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Atomic Nucleus and Neutron — Nuclear Physics Revisited with the Viewpoint of the Cold Fusion Phenomenon

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Abstract

Nuclear reactions induced by thermal neutrons are reviewed in connection with the new interest caused by the cold fusion phenomenon (CFP) where observed emergence of new elements and new nuclides in solids composed of host elements and hydrogen isotopes (CF-materials) at near room temperature without specific acceleration mechanisms. Nuclear physics developed in the 20th century has mainly investigated isolated nuclei and nucleons with temporal interaction between them and incidentally a nuclear matter with high density neutrons (neutron star matter) in relation to the existence of the neutron star in the universe. On the other hand, the experimental data sets obtained in the CFP as a whole have suggested the realization of a specific state (cf-matter) in CF-materials where occur nuclear reactions similar to those occurring at high energy regions in free space considered in nuclear physics and in neutron star matter. Examining nuclear reactions investigated in nuclear physics, we have noticed several new features of the neutron-nuclear interaction not taken up by now for explanation of extraordinary results obtained in the CFP. One of the interesting features is the nature of the boundary layer between a nucleus and a surrounding neutron matter. Increase of the ratio (n_o/n_i) of neutron densities of the outside neutron matter n_o and that of the inside nucleus n_i makes the energy of the boundary layer lower resulting in the decrease of the barrier height for an alpha-decay and finally in the increase of the decay probability (or the shortening of decay time). Another feature is a possibility of fission of nuclei with medium proton number Z by simultaneous absorption of several neutrons which is applicable to explanation of nuclear transmutations with a large variation of the nucleon

number A in the CFP. It is well known in nuclear physics that the fission reactions of nuclei with small Z (e.g. $^{6}_{3}Li$ and $^{10}_{5}B$) and large Z (e.g. $^{235}_{92}U$ and $^{239}_{94}Pu$) are induced or accelerated by absorption of a neutron even if the instability of a compound nucleus with a medium Z (e.g. $^{A+1}_{46}Pd$ (A = 102 – 110)) formed by absorption of a neutron is not enough to induce the fission of the nucleus. However, simultaneous absorption of several neutrons by a nucleus suggested in the CFP has given us a hint to investigate a possible fission of medium Z nuclei by this mechanism. These features of nuclei developed but not fully contemplated in nuclear physics are taken up in this paper in relation to the events found in the CFP.

1. Introduction

In the long history of the nuclear physics since the discovery of the nucleus by A. Rutherford in 1911, especially after the discovery of the neutron by Chadwick in 1932, there has been accumulated much knowledge about atomic nuclei of more than one hundred elements. However, the main knowledge is confined fundamentally to nuclei isolated in free space with some exceptions of a nucleus in temporal interaction with another one (and sometimes others). Some works, however, have been done on the nuclei immersed in a neutron sea (neutron star matter) in relation to the neutron star. Recently, there is a rapid progress of investigation of exotic nuclei which is giving an important key to connect the physics of isolated nuclei and that of neutron star matter.

The investigation of the cold fusion phenomenon (CFP), on the other hand, which has started at the end of 1980th revealed some characteristics of nuclei interacting each other in condensed matters containing hydrogen isotopes with high concentration (CF-materials). However, the CFP is now under investigation from various ways of approach without decisive explanation for its mechanism after its discovery about a quarter of a century ago. According to the successful approach to the problem by a phenomenological model [Kozima 1998, 2004, 2006, 2014a, 2014b], this unsolved problem seems to be related closely to the interaction of nuclei in solids (lattice nuclei) with neutrons trapped there. The interaction of a nucleus and neutrons has also been investigated in nuclear physics in relation to the exotic nuclei, synthesis of heavy elements in stars, and neutron star matter. Our knowledge obtained in the investigation of the CFP

may give a hint to develop physics of isolated nucleus and the neutron star matter investigated in 20th century into physics of interacting nuclei in transition-metal hydrides and deuterides.
In this paper, we reconsider the nuclear physics developed in the 20th century mainly as the science of nuclei isolated at their initial and final states interacting in between for a short period of time and partially as a science of nuclei immersed in a neutron sea. Our investigation is concentrated in the interaction between nuclei and neutrons in relation to our knowledge obtained in the CFP. In the TNCF model proposed by us and successful to explain various experimental facts in the CFP, there are several premises related to the nature of neutrons in CF-materials and their interaction with nuclei. The interesting knowledge about properties of nuclei useful to understand the premises of the model is investigated in relation to the CFP. Especially, following particular topics among others are picked up here to emphasize the close relation of nuclear physics and the CFP; the two-neutron separation energy is taken up in relation to the possible fission of medium mass number nuclei by absorption of several neutrons to explain experimental facts observed in the CFP [Kozima 2014b], the boundary layer between a nucleus and the surrounding neutron gas is in relation to the decay-time shortening of alpha-decaying nuclei [Kozima 2006, 2014a], and the extended distribution of neutrons in exotic nuclei is in relation to the neutron band formation in CF-materials by the super-nuclear interaction between neutrons in different lattice nuclei mediated by interstitial protons or deuterons [Kozima 2006, 2008].

2. Fundamental Knowledge of Nuclear Physics

In nuclear physics developed in 20th century, isolated nuclei interacting for a moment between their initial and final isolated states of them have been treated (e.g. [Blatt 1952]) except some exceptional cases such as the neutron star matter (e.g. [Negele 1973]). The nuclei have been assumed being in their isolated (ground) state in the initial and final stages even when they interact in between. Thus, the fundamental properties of nuclei have been disclosed as explained in text books (e.g. [Blatt 1952]). In recent years, however, there has been developed investigation of specific properties of neutrons in new fields showing existence of exotic nuclei with large excesses of neutrons over protons and also in syntheses of heavy elements in stars assisted by neutrons.

In addition to this general features of the nuclear physics developed in the 20th century, it should be emphasized that the statistical nature of nuclear processes is ubiquitous in nuclear physics. One of the most simple and well-known facts is the α-decay of radium nucleus (${}^{226}_{88}Ra$); we can not predict when a specific radium nucleus ${}^{226}_{88}Ra$ under investigation will decay to a radon nucleus (${}^{222}_{86}Rn$) by emission of an alpha particle (${}^{4}_{2}He$) but we know the constant of the statistical decay process describing the temporal variation of the number of ${}^{226}_{88}Ra$ nuclei in a system. This statistical nature of the laws ubiquitous in the world of elementary particles has been put aside in discussions about the reproducibility of measurements of physical quantities where elementary particles participate.

Following regions of energy and categories of nuclei used in nuclear physics [Blatt 1952] are convenient to use in discussion henceforth:

The ranges of energy ε of the incident particle are divided in five regions:

I. Low energies: $0 < \varepsilon < 1000$ eV.
II. Intermediate energies: 1 keV $< \varepsilon <$ 500 keV.
III. High energies: 0.5 MeV $< \varepsilon <$ 10 MeV.
IV. Very high energies: 10 MeV $< \varepsilon <$ 50 MeV.
V. Ultrahigh energies: 50 MeV $< \varepsilon < \infty$.

The target nuclei are divided into three categories according to their nucleon (mass) number A;

A. Light nuclei: $1 \leq A \leq 25$.
B. Intermediate nuclei: $25 \leq A \leq 80$.
C. Heavy nuclei: $80 \leq A \leq 240$.

In this section, we review the results related to the interaction between a nucleus and a thermal neutron developed in nuclear physics keeping our minds at the possible mechanisms of the CFP.

The light nuclei (group A) must be treated individually. It is almost impossible to apply any general rules describing nuclear reactions in that group. The reactions with intermediate or heavy nuclei are of different character in the five energy regions. The outstanding features of these regions can be characterized as follows: Regions I and II are almost exclusively confined to neutron reactions and the former (low energy) is characterized by the preponderance of resonance capture of neutrons in heavy nuclei.

Only few neutron reactions can take place with neutrons of low or intermediate energy. For intermediate nuclei the most important reactions are elastic scattering and radiative capture.

2.1 Number of stable isotopes of a nucleus ${}^{A}{}_{Z}\mathrm{X}$ with a mass (nucleon) number *A* and a proton number *Z*

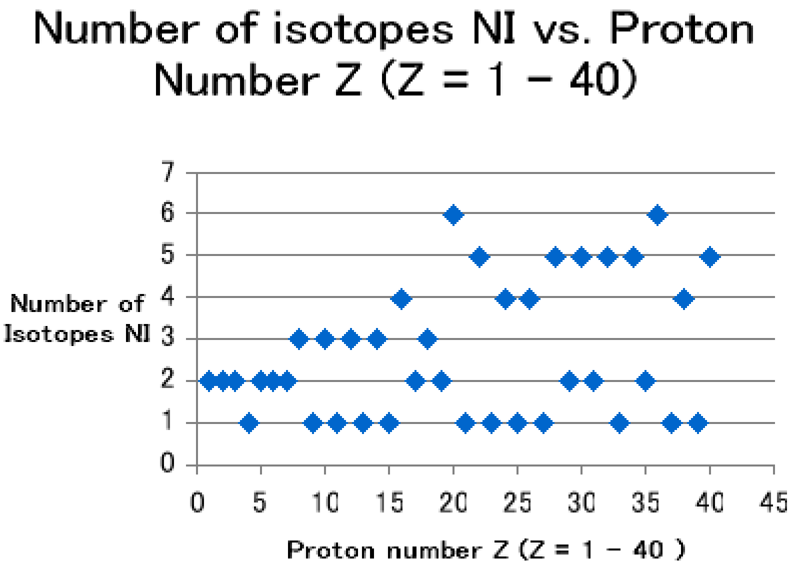
There are several stable isotopes ${}^{A}{}_{Z}\mathrm{X}$ of an element ${}_{Z}\mathrm{X}$ (or X) with different values of the nucleon number *A* (or of the neutron number *N* (= *A* – *Z*)) as shown in Fig. 2.1. The number of the stable isotopes, N_{I}, is a characteristic of the element ${}_{Z}\mathrm{X}$ reflecting the state of nucleons in the nucleus.

The first noticeable character of Fig. 2.1 is the low value of N_{I} for the elements with an odd proton number *Z*. Why? This question of the small number of isotopes for odd proton numbers *Z* is explained by the nuclear spectroscopy where the stability condition of a nucleus is explained as a function of the symmetry effect, the charge effect and the spin-dependence of nuclear forces [Blatt 1952]. The symmetry effect showing independence of the nuclear force from nucleon species (proton or neutron) plays an essential role in the investigation of fission of nuclei by absorption of neutrons.

The dependence of N_{I} on *Z* is a characteristic closely related to the fission of low proton number nuclei by absorption of a thermal neutron.

The nuclei with small *Z* and very large *Z* make fission when they absorbed a thermal neutron (or a neutron with zero energy). Examples of the former case are ${}^{6}{}_{3}\mathrm{Li}$ and ${}^{10}{}_{5}\mathrm{B}$ and the latter are ${}^{235}{}_{92}\mathrm{U}$ and ${}^{239}{}_{94}\mathrm{Pu}$. This fact may be related to the fact that there are a few stable isotopes for elements with small and with very large proton numbers *Z* as seen in Figs. 2.1 (a) and (b) and will be discussed in Sec. 2.4.

(a)



(b)

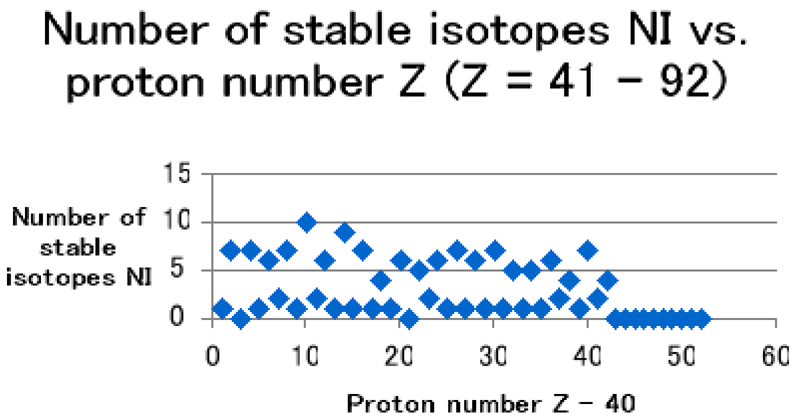


Fig. 2.1 Number of isotopes N_I vs. proton number Z of nucleus ${}^{A}_{Z}X$ (a) Z = 1 – 40 and (b) Z = 41 – 92.

2.2 Binding Energy and Binding Fraction

The total binding energy B of a nucleus ${}^{A}_{Z}X$ is defined by a following equation using the mass defect Δ;

$$B = ZM_pc^2 + (A - Z)\,M_nc^2 - U \equiv c^2\Delta, \qquad (2.1)$$

$$\Delta \equiv ZM_p + (A - Z)\,M_n - M_{nucl}$$

where U is the total energy of the nucleus expressed as $U = M_{\mathrm{nucl}}c^2$ with the mass of the nucleus M_{nucl}.

The binding fraction f is defined by B as follows:

$$f = B/A. \qquad (2.2)$$

In Fig. 2.2, f is plotted as a funciton of the mass (nucleon) number A for stable nuclei.

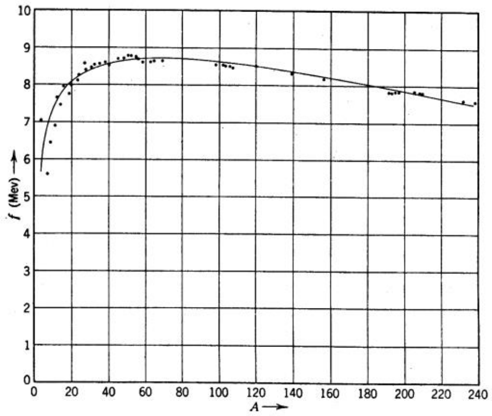


Fig. 2.2 Binding fraction f of stable nuclei as a function of mass number A [Blatt 1952].

The decrease of the binding fraction f at both ends of this figure, at small and large values of A, is another characteristic related to the above mentioned characteristic of the number of isotopes and is also related to the fission of nucleus by absorption of a thermal neutron as discussed in Sec. 2.5. The smooth variation of f in the medium region of A tells us stability of nuclei here against fission by absorption of a single neutron. The experimental evidence of nuclear transmutations suggesting nuclear fission of intermediate nuclei obtained in the CFP should be explained by the fission induced by multi-neutron absorption. Possibility of such reactions will be discussed also in Sec. 2.4 in relation to the two-neutron separation energy observed in exotic nuclei.

2.3Mass Formula

Nuclear ground state energy E is the negative of the binding energy B and is given by the Weizsaecker semi-empirical formula [Blatt 1952, VI Sec.2];

$$E = -B = -u_v A + 4u_r T_\zeta^2/A + 4u_c Z(Z-1)A^{-1/3} + u_s A^{2/3} \qquad (2.3)$$

Here, u_v, u_r, u_c and u_s are the volume energy constant per unit volume of the nucleus, the symmetry energy constant, the Coulomb energy constant, and the surface energy constant per unit area of the surface. We notice here that the surface energy term in the Eq. (2.3) should have close relation with the separation energy discussed in the next section. The boundary energy of the surface between a nucleus and a surrounding neutron sea, if it exists, gives influence on the alpha decay of the nucleus (cf. Sec. 2.9).

Separation Energy

The separation energy S_a(X) of a particle a from a given nucleus X is defined as the energy necessary to remove to infinity the particle a from the nucleus X in its ground state, leaving the residual nucleus Y (Y + a = X) also in its ground state. The values of S for a nucleon separation are close to the value of the binding fraction $f \approx 8$ MeV, i.e. the energy necessary to remove one nucleon is approximately equal to the average binding energy per nucleon. However, there is a general tendency for the separation energy of a nucleon to deviate from the binding fraction in a region of A where the binding fraction varies appreciably with mass number, i.e. in regions of small and large A. This is another indication of instability of nuclide in these regions.

2.3.1 Neutron separation energy S_n.

The neutron separation energy S_n from the nucleus with Z protons and N neutrons is expressed as

$$S_n = B(Z,N) - B(Z, N-1). \qquad (2.4)$$

This expression can be rewritten in the form

$$S_n = f(Z,N) + (A-1)[f(Z,N) - f(Z, N-1)]. \qquad (2.5)$$

Assuming that $f(Z,N)$ is a smooth function of A by a primary approximation, we obtain from (2.5)

$$S_n \approx f(A) + (A-1)\, \mathrm{d}f/\mathrm{d}A. \qquad (2.6)$$

For heavy nuclei, the binding fraction decreases with increasing A so that the separation energies are systematically smaller than the binding fractions. For $A > 200$, the separation energies are of the order of 5.5 to 6 MeV, whereas f is of the order of 7.5 MeV.

The dependence of S_n on A in Eq. (2.6) is closely related to fission of heavy nuclei by the absorption of a neutron as discussed in Sec. 2.5.

2.3.2 Alpha separation energy S_α

The same approximation used in the calculation of the neutron separation energy (2.6) is applied to the calculation of the alpha separation energy S_α. The result is

$$S_\alpha \approx 4f(A) - B(\alpha) + 4(A - 4)\, df/dA \qquad (2.7)$$

where $B(\alpha)$ = 28.23 MeV is the binding energy of the alpha-particle. Comparing (2.6) with (2.7) we can deduce a conclusion that the alpha separation energies for heavy nuclei may be expected to be much lower than the neutron or proton separation energies;

$$S_\alpha << S_n. \quad \text{(for heavy nuclei)} \qquad (2.8)$$

Indeed, very many heavy nuclei are unstable against alpha-particle emission from their ground states, i.e., S_α is actually negative.

This is a cause of acceleration of alpha decay by thermal neutron absorption feeding about 8 MeV to the nucleus.

2.3.3 Two-neutron separation energy $\boldsymbol{S_{2n}}$

It is interesting to notice that the two-neutron transfer is considered in exotic nuclei [Zdenek 2006]. The complex situation of the exotic nuclei in the region Z = 8 – 13 (O – Al) made researchers to make an attempt to clarify the behaviour of two-neutron separation energies $\boldsymbol{S_{2n}}$ in this region. They observed several stable nuclei in this region while their masses are not known yet. Nevertheless, their S_{2n} values must be positive and therefore the authors have included the "expected" $\boldsymbol{S_{2n}}$ values of the heaviest stable isotopes ${}^{22}_{6}C$, ${}^{23}_{7}N$, ${}^{29,31}_{9}F$ and ${}^{31,32}_{10}Ne$ with large circles in Fig. 2.3 [Zdenek 2006, Fig. 8]. The "expected" $\boldsymbol{S_{2n}}$ values for ${}^{29,31}_{9}F$ and ${}^{31,32}_{10}Ne$ point out the region where they probably have to be located due to their experimentally found particle stability (positive S_{2n} values). A behavior typical of the filling in shells can be seen from the characteristics corresponding to the ${}_{20}Ca$, ${}_{19}K$ and ${}_{18}Ar$ isotopes. The two shell closures at N = 20 and N = 28 are evidenced by the corresponding sharp decrease of the $\boldsymbol{S_{2n}}$ value when two neutrons are added after crossing magic numbers (N = 20 and 28). After this sharp drop at the drop point N_{dp} (corresponding to N_{shell} + 2) the values of $\boldsymbol{S_{2n}}$ step-down only slowly as the filling of the next shell starts to influence $\boldsymbol{S_{2n}}$.

The positive energy for the two-neutron separation says, conversely speaking, there occurs exothermic reactions when such an exotic nucleus as ${}^{50}_{20}Ca$ absorbs two-neutron from surrounding free neutron sea (cf-matter) becoming unstable for fission. This possibility may be related to the nuclear transmutation observed in the CFP as discussed in the next section and another paper presented at this Conference [Kozima 2014b].

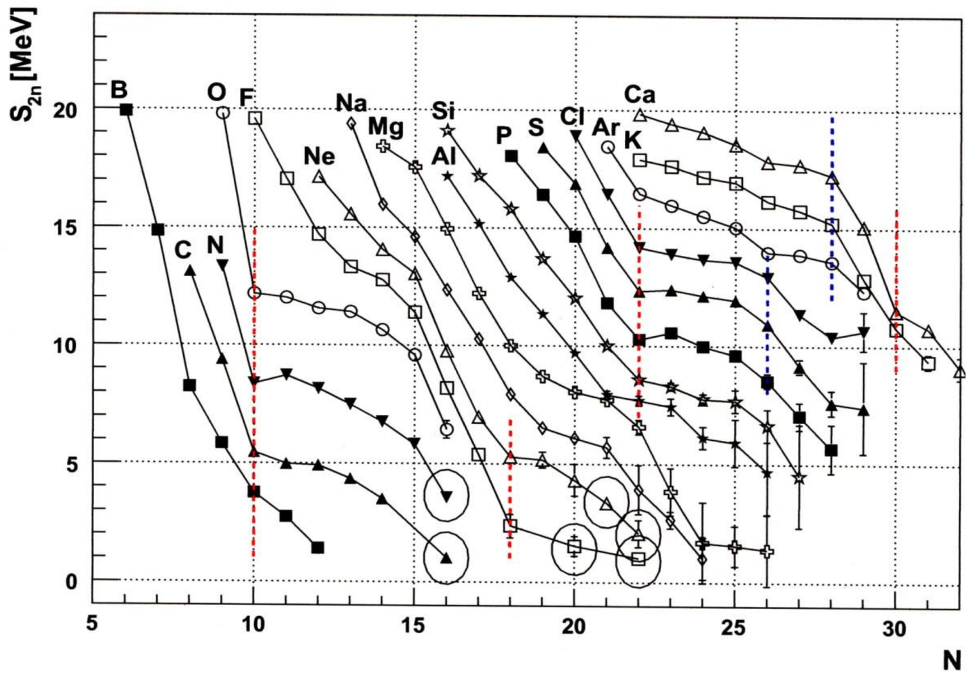


Fig. 2.3. Two-neuron separation energy S_{2n} vs. N – the drop points are visualized by vertical dotted red lines [Zdenek 2006, Fig. 8].

2.4 Fission

When a nucleus ${}^{A}{}_{Z}X$ absorbs a thermal neutron (or a neutron with zero energy), the resultant compound nucleus ${}^{A+1}{}_{Z}X$ makes a fission into several nuclei and nucleons. Experimentally, we know that the fission occurs for nuclei in both regions of a small Z (or nucleon number A), e.g. ${}^{6}{}_{3}$Li and ${}^{10}{}_{5}$B, and of a large Z (or nucleon number A), e.g. ${}^{235}{}_{92}$U and ${}^{239}{}_{94}$Pu.

Examples of the former are;

$${}^{6}{}_{3}\mathrm{Li} + n = {}^{4}{}_{2}\mathrm{He} + {}^{3}{}_{1}\mathrm{H} + Q_1, \qquad (2.9)$$

$${}^{10}{}_{5}\mathrm{B} + n = {}^{7}{}_{3}\mathrm{Li} + {}^{4}{}_{2}\mathrm{He} + Q_2 \qquad (2.10)$$

where Q_1 = 4.8 MeV, Q_2 = 2.79 MeV. It is interesting to notice that nuclide ${}^{7}{}_{3}$Li and ${}^{11}{}_{5}$B are stable and their natural abundances are higher than their sisters ${}^{6}{}_{3}$Li and ${}^{10}{}_{5}$B as discussed below.

Examples of the latter are;

$${}^{235}{}_{92}\mathrm{U} + n = {}^{95}{}_{39}\mathrm{Y} + {}^{139}{}_{53}\mathrm{I} + 2n + \mathrm{Q}_{3}, \qquad (2.11)$$

$${}^{235}{}_{92}\mathrm{U} + n = {}^{87}{}_{35}\mathrm{Br} + {}^{147}{}_{57}\mathrm{La} + 2n + \mathrm{Q}_3', \qquad (2.11')$$

$${}^{239}{}_{94}\mathrm{Pu} + n = {}^{94}{}_{40}\mathrm{Zr} + {}^{142}{}_{54}\mathrm{Xe} + 3n + \mathrm{Q}_4, \qquad (2.12)$$

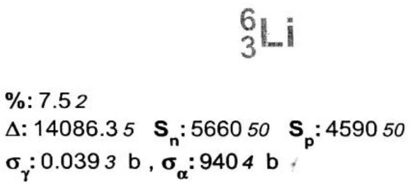
where $Q_3 \approx Q_3' \approx Q_4 \approx 200$ MeV. It is known that the process of fission may occur in about 30 different ways.

Extending our knowledge of fission reactions induced by single neutron absorption, it is possible to conclude that the fission of medium *Z* nuclei may be capable by simultaneous absorption of several neutrons in terms of a nucleon cluster ${}^{A}_{Z}\Delta$. The two-neutron separation of exotic nuclei discussed above in Sec. 2.4.3 may have close relation to this problem. Possibility of this process will be discussed further in Section 2.5.3.

Table 2.1 Natural abundance of lithium and boron [Firestone 1996].

Isotope	${}^{6}_{3}$Li	${}^{7}_{3}$Li	${}^{10}_{5}$B	${}^{11}_{5}$B
Natural abundance (%)	7.52	92.52	19.92	80.12

Interesting facts should be noticed about the existence of stable isotopes of ${}^{7}_{3}$Li and ${}^{11}_{5}$B despite the fact that reactions (2.9) and (2.10) occur respectively. The natural isotopic ratios of lithium and boron are listed up in Table 2.1. Furthermore, neutron absorption cross sections σ_γ ($\equiv \sigma(n,\gamma)$) and σ_α($\equiv \sigma(n,\alpha)$) are shown in Figs. 2.4 and 2.5 for ${}^{6}_{3}$Li and ${}^{10}_{5}$B, respectively.

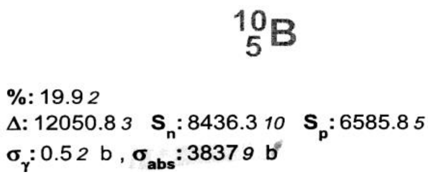

${}^{6}_{3}$Li

%: 7.5 *2*

Δ: 14086.3 *5* S_n: 5660 *50* S_p: 4590 *50*

σ_γ: 0.039 *3* b , σ_α: 940 *4* b

Fig. 2.4 Neutron absorption cross sections σ_γ and σ_α of ${}^{6}_{3}$Li [Firestone 1996].


${}^{10}_{5}$B

%: 19.9 *2*

Δ: 12050.8 *3* S_n: 8436.3 *10* S_p: 6585.8 *5*

σ_γ: 0.5 *2* b , σ_{abs}: 3837 *9* b

Fig. 2.5 Neutron absorption cross sections σ_γ and σ_α of ${}^{10}_{5}$B [Firestone 1996].

2.4.1 Fission (or *α*-emission) of light nuclei induced by absorption of a

thermal neutron

The fission of the low Z nucleus induced by a thermal neutron is known in nuclear physics for a long time but not taken up seriously due to its limited use in application. A few cases of the use of the reaction is the production of tritium by the reaction (2.9) with a fairly large absorption cross section 940.3 b of ${}^{6}_{3}Li$ and the detection of neutrons by the reaction (2.10) with a very large absorption cross section (≈ 3837 b) of the ${}^{10}_{5}B$.

It is noticed that the reaction products of reactions (2.9) and (2.10) are measured in the CFP;

n-${}^{6}_{3}Li$ while ${}^{7}_{3}Li$ is stable [Passell 2002].

$n + {}^{6}_{3}Li = {}^{4}_{2}He$ (2.1 MeV) + ${}^{3}_{1}H$ (2.7 MeV),

$Q = 4.8$ MeV

n-${}^{10}_{5}B$ while ${}^{11}_{5}B$ is stable [Passell 1996, 1997].

$n + {}^{10}_{5}B = {}^{7}_{3}Li$ (1.01 MeV) + ${}^{4}_{2}He$ (1.78 MeV),

$Q = 2.79$ MeV

The energy of about 8 MeV fed to the nucleus by absorption of a thermal neutron makes the compound nucleus unstable resulting in the fission of the nucleus. This process will be explained by the liquid drop model of the nucleus. It is noticed again that the compound nuclei ${}^{6}_{3}Li$ and ${}^{10}_{5}B$ in their ground states are stable and do not decay.

Explanation of the reaction ${}^{10}_{5}B$ (n,α) ${}^{7}_{3}Li$ [Blatt 1952 (Chap. 9, Sec. 5A)]

When boron is exposed to slow neutrons, the (n, α) reaction on ${}^{10}_{5}B$ is the leading process. The Q value of this reaction is 2.78 MeV. This reaction is of special interest because (n, α) reactions with slow neutrons do not occur very frequently. In intermediate and heavy nuclei, neutrons in energy regions I and II introduced above produce elastic scattering or capture (and in some cases fission). The occurrence of (n, α) reactions is usually excluded because of the preventive effect of the Coulomb barrier. In the case of boron, however, the favorable Q value and the low Coulomb barrier (about 2.5 MeV) between ${}^{7}_{3}Li$ and an alpha-particle make it possible that an alpha-particle is emitted by the compound nucleus with considerable probability. Alpha-particle emission competes successfully against neutron capture; the radiative capture cross section is less than 10^{-5} of the (n, α) cross section. The (n, α) reaction on ${}^{10}_{5}B$ can be considered a neutron-induced fission of boron into ${}^{7}_{3}$Li and ${}^{4}_{2}$He^{4}.

The alpha-particles are emitted into two channels, corresponding to the ground state of ${}^{7}_{3}$Li (Q = 2.78 MeV) and to the first excited state of ${}^{7}_{3}$Li (Q = 2.30 MeV). The emission probabilities for thermal neutron bombardment are in the ratio 93 to 7 in favor of the excited state.

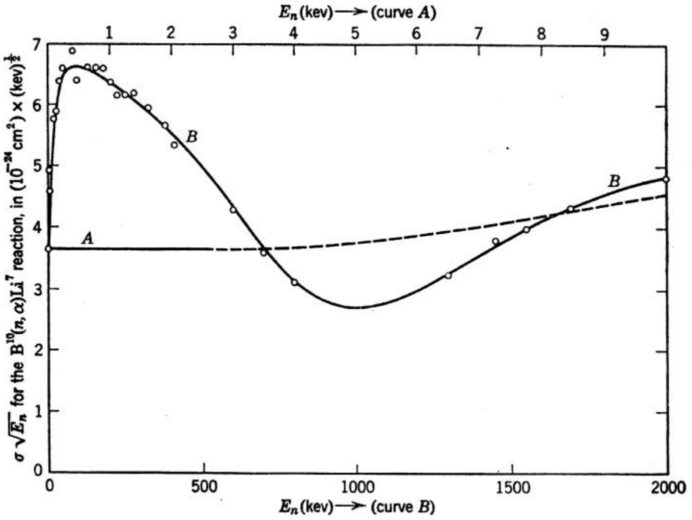


Fig. 2.6. σ (n, α) in boron. This plot shows the product $\sigma\ \sqrt{\varepsilon}$ in order to remove the $1/\sqrt{\varepsilon}$ factor. There are no reliable measurements between 1 keV and about 10 keV. The dashed part of curve A is a plausible interpolation. The horizontal part below 1 keV ($1/\sqrt{\varepsilon}$ dependence) is very well established ([Blatt 1952]).

The observed energy dependence of the (n, α) cross section of ${}^{10}_{5}$B is shown in Fig. 2.6 [Blatt 1952, IX Fig. 5.1]. For neutron energies up to 10 keV it is almost exactly proportional to $\varepsilon^{-1/2}$. The qualitative features of this curve can be understood by the Breit-Wigner formula for the reaction cross section, with a reaction width (in this case the width for the emission of the alpha-particles) of the order of 250 keV and resonance energy of about 100 keV. Such a large width is not unexpected in view of the large level distances in ${}^{11}_{5}$B, and in view of the weakness of the Coulomb barrier for alpha-emission. The $\varepsilon^{-1/2}$ dependence of the cross section at energies below 1 keV follows from the Breit-Wigner formula [Blatt 1952, VIII (7.25)]. It is remarkable and very characteristic of this reaction that the $\varepsilon^{-1/2}$ dependence extends to energies up to 10^4 eV. This is due to the large reaction width Γ^{s}_{α}. Hence the resonance factor is very slowly varying and the main energy dependence comes from the proportionality to $\lambda/2n$.

Similar explanation will be given to the reaction of ${}^{6}_{3}Li(n, \alpha){}^{3}_{1}H$.

2.4.2 Fission of heavy nuclei induced by absorption of a thermal neutron

The heavy nuclei possible to make spontaneous fission can be excited by an absorption-emission process of a thermal neutron to give the excess energy to the outgoing neutron without emitting residual particles which are observed in the reactions in free space.

The most important difference of the fission reactions at low and high values of the proton number is the generation of several (more than one) excess neutrons accompanied to the reaction at the latter case due to the surplus neutrons in the product nuclei. This characteristic has been used for the chain reaction of uranium and plutonium in atomic pile.

Illustrative fission reaction of a heavy nucleus ${}^{A}_{Z}X$ by absorption of a thermal neutron is written down as follows:

$${}^{A}_{Z}X + n = {}^{A'}_{Z'}X' + {}^{A''}_{Z''}X'' + 2n + Q, \qquad (2.13)$$

where $A = A' + A'' + 2$ and $Z = Z' + Z''$. Empirical distributions of A' and A'' in reactions of three nuclei ${}^{233}_{92}U$, ${}^{235}_{92}U$ and ${}^{239}_{94}Pu$ were shown in Fig. 2.7.

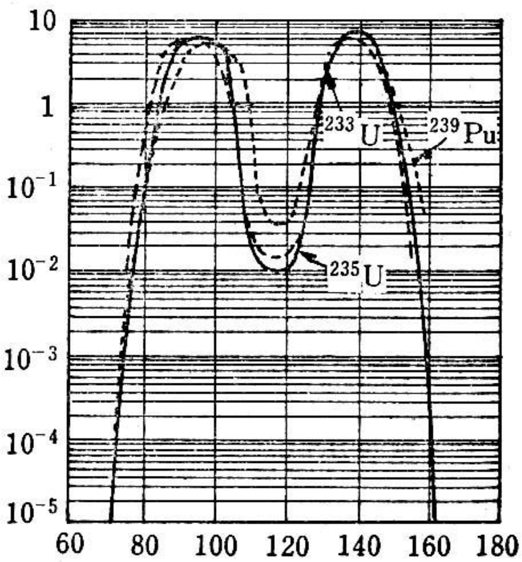


Fig. 2.7 Mass fission yield curves for ${}^{233}U + n$ (thermal), ${}^{235}U + n$ (thermal), ${}^{239}Pu + n$ (thermal). Yields (in log scale) for the three reactions were plotted as functions of mass number A of the product nuclei (e.g. X' and X'' in Eq. (2.5)) [Zukai 1974].

2.4.3 Fission of medium nuclei induced by absorption of a nucleon cluster

For the nuclei with medium numbers of proton numbers, there are few data of nuclear fission by absorption of a thermal neutron in nuclear physics. It is supposed that fission may be ignored in the *r*-process of heavy element production by absorption of a neutron for the nuclei with medium proton numbers ($Z < 80$) [Qian 2003].

However, the possibility of fission reaction for medium nuclei with proton numbers between 10 and 80 ($10 < Z < 80$) is not absurd if we notice a situation realized in a CF-material where a nucleus is dipped in a kind of free neutron sea, cf-matter. There is an interesting example of multi-neutron transfer from a nucleus: the two-neutron separation of exotic nuclei discussed in Sec. 2.4.3 [Zdenek 2006, Lu 2013]. In these examples, especially ^{6}He and ^{8}He, the single neutron absorption by ^{4}He and ^{6}He is not possible but two-neutron absorption is realistic. This is an interesting case of multi-neutron transfer between a nucleus and the surrounding neutron sea (cf-matter) considered in the CFP. We will discuss possibility of multi-neutron transfer using the knowledge of nuclear physics.

At first, as in the case of alpha decay, the boundary surface energy between the nucleus and the cf-matter decreases with the increase of the density ratio (n_o/n_i). Then the fission barrier will become lower than that in the case of isolated nucleus. This effect is similar to the case of alpha decay. Secondly, we can feed a nucleon cluster $^{A}{}_{Z}\Delta$ with Z protons and N ($= A - Z$) neutrons to a nucleus causing stability of the nucleus lower. As in the case of induced fission of light nuclei, $^{6}{}_{3}$Li and $^{10}{}_{5}$B by absorption of a neutron, we may have fission reactions of medium nuclei by absorption of a nucleon cluster $^{A}{}_{Z}\Delta$ from surrounding free neutron sea of neutron star matter or cf-matter in the CFP. It is easily conceivable that the more the number of neutrons ($A - Z$) in the cluster becomes, the easier the compound nucleus thus formed do fission. The various nuclei generated in the CFP have suggested the nuclear transmutation by fission of medium nuclei which may be explained by the mechanism explained above. Application of this idea to the CFP is given in a paper presented at this Conference [Kozima 2014b].

As in the cases of alpha and beta decays, interest of nuclear physicists has not been in the problems such as decay time shortening and fission barrier lowering caused by a free neutron sea treated in neutron star matter. It sis a realistic problem to consider a possibility of absorption of a nucleon cluster in CF-materials where lattice nuclei (nuclei at lattice points) are dipped in a free neutron sea (cf-matter).

2.5 Alpha-Decay and Effect of Neutron Absorption on It

The nuclides with large number of proton are unstable against emission of a part of its components, especially a group of two neutrons and two protons, alpha particle. When the alpha particle formed temporarily in the nucleus pass through the potential barrier (as shown in Fig. 2.8) at the boundary, the nucleus ${}^{A}_{Z}$X separates into two parts, one the alpha particle ${}^{4}_{2}$He and another remaining nucleus ${}^{A-4}_{Z-2}$X' . This reaction is the alpha decay of the nucleus ${}^{A}_{Z}$X.

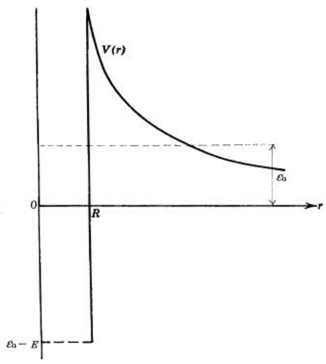


Fig. 2.8. Potential energy of two nuclei as a function of their distance (schematic) (After [Blatt 1952]).

In our qualitative picture, we assume that the alpha-particle starts out from the interior of the compound nucleus with a certain kinetic energy E (measured from the bottom of the interior well). It approaches the barrier at $r = R$ (nuclear radius) from the inside and may or may not pass through the barrier. If it does pass through the barrier, it has the kinetic energy ε_α far away (for $r \to \infty$). In this schematic picture, we can replace the conditions inside the compound nucleus by a constant potential $V(r) = \varepsilon_\alpha - E$ for $r \le R$ (Fig. 2.8).

The decay probability $2n\Gamma_\alpha /h$ of a compound state into the alpha-channel can be written

$$2n\Gamma_\alpha /h = \omega_0\, 4s_\ell\, KR/[(KR)^2 + \Delta_\ell^{\,2}] \qquad (2.14)$$

where ω_0 is the number of attempts per second of the alpha-particle to penetrate through the barrier (surface of the nucleus) into the outside expressed as

$$\omega_0 \approx D/h \qquad (2.15)$$

with D the level distance between levels of the same type (angular momentum and parity). The wave number K corresponds to the kinetic energy inside: $K^2 = 2(2n)^2M_\alpha E/h^2$. The magnitudes s_ℓ and Δ_ℓ are defined in terms of the behavior of the wave function in the outside region. For the magnitude of order estimation, we can take only the particle with $\ell = 0$ and then we can put $s_0 = kR$ and $\Delta_0 = 0$ where k is the wave number at infinity ($k^2 = 2(2\pi)^2M_\alpha\varepsilon_\alpha/h^2$).

Then, the expression (2.14) is rewritten as

$$2n\Gamma_\alpha /h = (\omega_0 h/nE)(2\varepsilon_\alpha/M_\alpha)^{1/2} \qquad (2.16)$$

This formula shows two dependences of the emission probability on the interior quantities ω_0 and E. The largest influence of thermal neutron absorption on the alpha decay of a nucleus may be through the change of E: The increase of internal energy of a nucleus by about 8 MeV makes the nucleus more unstable and the E is decreased. This effect makes the probability (2.16) larger. Another effect of the neutron absorption is through the change of the level distance D. It seems the level distance becomes larger for the shallower potential well contributing for the increase of emission probability.

It is interesting to notice the relation between the potential barrier for the alpha emission and the surface energy contributing to the equation of mass formula as $u_s A^{2/3}$ in Eq. (2.3) [Blatt 1952, Sec. VI-2]. The value of the coefficient u_s is estimated as $u_s \approx 13.1$ MeV. The total potential energy is lowered in absolute value compared to what we would get if we just considered a sphere of the size of the nucleus inside a very large volume of condensed nuclear matter.

From its origin of the surface energy, the value of u_s surely decreases with increase of the ratio of neutron densities n_o/n_i where n_o is density outside and n_i is that inside the surface of the nucleus when it is immersed in a neutron sea. Though the concept of the surface energy u_s is directly related to single particle behavior of nucleons in the nucleus, it is closely related to the alpha particle behavior in the nucleus and should have positive

correlation with the potential barrier for the alpha decay (c.f. Sec. 2.9).
This concept of the potential barrier for the alpha decay is applied to explain the decay time shortening in actinoid hydrides and deuterides and given in a paper presented at this Conference [Kozima 2014a].

2.6 Beta-Decay and Effect of Neutron Absorption by the Parent Nucleus on It

When a nucleus ${}^{A}_{Z}\mathrm{X}$ contains an excess number of neutrons over that in stable states, neutrons in the nucleus are unstable to be remained there and one of the neutrons experiences nuclear transmutation into a proton emitting an electron and a neutrino. This is the beta decay of the nucleus ${}^{A}_{Z}\mathrm{X}$ with a mass number A and a proton number Z into another nucleus with the same mass number but with a proton number Z+1, ${}^{A}_{Z+1}\mathrm{X}'$.

Half-lives of beta-emitter

The probability of decay into a given momentum interval dp of the electrons is given by a formula [Blatt 1952, VIII (2.13)];

$$P(p)\,\mathrm{d}p = C\,F(Z,E)p^2\,(E_0 - E\,)^2\,\mathrm{d}p, \qquad (2.17)$$

where C is a constant which in general depends on the specific nuclei involved in the decay, E_0 is the energy available from the nuclear transition, and $F(Z,E)$ is given approximately by

$$F(Z,E) = |\psi_e(0)|^2/|\psi_e(0)|^2_{\mathrm{free}} = 2n\eta/[1 - \exp(- 2n\eta)], \qquad (2.18)$$

where $\eta = 2\pi Ze^2/hv$ for electrons, $\eta = - 2\pi Ze^2/hv$ for positrons, v being the speed of the particle far away, Z the atomic number of the product (daughter) nucleus.

The half-life t_- of the beta-decay is defined by the total probability per unit time that a beta-active nucleus will decay given by integration of $P(p)$dp over all electron momenta in the beta-spectrum [Blatt 1952 XIII 4 (4.1)]:

$$\beta^- \text{ decay probability} = \ln 2\,/t_- = \mathrm{C}f_-\,(Z,E_0), \qquad (2.19)$$

where $f_-\,(Z,E_0)$ is the integral

$$f_-\,(Z,E_0) = \int_0^{p0} F(Z,E)\,p^2\,(E_0 - E)^2\,\mathrm{d}p. \qquad (2.20)$$

The upper limit of integration, $p_0 = (E_0^{\,2} - 1)^{1/2}$, is the maximum momentum in the electron spectrum, expressed by the unit mc.

The integral of (2.20) can be evaluated explicitly for Z = 0, i.e., for the case where the Coulomb effect on the spectrum is neglected. The result is

$$f_{-}(0,E_0) = (1/60)(E_0^2 - 1)^{1/2}(2E_0^4 - 9E_0^2 - 8) + (1/4)E_0 \ln[E_0 + (E_0^2 - 1)^{1/2}] \quad (2.21)$$

For very large E_0, this function is proportional to E_0^5. However, in the energy region of interest, $1.1 \leq E_0 \leq 10$, f_{-} does not follow an E_0^5 law but is more nearly proportional to $(E_0 - 1)^4$.

For the proton number Z not equal to 0, the integral (2.20) must be evaluated numerically.

Anyway, the beta-decay probability depends strongly on the total energy liberated by the nuclear transition of the beta decay. The absorption of a thermal neutron gives energy of about 8 MeV to the nucleus that may increase E_0 by an amount about this value resulting in the half-life shortening such as that observed in the CFP.

The beta-decays of nuclei after absorption of a neutron have been used to explain synthesis of heavy elements in stars where interaction between a nucleus and a neutron occurs frequently [Burbidge 1957, Qian 2003].

Interesting facts should be noticed about the existence of stable isotopes of ${}^{7}_{3}$Li and ${}^{11}_{5}$B in the cases (2.9) and (2.10). In relation to this fact, we may have a possibility of the decay time shortening of beta nuclei, e.g. compound nuclei ${}^{40}_{19}\mathrm{K}^*$ generated by reaction n+${}^{39}_{19}$K and ${}^{107}_{46}\mathrm{Pd}^*$ by n + ${}^{106}_{46}$Pd [Kozima 2014b, Sec. 6.4.3] while we have no data about it in nuclear data tables. The decay constants of ${}^{40}_{19}$K and ${}^{107}_{46}$Pd are written as 1.27×10^9 y and 1.3×10^9 y, respectively. These values may be measured at some time later after the reaction without regard to the amounts of the product nuclei ${}^{40}_{20}$Ca and ${}^{107}_{47}$Ag.

2.7 Exotic Nuclei and Neutron Levels at Zero Energy

Existence of exotic nuclei with large imbalance of the proton number Z and the neutron number N (= $A - Z$) in isolated states of a nucleus ${}^{A}_{Z}$X has attracted strong attention and has been extensively investigated in recent years. Several interesting features of the nucleus have been revealed by the investigation of the exotic nucleus [Wiedenhover 2007]: 1) Very neutron-rich nuclei are expected to exhibit diffuse surfaces which lead to a reduced spin-orbit coupling and “melting” of the shell structure. 2) Many examples for modification of shell structure in neutron-rich nuclei are known (N, Z<50). 3) What may be the more interesting question: What are the collective excitations of neutron matter? 4) What is the neutron-wavefunction? Pair transfer $^{16}C(p,t)^{14}C$ (+ γ ?). 5) Neutron-rich nuclei have shell structure different from their "stable" siblings and their proton-rich mirrors! 6) New collective excitations have to be expected: Neutron-only collectivity?

New information about the behavior of neutrons in exotic nucleus is obtained by a laser probing technique in ^6_2He and ^8_2He isotopes exhibiting an exotic nuclear structure that consists of a tightly bound ^4He-like core with additional neutrons orbiting at a relatively large distance, forming a halo [Lu 2013]. The charge radii of these light halo nuclei have now been determined for the first time independent of nuclear structure models.

Extended distribution of neutrons over that of proton and fairly good coincidence of theory and experiment are shown in Fig. 2.9 for ^6_2He and ^8_2He [Lu 2013].

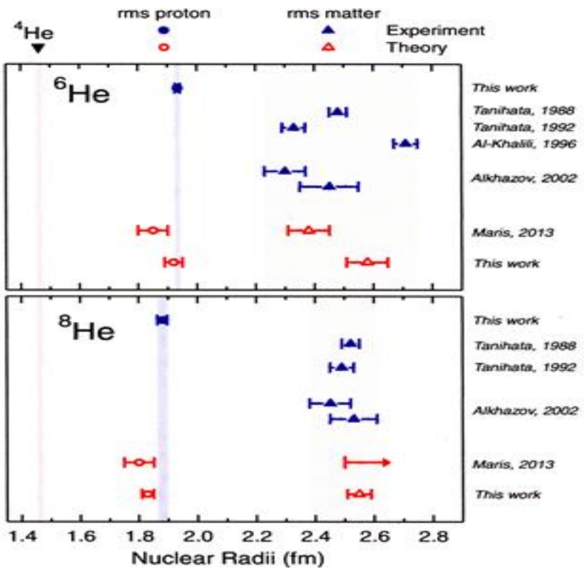


Fig. 2.9 Comparison between experimental and theoretical values of point-proton and matter radii for ^6_2He (top panel) and ^8_2He (bottom panel) [Lu 2013, Fig. 8]

Another data of extended distribution of neutrons are shown in Fig. 2.10 by the theoretical density distributions by the Green's function Monte Carlo (GFMC) calculation for ^4_2He, ^6_2He and ^8_2He.

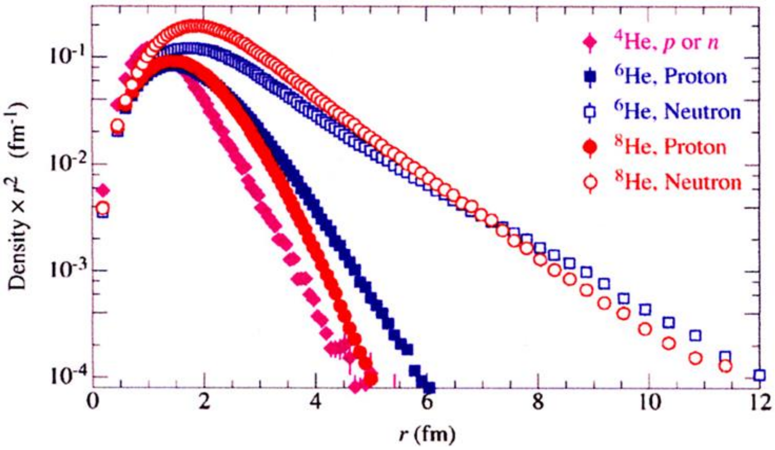


Fig. 2.10. Point-proton and point-neutron densities of the even helium isotopes as extracted from GFMC calculations [Lu 2013, Fig. 10]

Table 2.2. Half-lives, charge and point-proton radii in Li and Be isotopes [Lu 2013, Table VIII].

TABLE VIII. Half-lives, spin parities, experimental charge radii, and experimental and GFMC point-proton radii in the Li and Be isotope chains. Charge radii are based on isotope shift measurements in Li atoms (Nörtershäuser *et al.*, 2011a) and Be$^+$ ions (Krieger *et al.*, 2012) and are referenced to the values of the stable ^{6}Li and ^{9}Be, respectively, which are independently determined from electron scattering experiments. The first uncertainty of the charge radii has been determined from the quoted error of the isotope shift, whereas the second one includes the uncertainty of the reference radius. Radii are in fm. The GFMC values (Pastore *et al.*, 2013) are for the AV18 + IL7 Hamiltonian.

Isotope	$t_{1/2}$	J^π	r_c	r_p Expt	r_p GFMC
^{6}Li	Stable	1^+	2.589(0)(39)	2.45(4)	2.39(1)
^{7}Li	Stable	$3/2^-$	2.444(4)(43)	2.31(5)	2.28(1)
^{8}Li	840 ms	2^+	2.339(7)(45)	2.20(5)	2.10(1)
^{9}Li	180 ms	$3/2^-$	2.245(7)(47)	2.11(5)	1.97(1)
^{11}Li	8.5 ms	$3/2^-$	2.482(14)(44)	2.38(5)	
^{7}Be	53 d	$3/2^-$	2.646(10)(16)	2.507(17)	2.47(1)
^{9}Be	Stable	$3/2^-$	2.519(0)(12)	2.385(13)	2.37(1)
^{10}Be	1.5 Myr	0^+	2.361(9)(17)	2.224(18)	2.19(1)
^{11}Be	14 s	$1/2^+$	2.466(8)(15)	2.341(16)	
^{12}Be	24 ms	0^+	2.503(9)(15)	2.386(16)	

Some numerical data on the characteristics of exotic nuclei with small proton number Z are listed in Table 2.2 [Lu 2013].

The study of neutron-rich nuclei provides an important insight into the nuclear forces that hold these loosely bound systems together. Investigation of the nuclear forces in the extremely neutron-rich environment different from that in ordinary nuclear matter is in progress with use of this technique.

The experimental data showing the exotic nuclei, however, is limited to nuclei with proton numbers less than 50 at present. It is considered that there are no exotic nuclei for elements with Z larger than 50. One of the recent data is given in Fig. 2.11 and Table 2.3 for ${}^{32\text{–}35}_{12}$Mg [Kanungo 2011].

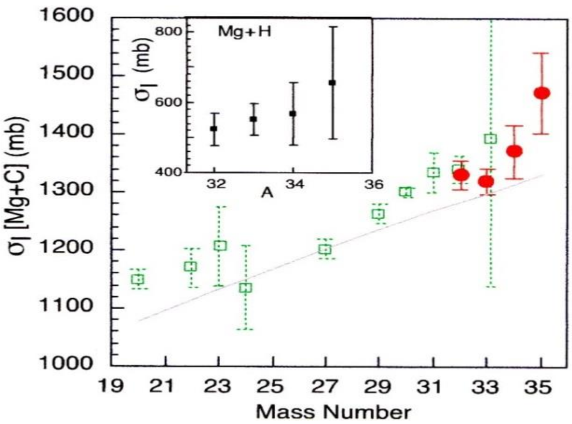


Fig. 2.11. (Color online) The measured interaction cross section for ${}^{32}_{12}$Mg – ^{35}Mg (circle) on a C target and (inset) on H [derived from a $(CH_2)_n$ target and C target data]. The open squares show data from Ref. [14] of [Kanungo 2011]. The line (normalized close to stability) shows the monotonic increase expected from an $A^{1/3}$ dependence on radii [Kanungo 2011].

Table 2.3. Measured interaction cross sections and the rms [R^{m}_{rms}(ex)] matter radii for ${}^{32\text{–}35}_{12}$Mg extracted from them are compared with the HF and RMF predictions . [Kanungo 2011]

Isotope	σ_I^C (mb)	σ_I^H (mb)	R^m_{rms} (ex) (fm)	HF [6][a] (fm)	RMF [20] (fm)
^{32}Mg	1331(24)	523(47)	3.17 ± 0.11	3.20	3.21
^{33}Mg	1320(23)	552(45)	3.19 ± 0.03	3.23	3.26
^{34}Mg	1372(46)	568(90)	3.23 ± 0.13	3.26	3.33
^{35}Mg	1472(70)	657(160)	3.40 ± 0.24	3.30	3.38

[a]The values are read from [6].

The situation will change largely if the nuclei are dipped in a free neutron sea, or cf-matter in the case of the CFP. It has not been tried theoretically to investigate possible existence of the exotic nuclei at medium mass numbers which we do usually encounter with in the CFP. We can imagine that the interaction of a nucleus and the free neutron sea stabilizes the nucleus in an extremely neutron rich state as a simulation done 40 years ago had shown [Negele 1973].

In a theoretical approach to solve riddles revealed in the CFP, the extended distribution of neutrons in hypothetical exotic nuclei with large excess of neutrons $N \gg Z$ was used to realize a situation in the CF-materials where neutron bands are formed by neutron-neutron interaction mediated by occluded hydrogen isotopes [Kozima 2006 Sec. 3.5.3.1]. The nuclear forces that hold these loosely bound systems together revealed by the investigation of exotic nuclei introduced above may have close relation to the super-nuclear interaction assumed in the TNCF model for the CFP. The CFP is most frequently observed in transition-metal deuterides and hydrides, especially in TiD_x (H_x), NiH_x (D_x), and PdD_x (H_x). Furthermore, these transition-metal nuclei have a common characteristic; existence of excited neutron levels near zero (evaporation levels) in an isolated nucleus, $3s_{1/2}$ in $^{A}{}_{22}Ti$ (A = 46 ~ 50), $3s_{1/2}$ in $^{A}{}_{28}Ni$ (A = 58 ~ 64), and $3p_{3/2}$ and $3p_{1/2}$ in $^{A}{}_{46}Pd$ (A = 102 ~ 110) as shown in Fig. 2.12 [Bohr 1969].

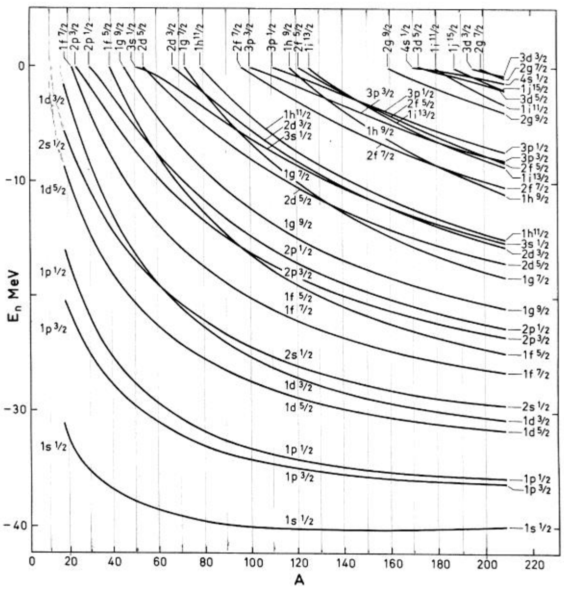


Fig. 2.12. Energies of neutron orbits calculated by C.J. Veje [Bohr 1969].

It is not known the relation of these excited neutron levels and the neutron halo in exotic nuclei at present even if we know that "Neutron-rich nuclei have shell structure different from their "stable" siblings and their proton-rich mirrors!" [Wiedenhover 2007]. From the viewpoint of the CFP, the relation should be very close and these neutron levels are contributing to the stabilization of the exotic nuclei of the corresponding nuclides. Therefore, the investigations on the CFP in PdH_x (D_x), TiD_x (H_x) and NiH_x (D_x) systems will give information about the neutron halo of exotic nuclei at lattice points, about the wavefunction of protons or deuterons at interstices, and about interaction of lattice nuclei and interstitial protons/deuterons.

2.8 Nuclear Cross Sections near Threshold for Neutrons

A nuclear (α, β) reaction shows certain characteristic properties when the channel energy of one of the partners, ε_α or ε_β, is very near zero [Blatt 1952 (Chap. 8)]. This is the situation we meet in the CFP and we cite the conclusions in this section.

Zero incident energy

Obviously, the reaction cross section $\sigma(\alpha, \beta)$ at $\varepsilon_\alpha \to 0$ is zero unless the reaction is exoergic: $Q_{\alpha\beta} > 0$. The cross section $\sigma(\alpha, \beta)$ for neutron-induced reactions for neutrons with $\ell = 0$ is given as

$$\sigma(\alpha, \beta) = \text{const. } \varepsilon_\alpha^{-1/2}, \text{ (for } \varepsilon_\alpha \to 0 \text{ in neutron induced reactions)} \quad (2.13)$$

which is the well-known $1/v$ law.

Zero outgoing energy

The asymptotic properties of $\sigma(\alpha, \beta)$ for $\varepsilon_\beta \to 0$ can also be stated in a similar form. This case occurs only if the reaction is endoergic: $Q_{\alpha\beta} < 0$. We get the cross section for neutrons with $\ell = 0$ (because most of the neutrons emerging at threshold have $\ell = 0$)

$$\sigma(\alpha, \beta) = \text{const. } \varepsilon_\beta^{1/2} \text{ (for } \varepsilon_\beta \to 0, \text{ outgoing neutrons)} \quad (2.14)$$

Elastic scattering

The asymptotic property of the elastic scattering for neutrons is given as follows in the same situation for the above cases;

$$\sigma(\alpha, \alpha) = \text{const. (for } \varepsilon_\alpha \to 0, \text{ elastic scattering of neutrons)} \quad (2.15)$$

The neutron scattering cross section approaches a constant value as the energy approaches zero.

2.9 Neutron Star Matter and Interaction of Nuclei with Neutron

An approach to nuclear phenomena somewhat different from those given above is the treatment of the neutron star matter (e.g. [Baym 1971, Negele 1973]). In this approach, nucleus is considered in its ground state at equilibrium with a free neutron gas outside. This is another valuable investigation to consider the situation appearing in the CFP from our point of view. Details of the relation between the CFP and the neutron star matter will be given in another paper [Kozima 2014b] presented in this Conference. We give here only interesting results obtained in nuclear physics in close relevance with the CFP. There are two features of the neutron star matter (NSM) related to the CFP; one is the interaction of a free neutron with an alien nucleus and another is the interaction of a nucleon cluster in the neutron star matter and an alien nucleus.

Baym et al. [Baym 1971] investigated the constitution of the ground state of neutron star matter and its equation of state in a regime from a density of 4.3×10^{11} g/ cm^3 (2.8×10^{35} nucleons/cm^3), where free neutrons begin to "drip" out of the nuclei, up to densities $\approx 5\times10^{14}$ g/cm^3 (3.4×10^{38} nucleons/cm^3), where standard nuclear-matter theory is still reliable in the free neutron regime by a compressible liquid-drop model. They estimated the energy of nuclei in the regime.

The main concern of their investigation is on the transition between the phase with nuclei and the liquid phase at higher densities. They found that nuclei survive in the matter up to a density $\approx 2.4\times10^{14}$ g/cm^3 (1.6×10^{38} nucleons/cm^3). The transition between the phase with nuclei and the liquid phase at higher densities occurs as follows: The nuclei grow in size until they begin to touch; the remaining inhomogeneity of the density smooths out with increase of the density until it disappears at about 3×10^{14} g/ cm^3 (2×10^{38} nucleons/cm^3) in the first-order transition. It is shown that the uniform liquid is unstable against density fluctuations below this density; the wavelength of the most unstable density fluctuation is close to the limiting lattice constant in the nuclear phase.

On the other hand, Negele et al. [Negele 1973] investigated the same problem using a simple form for the energy density of a nuclear many-body system. They constructed a reliable theory of a nucleon many-body system derived from the two-body nucleon-nucleon interaction. The relevant two-body correlations are incorporated in a two-body effective interaction, and the energy density is expressed as an extremely simple functional of the density and kinetic energy density via the density matrix expansion. Using the self-consistent Hartree-Fock calculation for the nuclear wave functions in a unit cell, they have determined the ground state configuration of matter at sub-nuclear density from lower densities of about 10^7 g/cm^3 (10^{31} nucleons/cm^3) up to 10^{14} g/cm^3 (10^{38} nucleons/cm^3) and also have shown the change of nucleus (nuclear cluster) surrounded by a dilute neutron gas: As the baryon density is increased, nucleus become progressively more neutron rich until neutrons eventually escape, yielding a Coulomb lattice of bound neutron and proton clusters (nucleon clusters) surrounded by a dilute neutron gas. The clusters enlarge and the lattice constant decreases with the increasing density.

One of the most striking features of their results is the degree to which the nuclei (nuclear clusters) in the free neutron regime resemble ordinary nuclei; the usual shell model level sequence is maintained throughout the free neutron regime and the interior nuclear density does not deviate significantly from the density of ordinary nuclei.

It should be noticed that the neutron density fluctuations at the low density region diminishes as the number of neutrons becomes sufficiently large and one approaches a statistical regime. In the application of their results to the situation in the CFP, we have a freedom to relax the condition to meet the actuality in the experimental data. The variety of the nuclear products in the CFP may have close relation to this fluctuation in the neutron density.

We may extrapolate the result to the rather lower densities of about 10^{10} nucleons/cm^3 in the CFP to obtain the Fig. 2.13.

From this oversimplified figure, we can guess the Z/A ratio is about 0.48 at $\log n_b = 10$ which will be used in the discussion of the CFP in the next papers [Kozima 2014a, 2014b].

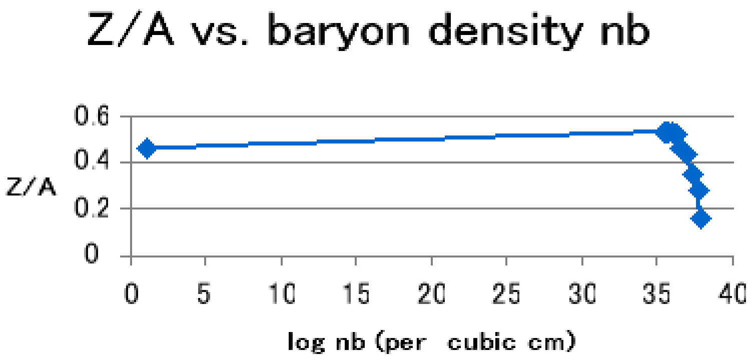


Fig. 2.13 Z/A vs. baryon density n_b (cm^{-3}) after Negele et al. [Negele 1973 Table 3]. The data of normal nuclei is taken as $\langle Z/A \rangle = 0.46$ at log $n_b = 1$.

The investigation of the neutron star matter introduced above [Baym 1971, Negele 1973] has been done assuming a thin free neutron gas in homogeneous space increasing the density of the gas up to about 1.6×10^{38} nucleons/cm^3 where the system becomes homogeneous neutron star. There is a serious problem to ask what occurs in the above system when there is a solid lattice of nuclei in addition to the thin free neutron gas. This problem will be a key to investigate the events observed in the CFP and be taken up in our following paper [Kozima 2014b].

In the CFP, the neutron density estimated with various experimental data sets ranges from 10^6 to 10^{13} nucleons/cm^3 if we use usually used cross sections for neutron-nuclear interaction in nuclear physics [Kozima 2006]. These values of the neutron density are rather small compared to the minimum value (10^{31} nucleons/cm^3) used by Negele et al. [Negele 1973] in their investigation of the neutron star matter. This point will be discussed in detail in another paper presented at this Conference [Kozima 2014b].

Nuclear Boundary Surface between a Nucleus and the Free Neutron Gas

The boundary surface between a nucleus with a neutron density n_i and the surrounding neutron gas with a neutron density n_o is schematically depicted in Fig. 2.14 after Baym et al. [Baym 1971].

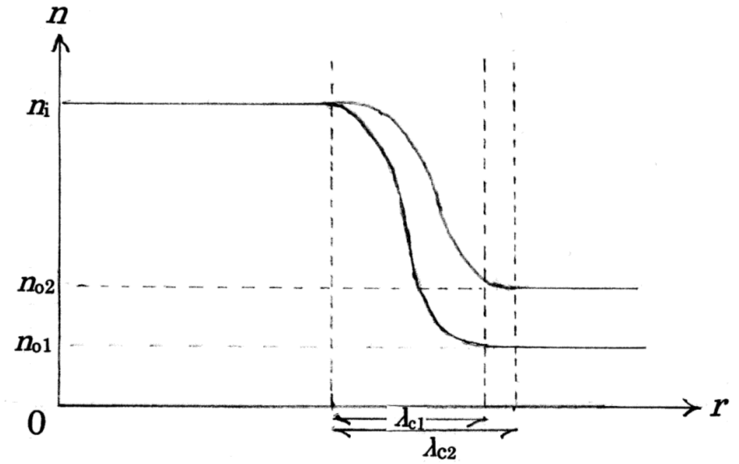


Fig. 2.14. Schematic distribution of neutron density n along an outward straight line r from the center of the nucleus. Two cases for different values of neutron density of the neutron sea n_o are plotted to illustrate the dependence of boundary surface on the density ratio n_o/n_i (cf. Eq. (2.18)).

The total surface energy per unit area of the boundary layer, E_{surf}, is calculated by Thomas-Fermi approximation and is proportional to $(n_i - n_o)^{3/2}$;

$$E_{surf} = C(n_i - n_o)^{3/2} = Cn_i^{3/2}(1 - n_o/ n_i)^{3/2} \quad (2.16)$$

with a constant C [Baym 1971]. The dependence of E_{surf} (= y) on the density ratio n_o/ n_i (= x) is plotted in Fig. 2.15.

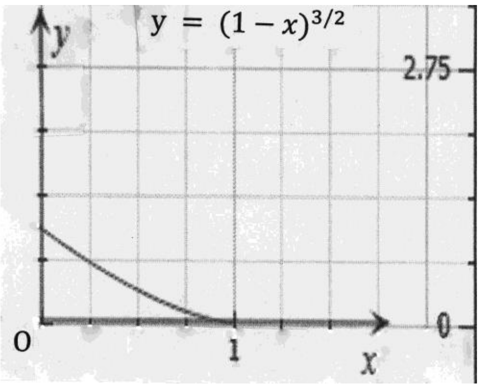


Fig. 2.15. Dependence of the surface energy E_{surf} (= y) on the density ratio n_o/n_i (= x).

The surface thickness λ_c is directly proportional to k_c^{-1}, with k_c the momentum of the nucleons just at the top of the square-well potential used for the order of magnitude estimation, which is given by the density of neutrons in the nucleus, n_i, and that of the free neutron gas outside the nucleus, n_o [Baym 1971、Eq. (4.27)]

$$k_c^3/1.5\, n_i^2 = n_i - n_o. \qquad (2.17)$$

Using the ratio $\eta \equiv n_o/n_i$ of neutron densities at outside to that at inside the nucleus, the thickness of the surface λ_c is written as

$$\lambda_c = C\,(n_i)^{-1/3}\,(1-\eta)^{-1/3}, \qquad (2.18)$$

where C is a constant of an order of magnitude 1. Dependence of λ_c on η ($\equiv n_o/n_i$) is plotted in Fig. 2.16 as a dependence of y (λ_c) on x (η) $\equiv x(n_o/n_i)$.

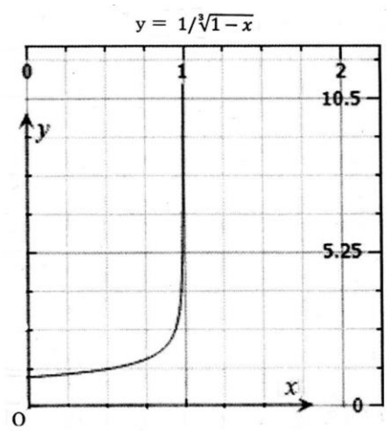


Fig. 2.16. Graph of $y = (1-x)^{-1/3}$ where $y \equiv \lambda_c$ and $x \equiv n_o/n_i$. The graph of this figure between $x = 0$ and 1 corresponds the thickness λ_c (2.18) of the surface boundary showing a weak dependence of λ_c on the density ratio $\eta \equiv n_o/n_i$ at small η and drastic decrease at $\eta \le 1$.

The weak dependence of the thickness λ_c on the density ratio $\eta \equiv n_o/n_i$ at small η ($\equiv n_o/n_i$) depicted in Fig. 2.14 suggests that the treatments in the phenomenological approach used in the TNCF model are meaningful if the extrapolation of the method used by Baym et al. [Baym 1971] is applicable to the case of the CFP ($n_o \sim 10^8 - 10^{12}$ cm^{-3}) where the density ratio η is supposed to be about $10^{10}/10^{38} = 10^{-28}$.

A possible result of the existence of surface boundary with a surface energy E_{surf} and a thickness λ_c between nuclear matter in the nucleus and outside neutron sea may be related to the acceleration of alpha decay (or the decay-time shortening) of a quasi-stable radioactive nuclei by formation of neutron star matter (or the cf-matter in the case of the CFP) surrounding them [Kozima 2014a, 2014b]. The nucleon cluster ${}^4_2\Delta$ formed in the nucleus transmits through the boundary, the probability of which depends on $\eta \equiv n_o/n_i$, resulting in alpha-decay of the nucleus.

The penetration factor P through a barrier is given by a formula [Schiff 1968];

$$P = \exp[-2 \int_{r1}^{r2} \kappa (r)\, dr], \qquad (2.19)$$

$$\kappa(r) = (2n/h)\{2m[V(r) - E\ ]\}^{1/2} \qquad (2.20)$$

The integrand of the equation (2.19) or the function (2.20) is proportional to the square root of potential energy looked up by the incident energy. The total energy of the boundary surface between a nucleus and the free neutron gas (2.16) serves to this probability for the penetration of a nucleon cluster ${}^4_2\Delta$ through the boundary.

Existence of the cf-matter outside the nucleus in the CF-material means $n_o \neq 0$. Then, the equation (2.19) suggests us that the decay-time shortenings of uranium [Dash 2003] and thorium [Monti 2005] are explicable in accordance with other events observed in the CFP with the formation of cf-matter in the CF-materials [Kozima 2014a, 2014b].

3. Conclusions

Since the discovery of the neutron by Chadwick in 1932, the neutron played the leading character together with the proton, which was found in 1918, in the physics of the atomic nucleus. Due to the characteristics of the neutron without electric charge and instability in free space with the lifetime of 887 s [Caso 1998], the neutron has been a riddle for 80 years revealing its entity little by little until now. At first, the nuclear force, describing the interaction of a neutron with a proton and another neutron, was the central problem and solved by introduction of a new particle, pion. It was considered the nuclear force is charge independent, i.e. the same between two nucleons, proton or neutron.

Progress in the nuclear physics has revealed a new phase of the neutron; characteristic of neutron-neutron interaction in exotic nuclei [Kanungo 2011, Lu 2013]. There are raised such questions on the properties of the neutron and their effects on the nucleus [Wiedenhover 2007].

1) Very neutron-rich nuclei are expected to exhibit diffuse surfaces which lead to a reduced spin-orbit coupling and “melting” of the shell structure.

2) Many examples for modification of shell structure in neutron-rich nuclei are known (N, Z<50).

3) What may be the more interesting question: What are the collective

excitations of neutron matter?
4) What is the neutron-wavefunction? Pair transfer $^{16}C(p,t)^{14}C$ (+γ?).
5) Neutron-rich nuclei have shell structure different from their "stable" siblings and their proton-rich mirrors!
6) New collective excitations have to be expected: Neutron-only collectivity?
In conclusion, we have to say that physics of the neutron is not completed yet but on its way of progress. In addition to these new developments around the neutron in the nuclear physics, we can add another feature of the neutron revealed in the solid-state nuclear physics. The cold fusion phenomenon (CFP), or phenomenon based on solid-state nuclear reactions, asked explanation of curious events solved only by nuclear reactions in room-temperature solid hydrides and deuterides (CF-materials). Due to absence of any acceleration mechanism to excite relevant particles over 1 keV, we have to make a supposition that there is the participation of neutrons in the events observed in the cold fusion phenomenon (CFP). Evidence of the participation of neurons have been obtained in experiments [Kozima 2006, Sec. 2.2.1.4] and the problem is proposed as how it is possible neutrons to exist and react with other nuclei in the system (CF-materials we named) resulting in various events in the CFP.
A phenomenological model was proposed where existence of neutrons with a density of around 10^{10} cm^{-3} (cf-matter) was assumed a priori in the CF-materials. The existence of such a neutron in CF-materials (mainly transition-metal hydrides and deuterides) has been investigated quantum mechanically using knowledge of metal hydrides obtained in solid state physics and of neutron halos obtained in nuclear physics [Kozima 2006, Sec. 3.7.5].
As has been discussed in our books and papers [Kozima 2004, 2006, 2008, 2013], the CFP is explained qualitatively and sometimes semi-quantitatively by our phenomenological model (the TNCF model). The model has been investigated quantum mechanically and the premises of the TNCF model have principally been explained by the formation of neutron bands due to the super-nuclear interaction, interaction between lattice nuclei mediated by interstitial hydrogen isotopes. The novel knowledge of exotic nuclei gives a strong support for the realization of the super-nuclear interaction due to the extended distribution of neutron

wavefunctions in them. If the cf-matter is realized by the formation of neutron bands, then the elaborate works on the neutron star matter give us a tool to explain various nuclear reactions necessary to explain experimental facts such as the decay-time shortening and nuclear fission of medium mass-number nuclei in CF-materials at near room temperature.
If the scenario depicted in the investigation of the cf-matter in the CF-materials be realistic, we may have a new development of neutron physics in solids with a high density of hydrogen isotopes (CF-materials). By the way, the existence of the cf-matter should be related with new phenomena, a part of which may be the CFP, in physics of metal hydrides. The physics of metal hydrides has been investigated for more than 100 years and is a central theme in relation to the hydrogen storage for applications. The CFP is a phenomenon closely related to the developing fields of nuclear physics and also solid state physics and gives us a perspective interesting enough to explore new physics of neutrons in solids not known until now.

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