult, since it is impossible to make experiments on neutron-neutron scattering. Two ways remain: either to look for n^2 in some sort of characteristic reactions (as has been proposed, for example, in[1]), or else to study the energy spectrum of a third particle produced in a reaction along with two neutrons (for example, the spectrum of the α particles from the reaction $H^3 + H^3 \rightarrow He^4 + n^2$).

Sakisaka and Tomita[4] have tried to get n^2 in the reaction $d + H^3 \rightarrow He^3 + n^2$, with subsequent registration of the dineutron by its radiative capture in Al^{27} and Bi^{209} with formation of Al^{29} and Bi^{211}. On the basis of the experiments with aluminum they declared for the existence of the dineutron with binding energy 3 MeV; the experiments with bismuth gave no definite result. Several months later another Japanese group (Katase, Seki, Akiyoshi, Yoshimura, and Sonoda[5]) repeated similar experiments, but with a negative result: the yields of Al^{29} and Bi^{211} were at background level. Negative results were also obtained by Schiffer and Vandenbosch in an attempt to find n^2 in a reactor.[6]

They placed an Al^{27} target in the reactor, and on the assumption that n^2 exists among the fission products looked for, but did not find, an activity corresponding to Mg^{28} [the reaction $Al^{27}(n^2, p)Mg^{28}$]. There has also been failure to confirm the direct production of dineutrons in nuclear reactions in a number of other researches.

The lack of success of all such attempts could be due to there being too small a cross section for the production of n^2. The point is that the smaller the binding energy of n^2 the larger its radius, and consequently the smaller the cross section for its production, which decreases as $B^{1/2}$, where B is the binding energy.

This hypothesis must be rejected, however, since if it were true then in all reactions with production of three particles, two of which are neutrons, the neutrons would come out with practically zero relative energy, and the third particle would carry off the maximum energy consistent with the conservation laws (limit of a very strong interaction in the final state). This is not observed experimentally. On the contrary, in the most carefully done experiments (for example, in those of V. K. Voĭtovetskiĭ, I. L. Korsunskiĭ, and Yu. F. Pazhin[3] on the reaction n + d → p + n + n) the shape of the spectrum of the third particle—the proton—shown in Fig. 1 is in clear contradiction with the existence of a dineutron, and at the same time agrees with the hypothesis that the two neutrons have a virtual level with energy 70 keV.

In principle there is a third way of looking for the dineutron—in terms of threshold singularities. If the dineutron exists and is produced in some reaction, for example, in $n + d \rightarrow p + n^2$, then in the energy dependence of the cross section for the reaction d(n, n)d there should be a characteristic singularity at the threshold for the production of n^2. The size of this singularity is of the order of the cross section for the production of n^2. This very fact makes the threshold method entirely unsuitable for a search for the dineutron, since even if there could still be some hope of its existence, it is firmly established that the cross section for its production is small. In fact, all of the experimental data agree on the fact that if n^2 does exist, then the cross section for its production in reactions has the upper limit $\sigma_{n^2} < 10^{-29}$—10^{-30} cm^2, whereas the cross section for scattering is always of the order of 10^{-24} cm^2. Thus to observe the singularity one would have to measure the cross section with an accuracy better than 0.001 percent—a task out of the question at present. It is not surprising that the experimental work on this point (the latest being that of Willard, Bair, and Jones[7]) has given negative results in the search for the dineutron.

If the dineutron existed, its size would be the largest for any nucleus. For a binding energy of the order of 100 keV the radius would be $R = 1/k \approx 1.2 \times 10^{-12}$ cm. An exact theory of the interaction of the dineutron with nuclei could be constructed. Unfortunately, experiment shows that this exotic particle does not exist. Everything has its good side, however. Knowing the energy of the virtual level of a pair of neutrons (70 keV according to the experiments[3]), we can draw a conclusion about the accuracy of the hypothesis of the charge invariance of nuclear forces. In fact, within the limits of experimental accuracy (~ 20 percent), the energies of the virtual levels in the systems np and nn are equal. On the other hand it is easily shown that a change of the energy ϵ of the virtual level by the amount $\delta\epsilon$ corresponds to a change of the depth U of the potential by

$$\delta U = \frac{2}{\pi} \sqrt{\frac{U}{\varepsilon}}\, \delta\varepsilon. \qquad (4)$$

Substituting the values U = 25 MeV, ϵ = 0.07 MeV, and $\delta\epsilon$ = 0.015 MeV, we find δU = 330 keV. Accordingly the depths of the nn and np potentials differ by not more than 330 keV, i.e., by not more than ~ 1.5 percent.

3. THE DIPROTON

A difference here from the case of the dineutron is that the question of the existence of a bound state of two protons has never arisen. Such a distinctive particle with mass $2m_p$ and charge 2e would have been detected long ago. Therefore we can speak only of a virtual state of the system of two protons. Within the framework of exact charge invariance the pp and pn interactions differ only because of electromagnetic corrections. Allowing for this, Schwinger long ago obtained from the data on pp scattering a quantity characteristic of the nuclear interaction between two protons—the energy ϵ_{pp} of the virtual state. Within the limits of error it was found to be 70 keV, or precisely equal to the value for the systems nn and np. It is true that the errors are rather large here, since pp scattering has been accurately studied only at energies $\gtrsim$ 100 keV, and furthermore it is not very clear where one should cut off the electrical interactions.

Therefore in principle the possibility was not excluded that the pp nuclear interaction is somewhat larger than for pn. If this is the case, then $\epsilon_{pp} < \epsilon_{pn}$, and a quasistationary He^2 may exist.

Our actual assumption is that the nuclear parts of the nn and pp interactions are the same. The total interactions differ, however, because of the Coulomb repulsion of the two protons. For the question of the existence of He^2 it is very important how the Coulomb interaction behaves at small distances. Indeed, let us imagine that for $r < a$ (a is the range of the nuclear interaction) the electrostatic potential is constant (Fig. 2, a). In this case the total potential will have the shape shown in this figure by the dashed curve; the bottom of the potential well is raised by the amount $U_{Coul}(a) = e^2/a$, just as the value at the point r = a is. If U(r) were equal to e^2/a everywhere for $r > a$, then we would get a potential (analogous to the nn potential) in which there is a virtual state with $\epsilon_0 = 0.07$ MeV. For $r > a$, however, U(r) falls off as

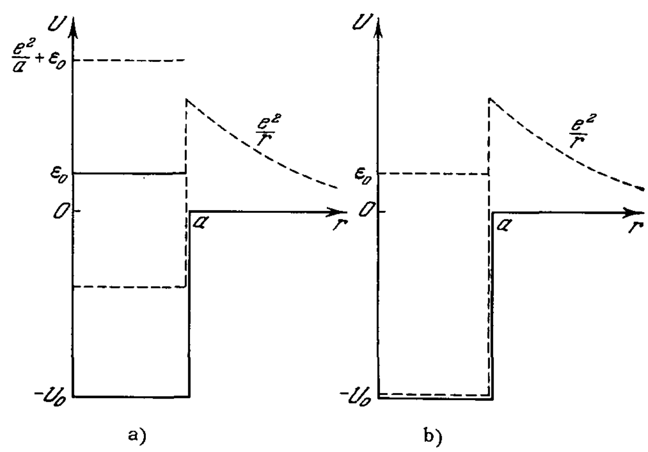

FIG. 2. Sketches of the shapes of the potential for neutrons (solid line) and for protons: a) for $U_{Coul}(r < a) = e^2/a$; b) for $U_{Coul}(r < a) = 0$.

e^2/r, and this makes the situation much worse; because of this the value of ϵ_0 is decidedly increased, and the virtual state becomes much less well marked.

Let us now consider the other extreme case (the most favorable for He^2) in which the Coulomb interaction is identically zero for $r < a$ (Fig. 2, b). The effective result of this is that an additional barrier is raised around the potential in which the virtual state exists. If the barrier is high enough, there can be a rather narrow quasistationary state in this combined field. In our concrete case of two protons, with $a \approx 2 \times 10^{-13}$ cm, $U_0 \approx 25$ MeV, simple calculations show that the height of the Coulomb barrier is too small. No quasistationary He^2 can exist in this case. Even in the extreme case considered, the appearance of such a state would require that the pp interaction be stronger (at least by ~ 1 MeV) than the nn interaction, so as to bring the position of the virtual level down to the very bottom of the Coulomb barrier.

Let us now turn to the experimental data. As has already been pointed out, the cross section for pp scattering is well explained without the assumption that there are any resonance states of the two-proton system. It must indeed be admitted that owing to the rather large experimental errors in the pp cross section a broad resonance could remain undetected.

If a quasistationary p^2 exists, it must manifest itself in reactions in which two protons are produced along with a third particle. A detailed investigation of the spectrum of the neutrons from the reaction d(p, n)2p, which was made by B. V. Rybakov, V. A. Sidorov, and N. A. Vlasov,[96] led to the conclusion that the shape of this spectrum can be entirely explained by the appearance of a virtual state of the system of two protons, i.e., by their interaction in the final state.

In fact, as has been shown by calculations of V. V. Komarov and A. M. Popova,[97] the shape of the neutron spectrum agrees with the data on pp scattering in the low-energy region.

Subsequently there have been studies of reactions in which a charged third particle is produced along with two protons. The results, however, are contradictory.

At the end of 1963 a note was published on experiments by Bilaniuk and Slobodryan,[8] who studied the reaction $He^3 + d \rightarrow H^3 + 2p$ at deuteron energy $E_d = 28$ MeV. The energy spectrum of the H^3 nuclei was measured, and it was found that at the upper end of the spectrum (relatively small energy of the protons) there is a strong resonance peak of width 2.8 MeV and with deep dips on both sides of it (the ratio of the maximum to the adjoining minima was 7 : 1); these experimenters declared on this basis that a quasistationary p^2 had been discovered with a lifetime of about 2×10^{-22} sec.

Some time later there appeared a paper by K. P. Artemov, V. I. Chuev, V. Z. Gol'dberg, A. A. Ogloblin. V. P. Rudakov, and Yu. N. Serikov.[9] They studied the same reaction $He^3(d, 2p)H^3$ at energies $E_d = 20$ and 25 MeV and the reaction $He^3 + He^3 \rightarrow He^4 + 2p$ at $E_{He^3} = 16$, 26, and 36 MeV. The energy spectra measured were those of the H^3 and the He^4, respectively. The two spectra were very similar in shape. No resonance maximum was observed, but only a smooth rise at the upper end of the spectrum. This indicates that the two protons are in a virtual, not a quasistationary, state.

There was also no quasistationary state detected in a precise kinematic analysis of the products from bombardment of hydrogen with deuterons at energy 21.1 MeV, the process p(d, 2p)n, which was made recently by Donovan, Kane, Mollenauer, and Zupanchich.[10] Therefore the results of [8] are evidently to be regarded as lacking confirmation, and the quasistationary state of He^2 as nonexistent. *

A special type of possible existence of virtual singlet diproton and dineutron at rather large distances from the nucleus (up to 10^{-11} cm)—under a centrifugal potential barrier acting on each nucleon separately, but not on the pair—has been treated in the quasiclassical approximation by one of the present writers[99] for the case of two-proton radioactive decay of the type $Ge^{58} \rightarrow 2p + Zn^{56}$. This paper makes a comparison of the probability of emission from the nucleus of two protons, each with energy E/2, so that their total energy is E—a process which suffers additional retardation by the centrifugal barrier—and the probability of emission of a paired "diproton," for which there is only the Coulomb barrier, but whose energy is $E - \epsilon_0$, where $\epsilon_0 \approx 70$ keV is the energy of the virtual $^1S_0$ level of the nucleon-nucleon system. It is easily verified that, besides the increased penetrability of the barrier as compared with the case of penetration by two independent particles, the pairing here leads to a "containment" by the barrier of the virtual singlet state of the pair of nucleons out to the distance $r_0 = \hbar(m\epsilon_0)^{-1/2}[l(l+1)]^{1/2}$ (where l is the orbital angular momentum of the shell from which the nucleons leave the nucleus), and accordingly also leads to a strengthening of the angular correlation of the emerging particles. This distance r_0 greatly exceeds not only the radius of the nucleus, but also the amplitude of the singlet nucleon-nucleon scattering or the effective size of the "free" diproton, $\hbar(m\epsilon_0)^{-1/2} \approx 2.3 \times 10^{-12}$ cm, and reaches 10^{-11} cm in many realistic cases.

This peculiar sub-barrier existence of virtual singlet pairs of nucleons far from the nucleus should manifest itself not only in 2p decay, but also in proc-

*This conclusion was also reached by one of the authors of[8], Slobodryan, after he had worked with Conzett, Shield, and Yamabe on more accurate measurements of the triton spectrum from the reaction $He^3(d, 2p)H^3$.[98]

esses of tunnel transfer of pairs of protons or neutrons—of the type of (Ne^{20}, O^{18}) or (O^{18}, O^{16})—in reactions of heavy multiply charged ions.

4. THE "TRINEUTRON" AND THE POSITION OF THE LEVEL T = 3/2 FOR A = 3

In a recent paper by a group of Jugoslav physicists,[11] who studied the spectra of deuterons and protons in the splitting of tritium by neutrons of energy 14.4 MeV, the question is raised as to the possible existence of a bound trineutron (a monochromatic line in the spectrum of the protons).

The existence of a bound trineutron would mean that for A = 3 the energy of excitation of the level T = 3/2 (over the level T = 1/2) lies below 8.5 MeV, and that there must exist a bound excited level of tritium (and possibly also of He^3, if the level T = 3/2 is located below 7.7 MeV). All of this seems extremely improbable.* In fact, the binding energy of the third neutron, which decreases systematically with decrease of Z, becomes negative already for He^5. Figure 3 shows the positions of the energy of the first excited level with $T = T_{ground} + 1$ (i.e., T = 1 for N = Z and T = 3/2 for N = Z + 1) for the nuclei with A = 2—36. Interpolation for A = 3 gives the value E(T = 3/2, A = 3) ≈ 13—15 MeV.

The retardation of the decay of three-nucleon states with T = 3/2 at such energies could be caused only by factors associated with the volume in phase space, and could scarcely give a width smaller than 1 MeV.

Indeed, let us make the simplest sort of crude estimate of this width. The probability that three particles with wavelength $\lambda\!\!\!^{-}$ will be found in a volume of radius R is proportional to $(R/\lambda\!\!\!^{-})^2$. Since owing to the Pauli principle one of the three neutrons in a trineutron must be in a p state, the probability for it to be in a nucleus of radius $R < \lambda\!\!\!^{-}$ will be still smaller: $(R/\lambda\!\!\!^{-})^{2l+1}$, or $(R/\lambda\!\!\!^{-})^3$. The result is then not a factor $(R/\lambda\!\!\!^{-})^2$, but $(R/\lambda\!\!\!^{-})^4$. For $R \approx 2 \times 10^{-13}$ cm and $\lambda\!\!\!^{-} \approx 3.2 \times 10^{-13}$ cm (which corresponds to $E_n = 2$ MeV) this factor is ~6.6; if we take the nuclear time to be $\tau_0 = 10^{-22}$ sec, then according to what we have just said we get $\tau = 6.6\,\tau_0$ and $\Gamma = \hbar/\tau \approx 1$ MeV.

The question of the position of the level T = 3/2 for A = 3, whose excitation is extremely improbable in pd or nd interactions, can be solved by means of kinematic analysis of reactions of the type of $He^3 + S^{32} \rightarrow (He^{3*}) + S^{32*}$ (T = 2). Selection of the cases that correspond to the excitation of a target nucleus with T = 0 by two units of isotopic spin enables us to separate out the formation of three nucleons—products of the decay of He^3 (or of T)—in a state with T = 3/2. That such a selection of transitions (T = 0) → (T = 2) can be made clearly is shown by the results of Garvey and his coworkers,[12,13] who worked with pt reactions and separated out the formation of states with T = 2 for the nuclei with A = 16, 20, 24, 44, 52.

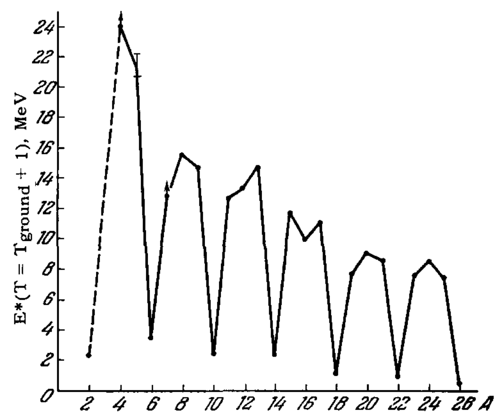

FIG. 3. Excitation energies of states with isotopic spin exceeding that of the ground state by unity, for nuclei with A = 2 – 26.

5. THE LEVELS OF THE α PARTICLE

From the point of view of the shell model the α particle is two neutrons and two protons filling the 1s shell: $(1s)^4$. In an excitation of the α particle one of the nucleons must go into the next shell ($1p_{3/2}$ or $1p_{1/2}$). This gives rise to states $(1s)^3 1p_{3/2}$ with the possible angular momenta $J = 2^-$ and 1^- and with isotopic spins T = 0, 1, and also states $(1s)^3 1p_{1/2}$ with $J = 1^-$, 0^- and T = 0, 1—eight states in all. The transition to the 2s state is also possible, and this forms the configuration $(1s)^3 2s$ with $J = 0^+$, 1^+ and T = 0, 1. In order to form an excited state with T = 2 from the S shell, it is necessary to remove two nucleons, which requires much more energy. Such states will lie much higher than those with T = 0, 1.

The position of an α-particle level with isotopic spin T = 1 is connected with the problem of the stability of the other two members of the isotopic triplet with A = 4—the nuclei H^4 and Li^4. In fact, the total energy of the nucleus (A, Z) can be written in the form

$$_ZM_N^Ac^2 = c^2(Zm_p + Nm_n) + E_k(A,\ Z) + E^A(T), \qquad (5)$$

where m_p and m_n are the masses of proton and neutron, $E_k(A, Z) \approx 0.6Z(Z-1)A^{1/3}$ MeV is the energy of the Coulomb interaction of the protons, and $E^A(T)$ is the energy caused by the nuclear interaction of the nucleons and is the same for all members of an isotopic multiplet.

It is easy to see that, for example, the difference of the mass defects of the nuclei Li^4 and He^{4*} in the state with T = 1 is

*G. S. Danilov has recently concluded, on the basis of the equation of Ter-Martirosyan and Skornyakov,[102] that there is no bound level in the system of three neutrons. Besides this, there was a negative result in the attempt of Stojic, Stepancic, Aleksic, and Popic[103] to detect n^3, as it might appear in the reaction T(n, p)n^3, by means of the subsequent formation of Mg^{28} in the reaction $Al^{27}(n^3, d)Mg^{28}$.

$$M(\mathrm{Li}^4)-M(\mathrm{He}^{4*}) = -(m_n-m_p)c^2+0.6\frac{4}{4^{1/3}} \approx 0.72 \text{ MeV}.$$

In order for the nucleus Li^4 to be stable against decay into He^3 + p, its mass defect must be less than 22.22 MeV (C^{12} mass scale). The mass defect of the excited nucleus He^{4*} (T = 1) must then be smaller than 21.5 MeV. Meanwhile the mass defect of the He^4 nucleus in the ground state is 2.4251 MeV. Accordingly, the requirement for the stability of Li^4 is that the energy of the first excited level of the particle with T = 1 be smaller than ~19.1 MeV. There is also an obvious connection between the position of an α-particle level with T = 2 and the stability of the tetraneutron.

There is a less obvious, but still definite, connection between the energy of a level of He^4 (T = 1) and the problem of the existence of H^5, and also of Be^5. This connection can be derived on the basis of regularities in the pairing energy of neutrons in a sequence of light nuclei.[14]

A collection of data on the energy values for various levels of the α particle, in correspondence with assumptions about the stability of various isotopes of light elements, is presented in Table I.

Let us now turn to the existing experimental data. The stability of the excited (0.98 MeV) state Li^{8*} and of the B^8 nucleus against multiple α decay excludes $E^*(He^4$, T = 1) < 17.4 MeV.

An analysis of the direct data on $p\alpha$ scattering shows that there are no bound excited states of the α particle, since their existence would lead to inelastic scattering of protons, which is not observed. Accordingly the α particle has no excited states with energy less than 19.81 MeV (the energy of disruption into H^3 +p). This at once shows that it is impossible for stable Li^4 and Be^5 to exist (see Table I).

The following discussion relates to levels where the α particle is already unstable, at least against the decay $He^{4*} \to H^3 + p$.

A survey of the state of this question in 1957 was given in a paper by G. F. Bogdanov, N. A. Vlasov, S. P. Kalinin, B. V. Rybakov, L. N. Samoĭlov, and V. A. Sidorov.[15] This gave an analysis of the following data from a number of papers by the authors of[15] and from some other papers (see references):

a) The energy dependence of the cross section for the reaction $T(pn)He^3$,[16] from which it can be concluded that there is a resonance maximum at $E^* \approx 22$ MeV (all energies are measured from the ground energy of the α particle), with width $\Gamma \approx 3$ MeV; it is possible that this maximum is due to two levels (2^- and 1^-) with smaller widths[17]—a supposition based on the angular distribution of the products of the reaction.

b) The spectra of the neutrons produced in T(dn) and He^3(dn) reactions at $E_d \approx 19$ MeV. A level with E^* = 22.0 ± 0.5 MeV appeared in the first of these reactions but not in the second, i.e., for He^4 but not for Li^4; this gives the hypothesis that T = 0 for this level.

c) The spectra of electrons[18] and protons[19] inelastically scattered by helium nuclei (at respective primary-particle energies of 400 and 181 MeV); in both cases there is evidence in favor of the existence of a level of the α particle with energy 22.5—22.7 MeV; the resonance peak in the spectrum of the scattered protons was found to be asymmetrical, which is a further point in favor of the existence of more than one level near 22 MeV.

d) The energy dependence of the cross section for nHe^3 scattering,[20] which is characterized by a broad maximum at $E_n \approx 2$ MeV (that is, $E^* \approx 22$ MeV); this maximum did not appear in the nT scattering, which speaks in favor of the isotopic spin T = 0 for the 22 MeV level.

e) The energy dependence of the cross sections for the reactions $T(p\gamma)He^4$[21] and $He^4(\gamma p)T$,[22,23] which shows no resonance at $E^* \approx 22$ MeV; this indicates that there is no E1 transition from this excited state to the ground state; this means that the 22 MeV level can have any angular momentum with T = 0 or an angular momentum J = 1^- with T = 1. The entire set of data we have listed indicated the presence near $E^* \approx 22$ MeV of a level with T = 0, or possibly two closely spaced levels with J = 2^- and 1^-.

In addition, the presence of a broad maximum of

Table I

Isotopic spin of level of α particle	If the energy of the level (MeV) is smaller than	a consequence would be	Isotopic spin of level of α particle	If the energy of the level (MeV) is smaller than	a consequence would be
arbitrary	19.81	nucleon (nuclear) stability of He^{4*}	T = 1	19.1	stability of Li^4
			T = 1	20.5	stability of H^4
T = 1	17.1	nucleon (nuclear) instability of Li^{8*} (0.98 MeV) ($Li^{8*} \to He^4 + H^4$)	T = 1	22	stability of H^5
			T = 2	24.5	stability of Be^4
			T = 2	28	instability of He^8 ($He^8 \to He^4 + n^4$)
T = 1	17.4	instability of B^8 ($B^8 \to He^4 + Li^4$)	T = 2	29	stability of n^4, quasistability of excited state H^{4*} (T = 2)
T = 1	18.6	stability of Be^5			

the cross section for nT scattering at $E_n \approx 4$ MeV (and evidently also of an analogous second maximum for nHe^3 scattering, which is masked by the first maximum at $E_n = 2$ MeV), as well as of a maximum in the cross sections of the direct and inverse reactions $T(p\gamma)He^4$[22,23] at $E_\gamma \approx 25$ MeV, led the authors of[15] to conclude that it is possible that there is a second excited level of the α particle at $E^* \approx 24$ MeV with T = 1, $J = 1^-$.

Finally, a group at the Physical Institute of the Academy of Sciences (U.S.S.R.)—A. A. Bergman, A. I. Isakov, Yu. P. Popov, and F. L. Shapiro[24]—has put forward the hypothesis that there is a still lower level of the α particle: $E^* \approx 20$ MeV, $J = 0^+$ or 1^+. This level, which is not stable against decay into p + T, is still stable against decay to n + He^3; that is, it corresponds to a negative energy of the neutron in the nHe^3 interaction. The presence of such a level manifests itself in a fact noted by the authors of[24], that the cross section for the nHe^3 interaction falls off more rapidly than by the $\sigma \propto 1/v$ law in the range of neutron energies up to 20 keV. An analysis of the energy dependence of $\sigma(n - He^3)$ led to the following alternative parameters of the level of the α particle at ~ 20 MeV[25]:

J	E_n of resonance	E^* (He^4)	Γ_p
1^+	—200 keV	20.3 MeV	200 keV
0^+	—500 keV	20 MeV	1200 keV

(here Γ_p is the proton width at excitation energy $E^* = 20.6$ MeV, which corresponds to the threshold of the decay $He^{4*} \rightarrow n + He^3$).

These characteristics of the level should show up in pT scattering at the respective energies $E_p = 800$ keV (1^+) or 500 keV (0^+). And indeed, according to measurements by the Los Alamos group,[26] there is a sharp rise of the cross section for pT scattering when E_p is decreased from 990 to 700 keV, though the authors of[26] interpret this in a different way.

The assumption of the authors of[24,25] that there is a level of the α particle at ~ 20 MeV were subjected to doubt by Bame and Cubitt,[27] who reported a deviation from the $\sigma \propto 1/v$ law in the reaction Li^6 + n, which had been used in[24,25] as a standard for comparing cross sections. Further measurements, however, which will be discussed below, confirmed the original conclusions of F. L. Shapiro and his coworkers and their reply[28] to the arguments of the authors of[27].

Returning to the situation at the time we wrote our review article,[1] we can characterize it in the following way: all of the levels of He^4 are virtual (higher than 19.8 MeV); the level at $E^* \approx 20$ MeV (most probably 0^+) is not reliably established; the level (or the 2^- and 1^- levels) at $E^* \approx 22$ MeV with isotopic spin T = 0 is the most reliable; the first level with T = 1 does not lie lower than $E^* \approx 24$ MeV, from which it follows that H^4 and H^5 are unstable.

In the last few years there have been many new researches, which have added much to the entire picture.

First, there have been new and careful studies of the reactions d + T and d + He^3. In the reactions T + d → n + p + T (Q = −2.2246 MeV, $E_{d\ thresh}$ = 3.71 MeV) and T + d → n + n + He^3 (Q = −2.989 MeV, $E_{d\ thresh}$ = 4.98 MeV) the neutron spectrum must be different depending on whether the three particles are formed at once or there is a virtual level of the (pT) or (nHe^3) system. At a given deuteron energy neutrons of higher energies are produced in the former of these two reactions, and therefore the most complete information is given by the shape of the neutron spectrum near the maximum value of the energy, which corresponds to combined emergence of p and T. The analogous "peak" of the neutron spectrum from the second reaction falls in the three-particle region of n + p + T and is therefore less clearly marked. The study made by Lefevre and others[29] of the shape of the neutron spectra at angle 0° for $E_d = 8.32$ MeV speaks in favor of a level of He^4 with $E^* = 20.0 \pm 0.2$ MeV. At the same time this work did not confirm the level at $E^* = 22$ MeV, which had been obtained earlier[15] in a study of this same reaction, it is true at a higher energy (E_d = 18—19 MeV). There has also been work on the T + d reaction by Poppe[30] and by Poppe, Holbrow, and Borchers,[31] in which the energy spectrum of the neutrons was measured over a wide range of energies (E_d = 6—11 MeV) and of angles of emergence of the neutron (θ = 0—70°). The analysis of these data persistently indicated the existence of a level of He^{4*} with $E^* = 20.1$ MeV and width $\Gamma \approx$ 300—400 keV. An important fact must be noted: The peak corresponding to He^{4*} in the neutron spectrum of T + d → n + (p + T) showed up especially clearly at E_d = 6 MeV, and that in the branch T + d → n + (n + He^{3*}), at 8—9 MeV. The unique and rather natural explanation of this is as follows: The 20.1 MeV level lies below the threshold for (n + He^3), but above that for (p + T). This means that the wave functions of the two pairs of particles in He^{4*} are altogether different, since the wave functions of n are decreasing exponentials and those of p are sinusoidal. Therefore in He^{4*} the two pairs (p + T) and (n + He^3) are not equivalent; in other words, here the very concept of isotopic spin to some extent loses its meaning. This in turn also explains the different behaviors of the two branches of the reaction. The possibility of this sort of effect in threshold states has been pointed out in a paper by A. I. Baz'.[32] This question is considered in detail below, in Sec. 6.

The spectrum of the protons from the reactions

$$He^3 + d \begin{cases} \nearrow p + (n + He^3), \\ \searrow p + (p + T) \end{cases}$$

for E_d = 6—14 MeV has been studied by Stewart, Brolley, and Rosen.[33] This experiment, however, did not make it possible to say anything about the levels of He^4, since the energy resolution was too crude. This reaction was studied more accurately by Young and Ohlsen,[34] and a clearly marked peak was found in the proton spectrum, corresponding to a level of He^4 with E^* = 20.08 ± 0.05 MeV and width 0.20 ± 0.05 MeV (Figs. 4 and 5). In this experiment the deuteron energy was varied over the range 6—10 MeV, and the angle of emission of the protons over the range θ = 14°—30°.

Extremely precise studies of the spectrum of protons from the dHe^3 reaction (bombardment of deuterium with He^3 nuclei of energy 31.5 MeV) have been made recently by Donovan, Kane, Mollenauer, and Parker.[35] These authors used a two-dimensional analyzer to select and compare various kinematic versions of the reactions in which three particles were produced in the final state. Figure 6 shows examples of their data on the comparison of the energies of protons (T_4) emitted at angle 50° and tritons or He^3 (T_3) at angle 21°. At the left the calculated curves are shown for various types of decay at these angles. The calculated curve for Tp coincidences runs through the region of the largest values of T_3 and lies outside the calculated curve of the He^3p coincidences. The other curves are for pp and dp coincidences. In the general case various points on the T_4—T_3 plot correspond to the kinematics of reactions in which two particles are produced; the curves shown on the diagram correspond to production of three particles, and the regions of space bounded by these curves correspond to reactions with production of four particles. The results of the

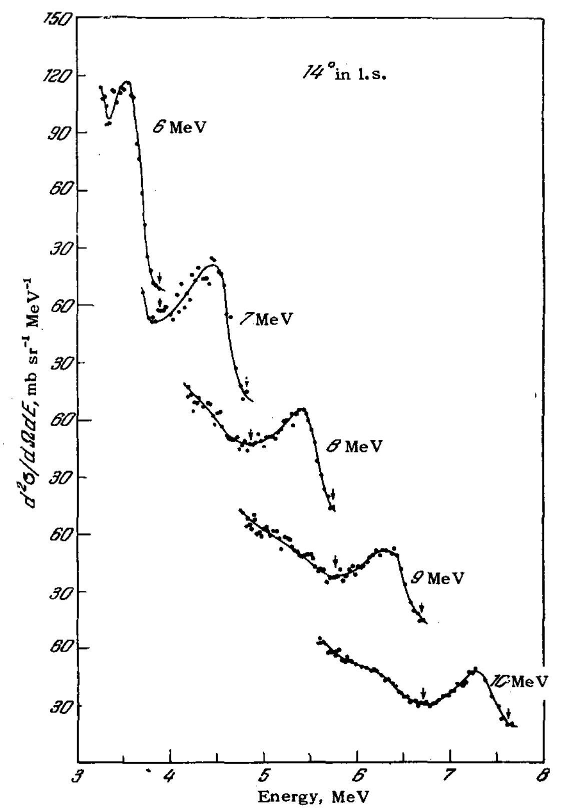

FIG. 4. Spectra of protons emitted at angle 14° from bombardment of He^3 nuclei with deuterons of energies 6 – 10 MeV.[34] Arrows show maximum possible energies of protons from the reactions He^3(d, pp)T (the larger energies) and He^3(d, np)He^3 (the smaller energies).

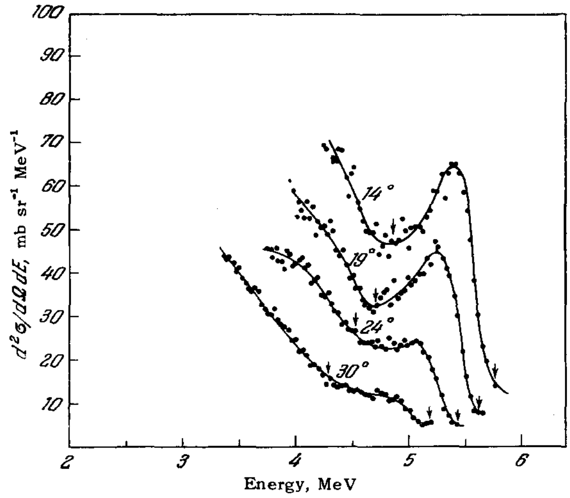

FIG. 5. Spectra of protons emitted at angles 14°–30° from bombardment of He^3 nuclei with deuterons of energy 8 MeV.[34] The meaning of the arrows is the same as in Fig. 4.

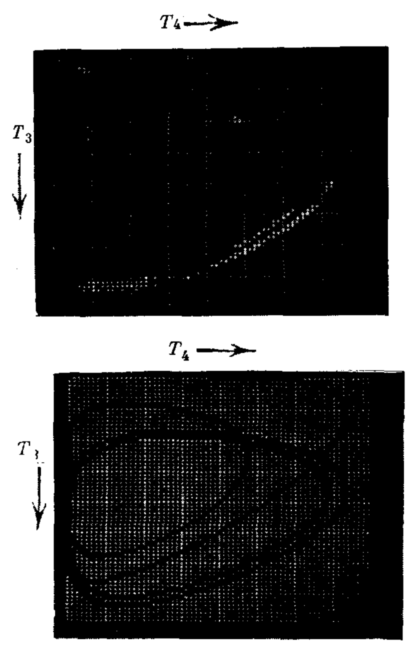

FIG. 6. Relation between proton energy and energy of triton or He^3 nucleus in the reactions He^3(d,pp)T and He^3(d, np)He^3. At the bottom, calculated curves for E(He^3) = 31.5 MeV; at the top, experimental data.[35] Values of T_3 are ordinates, of T_4, abscissas.

experiment are plotted on the right. The maxima of intensity (accumulation of points) at certain parts of the calculated curves are due to intermediate virtual states. An analysis of the positions of these accumulations for various angles of registration of T and p or He^3 and p makes it possible to establish the properties of the virtual states very accurately. In this way the authors of[35] discovered two excited states of He^4, and state their characteristics as follows:

$$E = 19.96 \pm 0.02 \text{ MeV}, \quad \Gamma = 125 \pm 25 \text{ keV},$$
$$E = 21.2 \pm 0.2 \text{ MeV}, \quad \Gamma = 1.2 \text{ MeV}, \quad \Gamma_p = \Gamma_n.$$

Considerable information about the levels of the α particle can also be obtained in experiments on pT scattering. For example, Jarmie, Silbert, Smith, and Loos[36] measured the cross section for pT scattering at E_p = 163—520 keV and found a resonance at the proton energy corresponding to an excited state of He^4 at E^* = 20.1 MeV. These authors themselves, however, did not draw the conclusion that the level exists, since in their opinion this resonance can be explained by an interference of the Coulomb and nuclear scatterings.

The results of some of the experiments we have listed have been analyzed by Werntz and Brennan[37] on the hypothesis of $^1S_0$ or $^3S_1$ excited state. These authors prefer a state $^1S_0\,(0^+)$. Good agreement with experiment is obtained if one takes for the position of the level E^* = 20.2 MeV, and sets the reduced n and p widths equal to $\gamma_p^2 = \gamma_n^2 = 3 \times 10^{-13}$ cm × 4.2 MeV.

There is still another chain of facts leading to an excited state of He^4 with energy about 20 MeV. Some time ago Frank and Gammel[38] made a phase-shift analysis of pT scattering for $E_p > 0.8$ MeV. The phase shifts obtained indicated the existence of a level with E^* = 20.4 MeV and reduced width 2.7 MeV. Not much significance was given to this conclusion, since the phase-shift analysis was made with very rough simplifying assumptions. Subsequently, however, it turned out that the s phases had nevertheless been correctly obtained; with them, a good explanation was obtained for the cross sections for pT scattering at E_p = 50, 120, and 175 keV measured by Yu. G. Balashko, I. Ya. Barit, and Yu. A. Goncharov.[39] Recently Yu. G. Balashko, I. Ya. Barit, L. S. Dul'kova, and A. B. Kurepin[40] have again confirmed the existence of an excited level of the α particle (E^* = 20.3 ± 0.12 MeV; 0^+), through a precise study of pT scattering in the range of angles 40°—152° (in the c.m.s.) and at proton energies E_p = 300—990 MeV.

Data of the Brookhaven[35] and FIAN (Physical Institute of the Academy of Sciences, U.S.S.R.)[39,40] groups have been subjected to detailed analysis and comparison by Meyerhof,[41] who came to the conclusion that to all of these data there corresponds a resonance energy $E^* \approx 20.4$ MeV, at which the phase of $^1S_0$ pT scattering passes through $\pi/2$. The transition matrix element $|M|^2$, however, which is proportional to $\sin^2\delta/\Gamma_p$, has its maximum at E^* = 20—20.1 MeV.

Accordingly the various papers devoted to the ~ 20 MeV level of the α particle are clearly talking about the same excited state that was first discovered by F. L. Shapiro and his co-workers.[24]

The level at excitation energy $E^* \approx 22$ MeV has been confirmed recently by the work of a large group of Japanese physicists.[42] They studied the inelastic scattering of 55 MeV protons by He^4 and found a group of inelastically scattered protons corresponding to a level of He^4 with excitation energy 22.5 ± 0.7 MeV and width 1.7 ± 0.5 MeV.

It is still unclear whether the results of the Brookhaven group stated earlier[35] (E^* = 21.2 MeV) give a more accurate position of the α-particle level $E^* \approx 22$ MeV, which was discussed long ago by N. A. Vlasov and his coworkers (cf. e.g.,[15]) and is also apparently confirmed in the Japanese work,[42] or whether it is a matter of two closely spaced levels, the separation being in the range of their widths. In concluding the discussion of the question of the levels of the α particle, we must emphasize the unquestioned importance of a detailed study of the angular distributions and polarizations of the particles in elastic scattering and in the interconversions of the "pairs" p + T and n + He^3. Such detailed studies will make it possible to fix reliably the absolute magnitudes and the energy dependences of all four phase shifts of s and p scattering and to check the isotopic-spin characteristics of the excited levels of the system of four nucleons.

Accordingly, all of the experimental work of the last few years leads to the following scheme (shown in Fig. 7) of the levels of the α particle: $E^* \approx 20$ MeV, stable against decay into n + He^3, but not stable against decay into p + T; 0^+, T = 0 (mainly) and 1 (admixture)—see Sec. 6. This level, long the subject of doubts, has now become the one most thoroughly studied. Next, one or two levels at E^* = 21—22 MeV (2^- and/or 1^-; T = 0); and finally, a "level" E^* = 24 MeV, which is the least clearly manifested. In our discussion of the properties of the hypothetical virtual nucleus H^4 we shall see that according to the data of[43] and[44] it must precisely correspond to the ~ 24 MeV level in He^4, which is an additional argument in favor of the value T = 1 for this level. At one time the value T = 2 was suggested for this state,[45] but, as we shall see later, there is no basis for this.

6. CASES IN WHICH THE CONCEPT OF ISOTOPIC SPIN CANNOT BE APPLIED

There is a widespread opinion that all states of light nuclei that are not very strongly excited have definite values of the isotopic spin. An argument for this is that in light nuclei the Coulomb energy is small

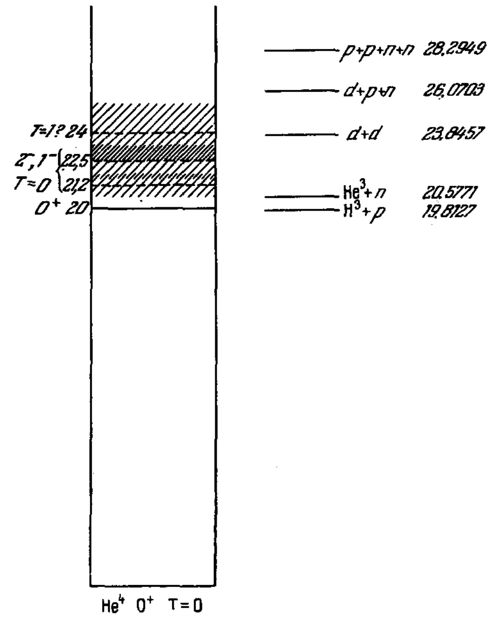

FIG. 7. Scheme of energy levels of the α particle.

[roughly, we can say that for such nuclei the Coulomb interaction energy per proton is 0.4(Z − 1)MeV and that the forces acting on the neutrons and protons in such nuclei are almost identical]. There is, however, a rather broad class of excited states in whose treatment one must be extremely careful with the use of the concept of isotopic spin. These are states of the intermediate nucleus which are near some threshold for disintegration.

In order to understand what the point is here, let us consider an idealized example. Suppose there are two pairs of isotopically conjugate particles, a + x and b + y (for example, p + T and n + He^3). Because of the Coulomb interaction the mass of the pair (a + x) is not the same as that of the pair (b + y) (the difference of the masses of n + He^3 and p + T, for example, is 0.765 MeV; the thresholds for disintegration of an α particle into p + T and into n + He^3 are marked in Fig. 7); let us denote the difference of the masses by Q. We now consider the structure of the excited states of the intermediate nucleus which is formed in collisions of the particles (a + x) or of (b + y).

We shall assume that in the range of distances between the particles r < R the interaction is large, and that in this region transitions a + x $\rightleftarrows$ b + y are possible. For r > R we shall suppose there is no interaction. In the internal region (r < R), where there is a large interaction between the particles, we can neglect the difference between neutrons and protons, and consequently we can introduce the concept of isotopic spin; in this region there exist two solutions of the Schrödinger equation, one which is unchanged by the interchange a $\rightleftarrows$ b, x $\rightleftarrows$ y (the state with T = 1) and another which changes sign on this interchange (the state with T = 0). These solutions are of the forms

$$\Psi_{T=1} = [\Phi(a) + \Phi(b)]\varphi_1, \quad \Psi_{T=0} = [\Phi(a) - \Phi(b)]\varphi_0 \quad (r < R),$$

where Φ(a) and Φ(b) are the internal wave functions of the pairs (a + x) and (b + y), and φ_1 and φ_0 are functions which describe the relative motion of these particles. The most general wave function of our system in the region r < R can be written $\sigma\Psi_{T=1} + \Psi_{T=0}$, where σ is a constant. This function must be joined continuously onto the wave function in the external region: $\Psi = \alpha\Phi(a)\chi_a + \beta\Phi(b)\chi_b$ (r > R). Here χ_a and χ_b describe the motion of the pairs (a + x) and (b + y) in the external region. For example, in the case of zero orbital angular momentum

$$r\chi_a = e^{-k_a r}, \qquad r\chi_b = e^{-k_b r},$$

$$k_a = \sqrt{\frac{2mE}{\hbar^2}}, \quad k_b = \sqrt{\frac{2m(E+Q)}{\hbar^2}}. \tag{6}$$

The conditions for continuity determine the values of the constants α, β, σ. We then find that if Q = 0 there are only two possible values for σ: σ = 0 or $\sigma = \infty$. The first corresponds to a state with T = 0, and the second to a state with T = 1. On the other hand, if Q ≠ 0, then σ takes intermediate values $0 < \sigma < \infty$; in this case the wave function of the system for r < R is a mixture of states with different isotopic spins.

Let us carry the analysis of this case to the end. We normalize the wave functions in the internal region in the following way:

$$[R\Psi_{T=0}(R)] = 1, \quad [R\Psi_{T=1}(R)] = 1. \tag{7}$$

We denote the derivatives of these functions by λ_0 and λ_1:

$$(R\Psi)'_{T=0}(R) = \lambda_0, \quad (R\Psi)'_{T=1}(R) = \lambda_1. \tag{8}$$

The most general solution in the internal region is of the following form:

$$\Psi = \sigma[\Phi(a) + \Phi(b)]\varphi_1(r) + [\Phi(a) - \Phi(b)]\varphi_0(r)$$
$$= \Phi(a)[\varphi_0 + \sigma\varphi_1] - \Phi(b)[\varphi_0 - \sigma\varphi_1],$$

where σ is an arbitrary constant. The conditions for joining this function to the external wave functions lead to two equations for the logarithmic derivatives [cf. Eqs. (7) and (8)]

$$\frac{\lambda_0 + \sigma\lambda_1}{1+\sigma} = \tau_a, \quad \frac{\lambda_0 - \sigma\lambda_1}{1-\sigma} = \tau_b, \tag{9}$$

where we have written $\tau_{a,b}$ for the logarithmic derivatives of the external wave functions at r = R:

$$r = R: \quad \tau_a = \frac{(r\chi_a)'}{(r\chi_a)}\bigg|_{r=R}, \quad \tau_b = \frac{(r\chi_b)'}{(r\chi_b)}\bigg|_{r=R}.$$

There is only one arbitrary constant σ in the system of equations (8). Therefore a solution is possible (and this means that a bound state exists) only if the two equations are compatible, i.e., if the equation

$$\sigma = -\frac{\tau_a - \lambda_0}{\tau_a - \lambda_1} = \frac{\tau_b - \lambda_0}{\tau_b - \lambda_1} \quad (10)$$

holds. We assume that there is no interaction between the particles for $r > R$. In this case the wave functions χ_a and χ_b are given by the formulas (6), and $\tau_a = -k_a$, $\tau_b = -k_b$. By Eq. (10) λ_1 and λ_0 are uniquely connected, and one of them can be chosen arbitrarily, for example λ_0. To simplify the formulas let us set $\lambda_0 = 0$. Then

$$\lambda_1 = \frac{2\tau_a\tau_b}{\tau_a + \tau_b} \text{ and } \sigma = \frac{\tau_b + \tau_a}{\tau_b - \tau_a}.$$

It can be seen from these formulas that the case $\lambda_0 = 0$, which we are considering, corresponds to a state in which for $\tau_a = \tau_b$ [i.e., for equal masses of the pairs (a + x) and (b + y)] the wave function contains only the component with $T = 1$. Thus in fact for $\tau_a = \tau_b$ the state has a definite value of the isotopic spin. The fact that $\tau_a \neq \tau_b$ leads to the appearance of an admixture of the state with $T = 0$.

Instead of σ it is convenient to introduce the quantity $\zeta = \sigma^2/(1 + \sigma^2)$, which is nothing other than the relative fraction of the state with $T = 1$. For the pure state with $T = 1$, $\zeta = 1$, and for that with $T = 0$, $\zeta = 0$.

Figure 8 shows the dependence of the quantity ζ on the binding energy E of the state (the energy is measured from the smaller of the two thresholds for disintegration into a + x). The calculations have been made for three values of the difference of the masses of the pairs (a + x) and (b + y): Q = 0.5, 1, and 1.5 MeV. It is seen at once that the closer the excited state is to the threshold, the stronger the effect. For $E \to 0$, $\zeta = 1/2$; this means that there are equal fractions of the states with $T = 0$ and $T = 1$. Thus the state does not have a definite value of the isotopic spin. In fact the situation is still worse. Up to now we have been speaking only of the region $r < R$; in the region $r > R$ the wave functions χ_a and χ_b of the pairs (a + x) and (b + y) are very different. For $E \to 0$, for example, $k_a \to 0$ and $\chi_a \to$ const, but $\chi_b \to e^{-k_{b_0} r}$ $(k_{b_0} = (2mQ/\hbar^2)^{1/2}$. At a sufficiently large distance from the nucleus the wave function of the system contains only the term which describes the pair (a + x). Thus for $r > R$ the pairs (a + x) and (b + y) are not equivalent, and in this region we cannot introduce the concept of isotopic spin at all.

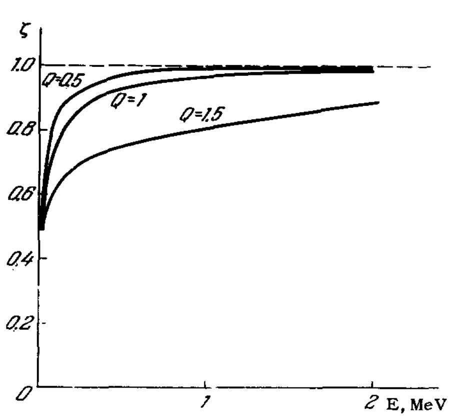

FIG. 8. Illustration of the fact that the concept of isotopic spin cannot be applied in the region near a threshold.

The calculation just now given is purely illustrative, but the qualitative result is generally valid, independent of the concrete model.

Therefore everything that has been said also applies fully to the ~ 20 MeV state of the α particle. In this particular case, however, the admixture of the state with $T = 1$ is small (~ 10 percent according to D. A. Zaikin and V. A. Sergeev[104]), and the state is mainly that with $T = 0$.

7. THE PROBLEM OF H^4

If H^4 exists, then the configuration energetically most favorable for it must evidently be either $(1s)^3 1p_{3/2,1/2}$, $(1s)^3 2s$, or $(1s)^2(2p)^2$, and accordingly possible states are 2^-, 1^-, 0^-, 1^+, 0^+, and obviously $T = 1$.

There are two possibilities:

a) H^4 is a truly stable structure, with lifetime limited only by β^- decay;

b) H^4 is capable of decaying into n + T; in this case H^4 decays within nuclear times.

As we shall see, the first possibility at present seems entirely implausible. First, the binding energy of H^4 cannot be larger than 3.50 MeV, since otherwise the direct decay Li^{8*} (0.98 MeV) $\to He^4 + H^4$ would be possible. Accordingly, the energy of the β decay $H^4 \to He^4$ is $E_{\beta max} > 17.1$ MeV. On the other hand, stability of H^4 against decay into n + T would mean that $E_{\beta max} < 20.6$ MeV. For this range of possible values $E_{\beta max}$ we can easily estimate a lower limit for the lifetime of H^4 against β^- decay. On the various assumptions about the angular momentum of H^4 we get the following rough estimates of the half-value period for β^- decay to the ground state of He^4:

J	$T_{1/2}$	J	$T_{1/2}$
2^-, 1^-, 0^-	$\geqslant 10$ min ($\log ft \approx 9$),	1^+, 0^+	$\geqslant 0.03$ sec ($\log ft \approx 5$).

As was pointed out above, no definite value of isotopic spin can be assigned to the excited state of He^4 with energy $E^* \approx 20$ MeV. But even if we assume that this state is isotopically identical with the nucleus H^4 (in the form of the spatial part of the wave function), i.e., assume the existence of a superallowed transition $H^4 \to He^{4*}$, still the half-value period will be $T_{1/2} > 3$ h; i.e., such a transition could evidently always be neglected in comparison with β^- decay to the ground state of He^4. Many researches have been devoted to the search for the β^- decay of a hypothetical H^4. The first such work was done as early as 1951 by McNeill and Roll,[46] who tried to detect the β^- decay of H^4 after bombardment of tritium with deuterons of energy 0.5—3.8 MeV; they searched in vain for any activity with half-value period from 0.006 to 3 sec, and also of about 100 sec.

In papers of Breit and McIntosh[47,48] the theoretical yield ratio $Y(H^4)/Y(Li^8)$ was derived for the reactions $T(dp)H^4$ and $Li^7(dp)Li^8$, for various values of the Q of the first of these reactions and for $E_d = 3.8$ and 4.1 MeV. Starting from the fact that no β-active H^4 had been found in[46], the authors of[47,48] derived an upper limit on the ratio of yields $Y(H^4)/Y(Li^8)$ on the assumption that $T_{1/2}(H^4)$ lies in the range from 0.001 to 100 sec. In this range the yield ratio in question increases from 0.1 to 3×10^4. Accordingly, the existence of H^4 with small $T_{1/2}$ is extremely improbable, although even in this case the restriction that follows from the negative result of[46] is an extremely weak one.

In 1955 A. Reut, S. Korenchenko, V. Yur'ev, and B. Pontecorvo[49] made an attempt to detect H^4 in the products from the splitting of carbon nuclei with 300 MeV protons. These authors looked for an activity with $T_{1/2} = (2—10) \times 10^{-3}$ sec and $E_\beta > 12$ MeV. There was no such activity, but they obtained the following results, with the indicated upper limits:

$$E_\beta > 12\,\mathrm{MeV},\ T_{1/2} = 2-4\cdot 10^{-3}\,\mathrm{sec},\ \sigma < 10^{-30}\,\mathrm{cm}^2,$$
$$E_\beta > 12\,\mathrm{MeV},\ T_{1/2} = 4-10\cdot 10^{-3}\,\mathrm{sec},\ \sigma < 10^{-29}\,\mathrm{cm}^2.$$

In 1962 a 3.5 MeV Van de Graaf accelerator was used to study[50] the hypothetical reactions $T(n\gamma)H^4$, $He^3(dn)Li^4$, $He^3(p\gamma)Li^4$, and $T(dp)H^4$. No β^--active H^4 was found, and on the assumption that $T_{1/2} = 5 \times 10^{-3}—5 \times 10^5$ sec the upper limit on the cross section for its production in the reactions in question was found to be $\sigma < 3 \times 10^{-30}$ cm^2.

In 1963 a note appeared[51] on an especially clean experiment: Spicer studied the reaction $Li^6(\gamma, 2p)H^4$, where there cannot be any competing β-activities besides H^4. The irradiation was made with a 35 MeV betatron, and activities with $E_\beta > 8$ MeV were looked for. Spicer's conclusion was: if H^4 exists and its lifetime is in the range 5×10^4 sec $< T_{1/2} < 5 \times 10^{-3}$ sec, then an upper limit on the cross section for production of H^4 is $\sigma < 0.6 \times 10^{-30}$ cm^2. Nefkens and Moscati[52] looked for β-active H^4 by irradiating the natural mixture of Li isotopes with 250 MeV bremsstrahlung. Again the result was negative; the cross section for production of H^4 was found to have the upper limits

$$\sigma < 6.7\cdot 10^{-34}\,\mathrm{cm}^2 \text{ for } T_{1/2} = 3\ \mathrm{min},$$
$$\sigma < 2.7\cdot 10^{-34}\,\mathrm{cm}^2 \text{ for } T_{1/2} = 1000\ \mathrm{min}.$$

Also no delayed γ rays were found in these experiments.

Finally, there appeared recently a paper by Pipic, Stepancic, and Aleksic,[53] who tried to detect the production of β-active H^4 in the reaction $Li^7(n\alpha)H^4$ by bombarding lithium with 14-MeV neutrons. The result of this work was also negative; on various assumptions about the half-value period of H^4, the following upper limits on the cross section for its production were found: $T_{1/2} \sim 10^4$ sec, $\sigma < 3 \times 1$ 10^{-31} cm^2; $T_{1/2} \sim 500$ sec, $\sigma < 7 \times 10^{-33}$ cm^2; $T_{1/2} \sim 10$ sec, $\sigma < 7 \times 10^{-30}$ cm^2.*

There have also been a number of papers on a different type of search for H^4, not involving the assumption that it is β-active. Norbeck and Littlejohn[54] bombarded B^{10} nuclei with Li^7 ions at energy 2.1 MeV and looked for production of N^{13} in the reaction $B^{10}(Li^7, H^4)N^{13}$. Stability of H^4 against decay into n + T corresponds to a threshold of 2.4 MeV for this reaction. Thus in principle production of H^4 could be observed if the binding energy of the neutrino is more than 0.16 MeV. The result was negative, however, and so was that of the work of Stewart, Brolley, and Rosen,[55] who studied the angular distribution of the charged products of the interaction of deuterons (at energy $E_d = 6—14$ MeV) with the nuclei T and He^3.

If the reaction $T(dp)H^4$ occurred with energy release from −2 to +2 MeV, this experiment would have revealed H^4 nuclei having longer ranges than the other singly charged particles. No such component was observed. It is true that also no monoenergetic group of protons was observed from the reaction $He^3(dp)He^{4*}$, which would correspond to any excited state of the α particle with energy less than 26 MeV.

A still more detailed study of the hypothetical reaction $T(dp)H^4$ was undertaken recently by Rogers and Stokes,[56] who studied the shape of the spectrum of protons at angles 20° and 45° when a gaseous tritium target was bombarded with 10 MeV deuterons.

An indication of the great precision of this work in comparison with[55] is that the authors of[56] were able to distinguish the contribution of the reaction $T(dn)He^{4*}$ with the production of a level of the α particle at ~20 MeV. Here also, however, production of H^4 could not be demonstrated; for the angle 20° the upper limit on the cross section for the reaction $H^3(dp)H^4$ (with binding energy of H^4 up to 1.8 MeV) was less than 0.001 of the cross section for the reaction $H^3(dn)He^{4*}$, and the corresponding factor for angle 45° (with binding energy of H^4 up to 5 MeV) was 0.004.

On the basis of all of these researches we must reject the existence of a nuclear-stable H^4. This same conclusion is given by an extrapolation of the data on the binding energy of a third neutron in various nuclei (see[1], and also[57]):

	H^4	He^5	Li^6	Be^7	B^8
B_n (MeV):		−0.957	5.663	10.7	13.93.

There remains, however, the question whether there is a virtual state of H^4, capable of disintegration into

*Subsequently these same authors[105] have set a still lower limit on the cross section for the reaction $Li^7(n\alpha)H^4$: $\sigma < 10^{-31}$ cm^2 for $0.1 < T_{1/2} < 10$ sec.

n + T. The existence of such a state was reported in a paper by Argan and others.[43] This group studied the reaction

$$\gamma + He^4 \rightarrow \pi^+ + n + T$$

with $E_{\gamma\,max}$ = 1 BeV in a 60-cm diffusion chamber filled with helium and placed in a magnetic field. From an analysis of the angular and energy distributions of the products of the reaction, and in particular an analysis of the distribution of angles between the planes $\gamma 0 \pi^+$ and $\gamma 0 T$ (where $\gamma 0$ is the direction of the primary γ-ray beam), the authors of[43] came to the conclusion that the form of these distributions is as if the reaction went in two stages with the production of n-unstable H^4: $\gamma + He^4 \rightarrow \pi^+ + H^4$, $H^4 \rightarrow n + H^3 + Q$, Q = 3.5–7 MeV. To this state of H^4 there must correspond an excited state of He^4 with E^* = 24–27.5 MeV.

Later, arguments appeared against the conclusions of[43]. Lohrmann, Meyer, and Wuster[58] calculated theoretically for the reaction $\gamma + He^4 \rightarrow \pi^+ + n + T$ the angular correlations in a two-dimensional momentum space in the plane perpendicular to the γ-ray beam which are caused by the law of conservation of momentum. It was assumed that there is no interaction between the particles produced. The calculation was made by the Monte Carlo method. The result was splendid agreement with the experimental data of Argan and others.[43] Similar conclusions were later reached by Hippel and Divakaran,[59] who made a detailed kinematical analysis of the photoproduction of π^+ mesons in helium—working in the impulse approximation and using no nT interaction in the final state—and also concluded that it is not at all necessary to introduce the assumption that H^4 exists in order to explain the results of the experiment of[43]. On the other hand, the conclusions of Argan and others[43] are supported by the results of a recent paper by Cohen, Canaris, Margulis, and Rosen,[44] who used a coincidence telescope to study the spectra of the products of the reactions $Li^6(\pi^-, H^2)H^4$ (?) and $Li^7(\pi^-, H^3)H^4$ (?) in the capture of stopped π^- mesons in lithium. In the first of these reactions, where there can be only the value T = 1 for the H^4, it was found that there is a neutron-unstable state of H^4 with decay energy 5.1 ± 1.5 MeV [which corresponds to $E^*(He^4, T = 1) \approx 25.6 \pm 1.5$ MeV], and width $\Gamma \lesssim 3$ MeV. The probability of formation of such a state in the capture of π^- mesons in Li^6 is estimated from the experiment to be $(1 \pm 0.5) \times 10^{-4}$. In the second reaction, where the values T = 1 and T = 2 can occur for H^4, according to the data of[44] there is probability $(3 \pm 1.5) \times 10^{-4}$ for production of a state of H^4 with decay energy 8.1 ± 1.5 MeV and width $\Gamma \lesssim 3$ MeV (i.e., $E^* = 28.6 \pm 1.5$ MeV). It must be stated that for T = 2 such a state would correspond to the existence of a weakly bound tetraneutron; for T = 1 there is some discrepancy between the results for the capture of π^- by Li^6 and Li^7 nuclei. It would be interesting to have additional verifying experiments on these and also on other processes, for example a kinematical analysis of reactions in which H^4 can be a third particle in the final state: $\pi^\pm + He^4 \rightarrow \pi^\pm + \pi^+ + H^4$ or $T + He^3 \rightarrow p + p + H^4$, or a study of complicated types of nucleon transfer in reactions of heavy ions, such as

$$_Z M_N^A + Li^7 \rightarrow {}_{Z+2}M_{N+1}^{A+3} + H^4.$$

We must also say a few words about the terminology. If the isotopic spin of a neutron-unstable state of H^4 is T = 1, then decay into $n + H^3$ occurs in a nuclear time, which is still not so very bad. But the decay energy of 3.5–7 MeV is too large for this state of H^4 to be called a virtual state. Even the very liberal interpretation of "state" which we adopted in Sec. 1 does not allow us to use it in this case. This can be seen especially clearly from the data on the so-called state of He^4 with E^* = 24 MeV, which must be the analog of the H^4. It is so broad (several MeV), in correspondence with a nuclear lifetime (10^{-22} sec), that it shows up in the experiments only as a very smooth and wide hump on the curves. But of course not every "hump" is a "state"! Therefore the only sense in which we can speak of the existence of H^4 and some other many-nucleon systems with an excess of neutrons is as peculiar "resonance" systems (of the type of the meson and hyperon resonances).

The discussion of the question of H^4 is not exhausted with the case T = 1. The wish to reconcile the argument given in[14], that stability of H^5 requires that H^4 satisfy the condition $E^*(T = 1) < 22$ MeV, with Nefkens' announcement[60] of the discovery of β^--active H^5 led Argan and Piazzoli[45] to suggest that the state of H^4 that they had described in[43] has T = 2. The isotopic-spin selection rules would then not allow it to manifest itself in the experiments made to look for excited states of He^4 (cf. Sec. 5). Since the direct decay

$$H^4 (T = 2) \rightarrow n + H^3,$$

is the only one possible if the excess excitation energy of H^4 (above the hypothetical binding energy of the neutron) is less than 6.26 MeV [which corresponds to $E^*(He^4) < 26.8$ MeV], and both it and the decay $H^4(T = 2) \rightarrow 2n + H^2$ can go only owing to a violation of the selection rules on T, if the excess energy of H^4 is less than 8.5 MeV [i.e., $E^*(He^4) \lesssim 29$ MeV] such a state would have a rather long lifetime, at least several orders of magnitude larger than 10^{-22} sec. In this case, however, a stable tetraneutron would exist with a large binding energy (~ 5 MeV), whereas it clearly should not exist owing to the decay $He^8 \rightarrow He^4 + n^4$ for the isotope He^8, which is relatively likely as a nuclear-stable structure, as considered below, in Sec. 10.

There is further evidence against the value T = 2 for the 24 MeV level of the α particle in the calculations of the positions of the first excited levels of light nuclei with the isotopic spins T = 1, 2 made by Franzini and Radicati[61] on the basis of a scheme of isotopic supermultiplets. For the α particle these authors got the energy 21.7 MeV for T = 1 and 34.1 MeV for T = 2. Without judging the absolute accuracy of these calculations, we must remark that the calculated difference of the energies of the levels with T = 2 and T = 1 is close to the true value, judging from the data for other nuclei. The authors of[6] state that the following inequality should hold for He^4: $E^*(T=2) - E^*(T=1) \geq (1/3)E^*(T=1)$.

Summarizing, we must reject the value T = 2 for the α particle with excitation energy ~ 24 MeV. At the same time we of course must not exclude the possibility that such a state may appear at higher excitation energies. Indeed, according to Levi-Setti[62] a kinematical analysis of the products from decay of the hypernucleus $_\Lambda He^4 \to \pi^- + p + He^3$ indicates that there is formation of an intermediate state Li^{4*} with excitation energy about 10.6 MeV, $\Gamma \approx 200$ keV, and proposed value T = 2.

The excitation energy of the α particle that corresponds to such a state is about 29.7 MeV, so that even with T = 2 its existence does not involve the requirement that the tetraneutron be stable. Here the main type of decay must be into four neutrons with $\Delta T = 0$. The total width can then be relatively small (hundreds of keV), from arguments about the effect of the phase-space volume in decay into a large number of particles. But the decay $Li^{4*}(T=2) \to p + He^3$, occurring with change of isotopic spin, must have a partial width much smaller still, and accordingly appear only as an improbable branching. In these experiments only cases of the "three-prong" decays of He^4 which we mentioned first were analyzed, and therefore no data on the probability of the decay channel were obtained.

Attempts[63] to observe the production of the state Li^{4*} (T = 2) by bombardment of Li^7 nuclei with He^3 ions at energy 32 MeV, in the reaction $Li^7(He^3, He^6)Li^{4*}$ were unsuccessful, and no He^6 nuclei at all were detected among the products of the interaction.

An interesting approach would be a careful study of the inelastic interaction of protons with He^3 nuclei, with a search for the emission of γ-rays, which is possible if excited states of Li^4 are formed as an intermediate stage.

8. THE TETRANEUTRON

The question of the existence of a bound system of four neutrons (tetraneutron) is of particular interest. If n^4 is nuclear-stable, then it is almost certain that heavier neutron nuclei also exist, and in the limit also large neutron "droplets." In other words, stability of n^4 would mean the existence of neutron nuclei, although this is not excluded even if there is no stable tetraneutron. The point is that owing to the existence of a surface tension there is a definite critical size of the minimal "neutron droplet," which could be much larger than a tetraneutron. This question was discussed in our review article,[1] and since that time no new data on the neutron liquid have appeared.

As for the tetraneutron, the few experimental data now known indicate that it does not exist. Finally, we can note that even if n^4 is indeed stable, its binding energy must be smaller than 1 MeV, if the existence of a β-active He^8 is confirmed; otherwise He^8 would decay according to the scheme $He^8 \to He^4 + n^4$ (see Sec. 10).

The only way a bound n^4 would decay is β decay

$$n^4 \xrightarrow{\beta^-} (H^4) \to H^3 + n.$$

Most probably n^4 must have the angular momentum 0^+. The final state is in the continuous spectrum, and can have arbitrary angular momentum and parity. Therefore β decay will unquestionably be allowed, and $E_{\beta max}$ is of the order of 8 MeV. From this we can estimate a lower limit on the lifetime: $T_{1/2} > 0.05$ sec.

The most reasonable way to look for n^4 is to study secondary reactions caused by it. Schiffer and Vandenbosch[6] looked for n^4 among fission products. It was assumed that if n^4 is produced in fission, then by putting into the reactor specimens containing nitrogen or aluminum one might observe the reactions $N^{14} + n^4 = n + N^{17}$ and $Al^{27} + n^4 = H^3 + Mg^{28}$ by measuring the activities corresponding to N^{17} and Mg^{28}. The results of the experiment showed that if n^4 is formed it is in very small quantities. Since neither N^{17} nor Mg^{28} was found, the authors of[6] concluded that the number of tetraneutrons produced per fission is smaller than 10^{-7} (according to the N^{17} evidence), and even smaller than 5×10^{-9} (according to Mg^{28}). This quantity is to be compared with the frequency of production of other particles in fission: 5×10^{-3} for He^4, 7×10^{-5} for p, 2×10^{-4} for H^3, 1.7×10^{-5} for d, and so on. Accordingly, the result of this experiment is negative.

Quite recently there has appeared a paper by O. Brill, N. Venikov, A. Kurashov, A. Ogloblin, V. Pankratov, and V. Rudakov,[64] who used the time-of-flight method with subsequent direct measurement of pulse amplitudes in a system of scintillators (not merely from the induced activity) to measure the cross section for production of the hypothetical n^4 in the irradiation of a target of Ca^{48} with C^{12} ions (72 MeV) and with He^3 ions (39 MeV). No production of n^4 was detected, and the result for the cross section was $\sigma(n^4) < (4-6) \times 10^{-30}$ cm²/sr. In this same work the failure to observe production of n^6 gave the upper limit $\sigma(n^6) < 10^{-30}$ cm²/sr. There has also been no success so far in looking for bound tetraneutrons by observing the spectrum of He^3 nuclei from the capture of π^- mesons by Li^7 nuclei[44]: $Li^7(\pi^-, He^3)4n$.

Accordingly, all of the experimental work done up to this time speaks against the existence of the tetraneutron. Negative conclusions as to the existence of

n^4 were also drawn by Jänecke[65] on the basis of a systematics he developed for the energies of isotopically excited states of light nuclei.

Arguments that the tetraneutron is unstable are developed in a paper by N. A. Vlasov and L. N. Samoĭlov.[66] These authors call attention to the fact that among all known nuclei there is not a single case in which the binding energy of a proton does not increase when two neutrons are added. Therefore the difference between the binding energy of the proton in H^5

$$B_p(\mathrm{H}^5) = M_p + M_{n^4} - M_{\mathrm{H}^5}$$

and that of the proton in H^3

$$B_p(\mathrm{H}^3) = M_p + 2M_n - M_{\mathrm{H}^3}$$

must be positive.

On the other hand,

$$B_p(\mathrm{H}^5) - B_p(\mathrm{H}^3) = M_{n^4} - 4M_n - Q,$$

where $Q = M_{H^5} - M_{H^3} - 2M_n$ is the energy of the decay $H^5 \rightarrow H^3 + 2n$. It follows from this that $M_{n^4} - 4M_n > Q$; that is, the instability of the tetraneutron ($M_{n^4} > 4M_n$) is a direct consequence of the instability of H^5 ($Q > 0$).

If the energy of the first excited state of He^4 with $T = 1$ is $E^*(He^4, T = 1) \approx 24$ MeV, then $Q \approx 4$ MeV, from which it follows that the energy of the first excited level of He^4 with $T = 2$ is $E^*(He^4, T = 2) > 33$ MeV, because it must be at least 4 MeV larger than the maximum energy of this level that would correspond to stability of the tetraneutron.

This estimate for $E^*(He^4, T = 2)$ is in good agreement with that given in[61] on the basis of ideas about isotopic supermultiplets.

In conclusion we mention some schemes for possible further searches for the tetraneutron. The isotopic spin of n^4 is $T = 2$. There must also be a corresponding level in the α particle. If the energy of this level lies below the threshold for disintegration of the α particle into four nucleons (28.3 MeV), then its width will be quite small (of the order of 0.1 to 10 keV), since all other ways for He^{4*} ($T = 2$) to decay are forbidden by the selection rules on T and can occur only owing to deviations from charge invariance or to electromagnetic interaction. Even with confirmation of the stability of He^8 there is still a possible range of energies for this level: 28—28.3 MeV, which would correspond, for example, to an extremely narrow level in the pT interaction, somewhere around $E_{p\,lab} = 10.9$—11.3 MeV, and analogous levels in the pHe^3, nT, and nHe^3 interactions (cf.[1,106,107]). In addition, even if the energy of the $T = 2$ level of the α particle were higher (28.3—29 MeV) but still in accordance with the existence of a bound tetraneutron (with binding energy less than 0.7 MeV), this level would still be rather narrow, because it corresponds to decay into four nucleons. Therefore even in the region $E_{p\,lab} = 11.3$—12.3 MeV the presence of a relatively narrow level in the pT and other similar interactions (with an extremely small partial width of elastic scattering) would speak in favor of the existence of a bound tetraneutron.

Another way to detect n^4 is to look for double charge transfer,

$$\pi^- + \mathrm{He}^4 \rightarrow \pi^+ + n^4.$$

The cross section for such processes is rather large (for the nuclei in a photographic emulsion $\sigma \approx 5 \times 10^{-28}$ cm^2[67]) so that this is a convenient reaction from the experimental point of view.* Also interesting is the suggestion in[66] of an analysis of the "mass loss spectrum" in the reaction $T + T \rightarrow p + p + (n^4)$, and also the study of singularities in the transfer of four neutrons in reactions produced by heavy ions and reactions of the type $Ne^{22} + Ne^{22} \rightarrow Ca^{40} + 4n$.

9. THE ISOTOPE H^5

There is at present no general agreement as to whether or not the isotope H^5 exists, although most investigators (including the present writers) believe that this isotope is unstable against decay with neutron emission.

The properties of H^5 are extremely closely connected with the question of the position of the lowest level with $T = 3/2$ in He^5: for an excitation energy of this level $E^*_{He^5}(T = 3/2) < 19.4$ MeV, H^5 would be neutron-stable. The well known level of He^5 with the excitation energy $E = 16.7$ MeV ($J = 3/2^+$; $T = 1/2$) has the structure $(1s)^3(1p)^2$. It can be imagined intuitively as a triton and a deuteron bound together, which are in an s or a d state. In the $^1S_0$ state two nucleons have $J = 0^+$ and $T = 1$. As is well known, this state is located 2.3 MeV higher than the bound $^3S_1$ state (the deuteron). Therefore it might be supposed that possibly there is a state of He^5 with $T = 3/2$ and lying about 2.3 MeV above the 16.7 MeV state, the structure being a triton plus a neutron and a proton in the $^1S_0$ state. For a state of this sort $J = 1/2^+$. Starting from precisely this idea, Blanchard and Winter[68] advanced the hypothesis that $E^*_{He^5}(T = 3/2) \approx 19.1$ MeV, and that consequently H^5 exists with a reserve of stability of ~ 0.4 MeV. This estimate is very crude, however, and of course cannot be an argument in favor of the existence of H^5.

The range of excitation energies $25 > E^* > 16.5$ MeV in He^5 has been rather well investigated. There are measurements of the total nHe^4 cross section[69] for $E_n = 20$—29 MeV, in which no "traces" of a level with excitation energy 19—20 MeV were found. This ~ 19 MeV level also has not shown up in the dH^3

*In a paper by Davis and others[100] it is reported that such an attempt to observe the formation of the tetraneutron was made, but with negative results.

interaction,[70] although here there was a hint of a broad level at $E^* \approx 22$ MeV. Still, in a later paper[71] on a study of the dH^3 and dHe^3 reactions there seemed to be signs of a broad level with $E^* \approx 19.7$ MeV. All of these experiments, however, are not very convincing, since the (nα) and (dT) systems both have $T = 1/2$, so that in these reactions a level with $T = 3/2$ could appear only owing to violations of charge invariance—i.e., very weakly. Only if $E^*_{He^5}(T = 3/2) < 18.86$ MeV could a narrow ($\Gamma \sim 0.1$—10 keV) resonance maximum appear in the cross sections of the nα and dT interactions.

Much more convincing would be direct observation of β^- decay of H^5:

$$H^5 \xrightarrow{\beta^-} He^5 \rightarrow He^4 + n, \; E_{\beta_{max}} < 19.64\,\text{MeV}, \; T_{1/2} \geqslant 100\,\text{msec}.$$

There have been several papers on the search for such an activity. Cence and Waddell[72] made an experiment in which they bombarded targets of Li^6 and Li^7 with 340 MeV bremsstrahlung and looked for delayed neutrons in the reaction

$$\gamma + Li^7 \rightarrow 2p + H^5 \xrightarrow{\beta^-} He^5 \rightarrow He^4 + n.$$

The registration of the neutrons was made with a BF_3 counter between the pulses of the synchrotron. In this way (γ, 2p) reactions were observed with the nuclei B^{11} and F^{19}, but not with Li^7; in the last case the effect was the same for Li^6 also, i.e., all of the neutrons registered were from background. It was shown that if the half-value period of H^5 is $T_{1/2} \approx 10^{-2}$ sec, then the cross section for production of this isotope is less than 3×10^{-32} cm^2, i.e., less than 1 percent of that expected by analogy with the reactions with B^{11} and F^{19}. The same figure had been obtained earlier by Tautfest,[73] who did the same experiment. According to the argument given in[14] the instability of H^5 is also evident from the absence of excited levels of the α particle with $T = 1$ for $E < 22$ MeV. This made all the more surprising the publication in 1963 of a note about the work of Nefkens,[60] who announced a new β^- activity with $T_{1/2} = 110 \pm 30$ msec and $E_{\beta max} > 15$ MeV, obtained as the result of bombarding Li^7 with 320 MeV bremsstrahlung. The functioning of the apparatus was checked with the reactions $Be^9(\gamma p)Li^8$, $C^{13}(\gamma p)B^{12}$, and $C^{12}(\gamma\pi^-)N^{12}$. A test as to whether the activity "blamed" on H^5 was produced as the result of reactions caused by slow neutrons or other secondary particles deep inside the target gave a negative result. Therefore Nefkens, on the basis of the values of $T_{1/2}$ and $E_{\beta max}$ and of the measured yield of the new activity [$\sigma = (1.8 \pm 0.6) \times 10^{-30}$ cm^2 (effective quantum)$^{-1}$], drew the conclusion that he had registered the reaction $Li^7(\gamma, 2p)H^5$, that is, that H^5 is stable against decay into $H^3 + 2n$. It must be said, however, that whereas in the previous work[72] control experiments had been made with a target of Li^6 (H^5 cannot be produced by bombardment of Li^6 with γ rays), Nefkens did not make any such measurements.

Immediately after the publication of[60] experiments were done to check Nefkens' results. A paper by Schwarzschild and others[74] reports on experiments on the bombardment of a Li^7 target with 2 BeV protons from the Brookhaven cosmotron. More highly developed measuring apparatus than in[60] was used, and it was shown that the ratio of the yields of the reactions $Li^7(p, 3p)H^5$ and $B^{11}(p, 3p)Li^9$ is very small, in any case less than 5×10^{-4}, whereas Nefkens had found for the analogous ratio for the (γ, 2p) reactions a value two orders of magnitude larger. Meanwhile, if H^5 existed, according to calculations by the Monte Carlo method the yields of the two reactions should be of the same order of magnitude. Therefore in[74] it is concluded that there is no nuclear-stable H^5. This conclusion is also favored by the extrapolation to $Z = 1$ of the data on the binding energies of the pair of third and fourth neutrons (see Fig. 9, taken from[74]).

Two other experimental researches of the last year speak against the results of Nefkens.[60] V. N. Andreev and S. M. Sirotkin[75] looked for H^5 nuclei in the fragments from fission of U^{235} by thermal neutrons (as had been done in[6] for the tetraneutron; see Sec. 8). It could be expected that H^5 should be produced in fission with a probability of the same order of magnitude as that for H^3. On the other hand, it was known that in the fission of U^{235} a group of delayed neutrons is observed with $T_{1/2} \approx 0.13$—0.23 sec, the yield of such particles being $(6.6 \pm 0.8) \times 10^{-4}$ per fission. The suspicion arose that these neutrons come precisely from the β^- decay of H^5 with subsequent disintegration of the He^5. By means of a system of several ionization chambers, providing measurements of the range and of dE/dx, a study was made of all the

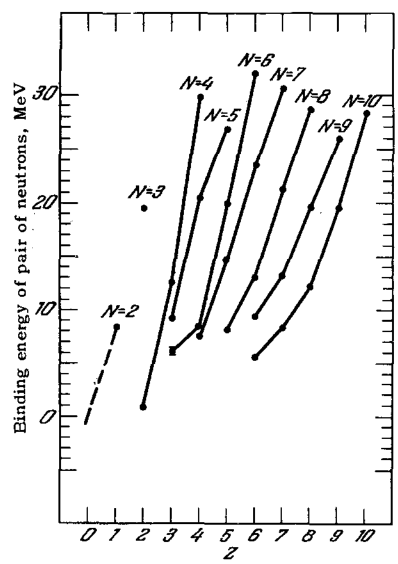

FIG. 9. Binding energies of pairs of neutrons [the (N − 1)st and Nth] for nuclei with Z = 1 − 10.

long-ranged particles, and it was found that with this method $(2.4 \pm 0.7) \times 10^{-5}$ H^3 nuclei and $(1.9 \pm 0.2) \times 10^{-3}$ He^4 nuclei were registered per fission. As for H^5, none was found. It amounted to less than 7×10^{-6} per fission, i.e., less by some tens of times than the delayed neutrons. Thus these neutrons cannot be connected with H^5.

Finally, Sherman and Barreau[76] failed to detect the production of β^--active H^5, although these authors literally followed in the footsteps of Nefkens, bombarding Li^7 nuclei with bremsstrahlung of maximum energy 210 MeV and registering β activity of large energy in the intervals between pulses of the accelerator. The authors of[76] state that if $T_{1/2}(H^5) \approx 0.1$ sec, then the yield of the isotope H^5 in their experiments corresponded to $\sigma < 2 \times 10^{-31}$ cm²/(effective quantum); that is, it was smaller than found by Nefkens by at least an order of magnitude. Other possibilities, not in contradiction with the negative result of[76], reduce to the extremely dubious hypotheses that $T_{1/2}(H^5) \ll 0.003$ sec or that $T_{1/2}(H^5) \gg 0.1$ sec. It is interesting that Sherman and Barreau pointed out the danger of registering as apparent β activity inelastically scattered electrons that appear at the target in the period of the accelerator pulse. It is perhaps in this way that the "mystery" of the hypothetical β activity of H^5 observed by Nefkens will be explained.

Searches for a neutron-stable, and also for an unbound "resonance" state of H^5 were made in[44] by an analysis of the spectrum of deuterons from the capture of π^- mesons by Li^7 nuclei: $Li^7(\pi^-, H^2)H^5$.

The result was uncertain—the probability of this type of capture is in any case less than 10^{-4}. As an additional check the authors of[44] propose making observations of the spectrum of particles in the reaction $Be^7(\pi^-, He^4)H^5$ (?).*

Summarizing all of these data, we can come to the rather firm conclusion that no neutron-stable H^5 exists. Accordingly, the level with $T = 3/2$ in He^5 lies above the threshold for disintegration of that nucleus into $H^3 + n + p$, and therefore this must be a broad level. Evidently this is the level of He^5 at $E^* \approx 21-22$ MeV that has been observed in several researches. Meanwhile we can also indicate some additional possible experiments to test the stability of H^5, or rather additional possible demonstrations of the instability of H^5. In this connection we may mention reactions of heavy ions, such as

$$_ZM_N^A + Li^6 \rightarrow H^5 + {}_{Z+2}M_{N-1}^{A+1},$$

the reactions $Li^6(n, 2p)$ and $Li^6(\pi^-, p)$, $He^4(n, \pi^+)$, and the desirability of looking for groups of monochromatic protons, and also delayed neutrons, in the reaction $T + T \rightarrow p + (H^5)$ near $E_T = 17$ MeV.

*Booth and his co-workers[101] have also been unsuccessful in trying to observe the production of H^5 in the reaction $Li^7(\pi^-, pn)H^5$.

The absence of a stable H^5 also eliminates the question of the existence of a neutron-stable isotope H^7, which was mentioned in[14]. There is much independent interest in the question of heavy hyperisotopes of hydrogen and helium, which has been treated in particular in an article by Dalitz and Levi-Setti.[77] This, however, is outside the scope of the present article.

We shall not touch here on the question of new isotopes with mass numbers A = 6, 7. The instability of H^4 and H^5 already settles the question of the instability of H^6, and thus also of the absence of bound excited levels of He^6 and Li^6 with isotopic spin T = 2. Such levels can only lie above the energy for decay of the nucleus into tritium and three nucleons, and the only limit on their widths is set by the necessity of decaying at once into four particles. The idea has been advanced earlier by V. V. Balashov[78] that a level of Li^4 with energy 10.8 MeV has the isotopic spin $T = 3/2$, and that consequently the nucleus He^7 is stable against decay into He^6 and a neutron [for which a necessary condition is $E^*(T = 3/2, A = 7) \lesssim 11.2$ MeV]. The special position of Be^9 makes it hard to judge the stability of He^7 by extrapolating the values of the binding energy of the fifth neutron to Z = 2. Indirect arguments in favor of a positive binding energy of the neutron in He^7 are given in a recent paper[79] on the observation of a heavy hyperfragment of helium (${}_\Lambda He^8$ or ${}_\Lambda He^9$). Nevertheless, it is very doubtful that He^7 is stable, since He^5 is already unstable against the decay $He^5 \rightarrow He^4 + n + 0.96$ MeV. In fact, as is especially clear from the examples of O^{16} and Ca^{40}, when excess neutrons are added to a doubly magic "core" to fill the next shell, the binding energy of both odd and even neutrons decreases somewhat with increase of the number of neutrons. Therefore there are no grounds for expecting that He^7 will be more stable than He^5. Janecke also concluded that He^7 is unstable on the basis of a systematization of the data on the excitation energies of various isotopic states of light nuclei.[65] Even if we ascribe the value $T = 3/2$ to one of the known levels of Li^7, this applies most readily to the level 12.4 MeV, which is essential for the discussion of the question as to the stability of He^8, to which we are just now coming.

10. THE ISOTOPE He^8

In all of the preceding examples of neutron-excess isotopes of the lightest elements it has turned out that they almost certainly do not exist. In this sense the isotope He^8 may be a pleasant exception; these is no basis for asserting that the nucleus He^8 is certainly unstable against neutron emission. The most likely configuration for He^8 is $(1s)^4(1p)^4$. From energy arguments it is clear that the four neutrons in the 1p shell must be grouped into two pairs of neutrons, in each of which pairs the two neutrons are in a $^1S_0$ state relative to each other. The most plausible value of the total angular momentum for the system is $J = 0^+$. The question as to the possible existence of He^8 was first considered by two of the authors of the present review (Ya. B. Z. and V. I. G.) in[80] and[14].

Let us first consider a number of empirical regularities. In order for He^8 to be stable against decay into $He^6 + 2n$, it is necessary that in Be^8 the distance between the first levels with T = 2 and T = 1 satisfy the condition

$$E^*(T=2) - E(T=1) < 13\,\text{MeV},$$

and when we take account of the position of the first level with T = 1 we get $E^*(T = 2) < 29.6$ MeV. On the other hand it is known (1) (sic) that in nuclei with A = 4m the energy $E^*(T = 2)$ is a smooth function of m, so that it is worth while to recall the known values of this quantity for heavier nuclei:

A	20	16	12
$E^*(T=2)$:	16.8	23.1	27—28 MeV*.

As A decreases the value of $E^*(T = 2)$ increases, but it is seen that extrapolation to A = 8 is difficult. It is important, however, that the figure $E^*(T = 2) = 29.6$ MeV for Be^8 is not clearly unreasonable.

Next, in He^6 the pairing energy of the neutrons is 2.86 MeV, and in Li^9 it is 2.02 MeV.[81] It is reasonable to assume[14] that the pairing energy in He^8 should lie somewhere between these two limits. It follows from this that for the existence of He^8 the first state of Li^7 with T = 3/2 must have the energy—

necessary condition: $E^*_{Li^7}(T=3/2) < 12.7$ MeV,
sufficient condition: $E^*_{Li^7}(T=3/2) < 12.3$ MeV.

In[14] an argument was given in favor of the value $E^*_{Li^7}(T = 3/2) = 12.4$ MeV; this level can be seen in the reaction $Li^7(\gamma n)Li^6$ (here T = 1/2, 3/2 are possible), but does not appear in the reaction $Li^7(\gamma T)He^4$ (here only T = 1/2 is possible); see the scheme of levels.[82]

An extrapolation of the binding energy of the pair of neutrons (5th and 6th) for the nuclei C^{12}, B^{11}, Be^{10}, Li^9 (Fig. 9) gives for He^8 a binding energy close to zero. We thus see that the entire extrapolation leads to a binding energy near zero for He^8. Although this cannot be regarded as a proof that He^8 exists, its stability is made probable.

If He^8 is neutron-stable, it must undergo β decay according to the scheme shown in Fig. 10, with $E_{\beta max} = 12.8$ MeV and $T_{1/2} \approx 10$—20 msec (for log ft = 3.5). Transitions to the ground and second levels of Li^8 are forbidden by the spin. The transition to the 3.22 MeV level is allowed, and in this case we

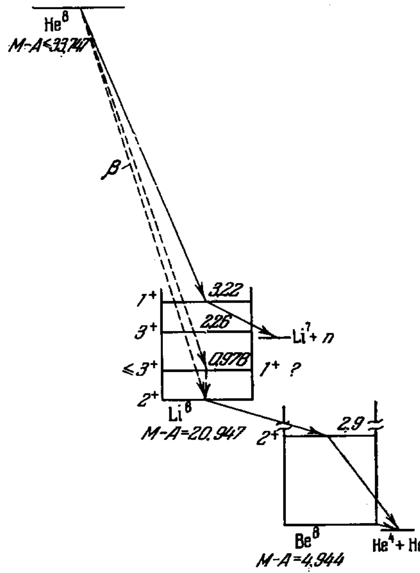

FIG. 10. Hypothetical decay scheme of the isotope He^8 (if it is stable against the decay $He^8 \to He^6 + 2n$).

have a chain of transitions

$$He^8 \xrightarrow{\beta^-} Li^{8*} \to Li^7 + n.$$

If the angular momentum of the 0.978 MeV level is 0^+ or 1^+, then the decay goes according to the scheme

$$He^8 \xrightarrow{\beta^-} Li^{8*} \xrightarrow{\beta^-} Be^8 \to 2\alpha,$$

which is ideal for experimental observation.

The first claim to the discovery of He^8 was made by O. V. Lozhkin and A. A. Rimskiĭ-Korsakov[83] in 1961. In an emulsion irradiated with 930 MeV and 9 BeV protons two T-shaped tracks were observed with a small grain density uncharacteristic of Li^8 in the "ingoing" arm (25 percent smaller than for Li^8, and even 10 percent smaller than for He^4). The decay tracks were identified as belonging to α particles. It was concluded from this that the two tracks depicted the decay of a nucleus with Z < 3 into two α particles, i.e., the process

$$He^8 \to Li^8 \to Be^8 \to 2\alpha.$$

The β^- tracks could not be visible in the emulsion, and this makes the interpretation of these two cases ambiguous, although the supposition that these tracks actually correspond to the decay of He^8 looks very plausible.

A later paper by Nefkens[84] also contained a conjecture that He^8 had been observed. He irradiated boron (the natural mixture and 99 percent B^{11}) with 320 MeV bremsstrahlung. The pulse frequency of the accelerator was of the order of 1 pulse per sec, and the behavior of the β activity with time was measured in the intervals between the pulses. The threshold for registration of the electrons was varied from 5.9 MeV to 8.5 MeV. The total effective cross section for production of all β-active nuclei was σ > 100 micro-

*It is seen that $E^*(T = 2)$ for C^{12} is close to the energy for decay of the α particle into four neutrons. In[86] the value 11.7 MeV is given for the energy of the β^- decay of Be^{12}, from which $E^*(T = 2)$ for A = 12 is ≈ 28.2 MeV.

barns/(effective quantum). The main part of the activity was from Li^8 ($E_{\beta max}$ = 13 MeV and $T_{1/2}$ = 0.8 sec). Besides this, however, a considerable activity was observed with $T_{1/2}$ = 100—200 msec, $E_{\beta max}$ = 13.1 ± 0.5 MeV, and $\sigma \approx$ 30—45 microbarns/(effective quantum), most likely belonging to Li^9, which had been studied earlier by Tautfest.[85] Besides these activities, there was also a third group of electrons, corresponding to a decay with $T_{1/2}$ = 30 ± 20 msec, $E_{\beta max}$ = 13 ± 2 MeV, ln ft = 4.3, and σ > 6 microbarns/(effective quantum). All of these values can well be explained on the assumption of the reaction $B^{11}(\gamma, 3p)He^8$ and subsequent β decay of the He^8 to the 0.975 MeV level of Li^8. Nefkens[84] checked the possibility of production of this short-lived activity from impurities of other elements in the target, but it was found that such impurities could not explain the observed effect. On the other hand, an extremely important control experiment was not done—the irradiation of a target of B^{10}, in which He^8 cannot be produced. Against the existence of He^8 there are the experiments of Poskanzer, Reeder, Dostrovsky, and Davis,[86] who studied reactions of the type (p, 4p) with the Brookhaven cosmotron. In this way these authors accomplished the first production of the new isotope Be^{12} in the reaction $N^{15}(p, 4p)Be^{12}$; by bombarding F^{19} they obtained C^{16}; but they did not find the reaction $B^{11}(p, 4p)He^8$ with production of the expected short-period β^- activity. The authors of[86] came to the conclusion that if Be^{12} had indeed been produced, the probability of its undergoing a decay with emission of delayed neutrons is less than 1 percent. Accordingly there is again no strict proof that He^8 exists, although in the light of all that we have said it is still more probable than is the case for all the other isotopes we have been considering. Of course here too further experiments are necessary. Perhaps the most promising way of producing He^8 is by reactions using heavy ions, of the type

$$_ZM_N^A + Be^9 \rightarrow {}_{Z+2}M_{N-1}^{A+1} + He^8 \quad \text{or} \quad {}_ZM_N^A + Li^7 \rightarrow {}_{Z+1}M_{N-2}^{A-1} + He^8,$$

for which there is usually a fairly large cross section. There are also possible experiments on the observation of the reactions $Li^7(n, \pi^+)$, $Be^9(n, 2p)$ or $Be^9(\pi^-, p)$, $B^{11}(\pi^-, He^3)$, $N^{15}(\pi^-, Be^7)$, and so on. Furthermore it would be extremely desirable to make a direct search for cases of three-stage decay, $He^8 \rightarrow 2\beta^- + 2\alpha$, for example, by means of chambers or photographic emulsions.

We point out once more the internal connection of the data on n^4, H^4, H^5, and He^8 (cf.[107]). In fact, the entire logic of many papers that followed Nefken's note[60] on the discovery of β^--active H^5 was directed at reconciling this announcement with the conclusion that one of the present authors had drawn[14] on the basis of the data on the pairing energies of neutrons—that a necessary condition for the stability of H^5 is that $E^*_{He^4}(T = 1) < 22$ MeV.

From this there arose hypotheses that the isotopic spin of the level of the α particle at ~ 20 MeV is T = 1,[37] that the hypothetical "resonance" state of H^4 has T = 2—i.e., for a level of the α particle at ~ 24 MeV—and consequently also that the tetraneutron is stable.

But the hypothetical existence of a β^--active He^8 fixes the position of the level of the α particle with T = 2 by the condition $E^*_{He^4}(T = 2) > 28$ MeV; that is, a proof that He^8 is stable would destroy the argument given just now: the 24 MeV "level" would again receive the value T = 1, H^4 and H^5 would be certainly neutron unstable, and there are strong restrictions on the existence of the tetraneutron; its binding energy cannot be more than 1 MeV. Thus the later work of Nefkens[84] destroys the argument which is essential for the acceptance of his results[60] on H^5. Meanwhile, the question about He^8 itself is still an open one.

11. HEAVIER ISOTOPES

During the years since the publication of our review article[1] a considerable number of neutron-excess (Be^{12}, C^{16}, N^{18}) and neutron-deficiency (C^9, O^{13}, Ne^{17}, Mg^{21}, Si^{25}, Si^{29}, A^{33}, Ca^{37}, Ti^{41}, $Kr^{72 (or\ 73)}$) isotopes of light elements have been discovered, and in all cases there is splendid agreement between the predicted and the experimentally observed properties of these isotopes—the masses, the decay energies, and even the lifetimes and the decay mechanisms.

This agreement is the basis for our present recommendation of some further searches; in this connection we mention some of the methods and estimates given in our previous papers.

In studying the properties of neutron-excess isotopes it is very essential to determine whether, as was postulated in[80], the filling of shells in which there is already some number of excess neutrons continues to completion. In particular, complete filling of the $d_{5/2}$ shell would mean the existence of β^--active isotopes C^{17-20}, N^{19-21}, $O^{21,22}$, $F^{22,23}$, and complete filling of the $f_{7/2}$ shell the existence of S^{39-44}, Cl^{41-45}, A^{43-46}, $K^{46,47}$.

To determine whether such isotopes exist there is undoubted interest in all sorts of ways of systematizing the data and estimating theoretically the energies of excited nuclear states with various values of the isotopic spin. A number of papers on the energetics of various isotopic states have been published recently by Janicke[65] and by Wilkinson (cf., e.g.,[87]). Janicke[88] has also given a detailed analysis of the modes of decay of neutron-deficiency isotopes of the light elements.

There is a simple relation, first derived in[89], which is extremely useful in describing the properties of such isotopes and which provides a relation, based on isotopic invariance, between the binding energies B_p of a proton in a nucleus containing Z protons and N neutrons, and B_n of a neutron in the mirror nucleus containing Z neutrons and N protons, and the difference between the binding energies of a neutron and a proton in the isotopically self-adjoint nucleus that contains Z neutrons and Z protons:

$$\Delta B_{np}=B_n\,({}_N M_Z^A)-B_p\,({}_Z M_N^A)=B_n\,({}_Z M_Z^{2Z})-B_p\,({}_Z M_Z^{2Z})=B_0.$$

We have the approximate relation

$$\Delta B_{np}\approx 1.2\,\frac{Z-1}{(2Z-1)^{1/3}}\left\{1+\left(\frac{A-2Z}{3A}\right)^2\left(1+\frac{1}{A-2Z}\right)+\ldots\right\}$$

$$\approx 1.2\,\frac{Z-1}{(2Z-1)^{1/3}}\,\text{MeV}.$$

This simple relation enables us not only to predict the properties of new isotopes, but also to find mistakes in data already long accepted, as it would seem. A good example of this is the isotope Na^{20}, for which collected tables[90] give a value of the mass defect determined from the determination made[91] in 1950 of the threshold of the reaction $Ne^{20}(pn)Na^{20}$, which gave on the C^{12} scale the value 8.28 MeV. It had already been stated in[92] that this value is too high by about 1.5 MeV. In fact, the mass defect of Na^{20} can be determined from the three relations

$$B_n\,\underset{6,60}{(F^{20})}-B_p\,(Na^{20})\approx B_n\,(Na^{22})-B_p\,(Na^{22})=4.30\ \text{MeV},$$

$$B_n\,(Na^{21})-B_p\,\underset{13,00}{(Ne^{21})}\approx B_n\,(Ne^{20})-B_p\,(Ne^{20})=4.03\ \text{MeV},$$

$$B_n\,(Na^{20})-B_p\,\underset{10,63}{(F^{20})}\approx B_n\,(F^{18})-B_p\,(F^{18})\quad=3.54\ \text{MeV},$$

and in the last case we still need to know the mass defect of Na^{19}, which can be found easily from the relation

$$B_n\,\underset{3,96}{(O^{19})}-B_p\,(Na^{19})=B_n\,(Na^{22})-B_p\,(Na^{22})=4.30\ \text{MeV},$$

from which we have $B_p(Na^{19}) = -0.34$ MeV, and the mass defect of Na^{19} is 12.96 MeV. Accordingly, $B_p(Na^{20}) \approx 2.30$ MeV, $B_n(Na^{21}) \approx 17.03$ MeV, and $B_n(Na^{20}) \approx 14.17$ MeV, from which the mass defect of Na^{20} is found to be 6.75—6.85 MeV, that is, 1.4—1.5 MeV smaller than the present accepted value.

Very recently the incorrectness of the old value of the mass defect of Na^{20} has been directly proved experimentally by Garvey and his coworkers[13] (see also[108]).

The correction of the value of the mass defect of Na^{20} is also important for the regularities in the energies of neutron pairings. Starting from the values obtained above for the binding energies of a neutron in the nuclei Na^{20} and Na^{21}, we get for the pairing energy of the ninth and tenth neutrons in sodium $E_{pair} = B_n(Na^{21}) - B_n(Na^{20}) = 2.86$ MeV. The old value was $E_{pair} = 5.81$ MeV.

In the series of the pairing energies of the ninth and tenth neutrons we now have the values:

	$N^{16,17}$	$O^{17,18}$	$F^{18,19}$	$Ne^{19,20}$	$Na^{20,21}$	$Mg^{21,22}$
E_{pair} :	3.37	3.90	1.30	5.25	2.86	4.5 MeV.

The pairing energy is smaller in isotopes with odd Z than in their even neighbors, because of the necessity of breaking the deuteron-like (T = 0) bond of the odd proton and neutron. Previously sodium departed sharply from this rule, which is a further confirmation of the erroneousness of the old data. Regularities in the variation of the pairing energies of nucleons can also serve as a criterion for the sequence of filling of shells when an "even" neutron or proton is added to a nucleus with odd N or Z. Of interest in this connection is the isotope C^{16}, for which, according to the data of[93], the binding energy of a neutron is $B_n = 4.25$ MeV, which corresponds to $E_{pair} = 3.03$ MeV—a value which deviates by not less than 0.34 MeV from the regularity just displayed. If there is no error in the determination of the binding energy of neutrons in C^{16} (toward too low values) and/or in C^{15} (toward too high values), this would mean that in the nucleus C^{16} the ninth and tenth neutrons are in different states than in the nuclei of subsequent elements.

We note, finally, that extremely simple arguments based on isotopic invariance (which, as is shown in recent papers,[12,94] is obeyed quite well even for such relatively heavy nuclei as Fe^{52} or Zr^{90}) enable us to find out (cf.[109]) a number of errors in the existing calculations of the masses of not yet discovered nuclei, for example in the extremely valuable tables of Cameron[95] and of Seeger,[110] which have been widely used in recent years for all sorts of predictions. In fact, the total energy of the β^+ decay ${}_Z M_N^A \to {}_{Z-1}M_{N+1}^A$ is obviously given by

$$Q_{\beta+}=E^A\left(T=\frac{(N-Z)}{2}\right)-E^A\left(T=\frac{(N-Z)}{2}-1\right)$$

$$+\,Q\,\frac{2Z-1}{A^{1/3}}-(m_n-m_p)\,c^2,$$

where $E^A(T)$ is the specific energy of the nuclear interaction for the given A and T, the term in Q is the Coulomb energy ($Q \approx 0.6$ MeV; we shall not consider the various corrections here), and m_n and m_p are the masses of neutron and proton.

If the initial and final nuclei are in the same isotopic state, the β^+ decay is superallowed, with the total energy

$$Q_{\beta+}\,(\Delta T=0)=Q\,\frac{2Z-1}{A^{1/3}}-(m_n-m_p)\,c^2.$$

In β^+ decay of nuclei with $Z > N$ the value of T_Z, and consequently also the minimum value of T, decreases by unity, and the value of T for the ground state of the final nucleus is either smaller by unity (than for the normal sequence of levels with different T values), or else the same as (for inverted sequence), the value of T for the ground state of the initial nucleus. Therefore $Q_{\beta^+}(Z > N) \geq Q_{\beta^+}(\Delta T = 0)$, and superallowed β^+ decay is energetically possible for all isotopes with $Z > N$, beginning with B^9. Conversely, for β^+ decay of isotopes with $Z \leq N$ we have $Q_{\beta^+}(Z \leq N)$

$\leq Q_{\beta^+}(\Delta T = 0)$, and superallowed β^+ decay is possible only for isotopes with the inverted sequence of T values in the ground and excited states.

Meanwhile the tables[95,110] give values of Q_{β^+} such as:

$$Ca^{38}: Q_{\beta+} = 3.85 \text{MeV}^{95}, \quad Q_{\beta+}(\Delta T = 0) \approx 6.2 \text{ MeV};$$
$$As^{66}: Q_{\beta+} = 11.2 \text{MeV}^{95}, 10.2 \text{MeV}^{110}, \quad Q_{\beta+}(\Delta T = 0) \approx 8.7 \text{ MeV}.$$

It is obvious that there are sizable errors here in the calculations of masses, and this must be taken into account in every kind of conjecture as to the properties of isotopes not yet discovered. An example of this is the isotope Ti^{41} recently produced in the Brookhaven laboratory.[111] In an earlier paper[112] one of the present authors had concluded, on the basis of values given in[95] for the energy of the β^+ decay of Ti^{41} (Q_{β^+} = 9.9 MeV) and the binding energy of a proton in the daughter nucleus Sc^{41} (B_p = 2.9 MeV), that there is little probability of the emission of delayed protons after superallowed β^+ decay in this case. The data of the tables in[110] lead to a similar conclusion. Meanwhile it follows from the relation[89] $\Delta B_{np} = B_0$ that emission of delayed protons is possible even after the superallowed β^+ decay of T^{41} (Q = 12.6 MeV). The experiments[111] have confirmed both this conclusion and the argument given in[112] that the possibility of emission of protons even after the superallowed β^+ decay decidedly increases the probability for the observation of delayed protons. Therefore in the entire domain in which there are data on mirror nuclei with N > Z one should use for estimates of the properties of neutron-deficiency isotopes not the tables such as[95], but the relations[89] $\Delta B_{np} = B_0$ or $\Delta B_{np} \approx 1.2(Z-1)(2Z-1)^{-1/3}$ MeV. When one does not have the necessary information about the mirror nuclei one must carefully compare the tabulated mass values and energy values with the characteristics of the change of isotopic spin in different types of decay, in order to bring to light any possible errors in the calculated data and to assure sufficiently critical use of these data.

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