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Neutron Band, Neutron Cooper Pair and Neutron Life Time in Solid

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ABSTRACT

Quantum state of low energy neutrons in solid is investigated in relations with cold fusion and nuclear transmutation. Neutrons in a crystal lattice interacting with nuclei on the lattice points have an energy spectrum with band structure. In one-dimensional Kronig-Penny model with lattice parameter a, the lowest energy band has the minimum at wave number vector of $\pm\pi/a$ with an energy $E_{\pi/a}$. A neutron Cooper pair with an energy lower than $2E_{\pi/a}$ is formed from two neutrons in the lowest energy states with wave vectors $k = \pm\pi/a$ and spins $\pm 1/2$.

Furthermore, stability of a neutron in a crystal lattice is estimated in an approximation with the following assumption: The energy difference between a neutron and a decayed state of the neutron, i.e. a proton, an electron and a neutrino, in a crystal lattice is equal to the averaged energy difference $< \Delta\varepsilon >$ between averages of neutron-in-nucleus and proton-in-nucleus states.

When the energy difference $< \Delta\varepsilon >$ is negative, the neutron in the crystal is stable against beta decay and is free from destiny of decay with life time 11 minutes in the free state.

1. Introduction

After the discovery of the excess heat supposed to be due to the cold fusion (CF), various facts have been disclosed in materials containing a lot of hydrogen isotopes. A common key materials are, of course, hydrogen isotopes, i.e. hydrogen H and deuterium D.

At first, only deuterium had been used for CF and hydrogen was considered inactive and stable against fusion and has been used even for reference system to check CF events. The situation changed very much to recognize that hydrogen H is also responsible for the CF phenomenon.

Change is also occurred in the type of the state of hydrogen isotopes existing in CF materials. Originally, only metal hydrides have been used but now there are many compounds including proton conductors, oxide superconductors and other compounds which can absorb much hydrogen isotopes and also compounds which contain hydrogen isotopes as one of its components like KD_2PO_4.

It is also noticed that nuclear transmutation occurs in metallic electrodes when electrolysis of light or heavy water takes place or discharge in hydrogen gas or deuterium gas occurs. In the nuclear transmutation, elements and/or isotopes with larger mass number than 5 not exist before were observed after the experiment. Excess heat production is accompanied with the nuclear transmutation. It is reasonable from our point of view to include this phenomenon, nuclear transmutation, into CF as one of its phenomena.

It is recognized that unstable or non-equilibrium state is indispensable to realize CF phenomenon in any system. To realize unstable states, it is used compound structures of sample with multi-components, variations of electrolysis voltage, sample temperature and gas pressure, etc. It is remarkable that in ferroelectrics and superconductors CF phenomenon occurs only in transition temperature domain.

There is also variety of CF products; in addition to the initially observed large excess heat, there are neutrons with various amounts and energies, tritium with various amounts, sometimes ^{4}He, gamma ray, X-ray, proton, other nuclear products, transmuted nuclei etc.

One of the most distinguished characteristics of these events in CF is its low reproducibility. Though efforts of sincere researchers improved its qualitative reproducibility, and therefore statistical reproducibility, the quantitative reproducibility expected for single-particle phenomena is not exist in CF phenomenon suggesting its statistical nature.

In any theory of CF, it is necessary to find out a missing factor (MF) as an indispensable member which is not recognized in Physics until now and is responsible for CF phenomenon. It is commonly recognized that the MF for CF has not been found till now, even though there are differences in recognition whether it will change some of existing principles or it will be deduced from them.

The present author has chosen the latter way in constructing TNCF model because he believes in fundamental principles of present Physics. In this paper, new physics of low energy neutrons in crystal are presented in a trial to interpret CF phenomenon consistently in TNCF model in its recent version. The MF in the model is only the trapped neutron without any change in physical principles. Mechanism to trap neutron in crystal lattice rests on the undeveloped physics of "neutrons - 'lattice nuclei' system" interacting with nuclear force and will be discussed in Sections 2 ∼ 5.

2. Neutron Energy Band in Crystal Lattice

A neutron with mass m and de Broglie wave length comparable with lattice constant of the crystal behaves as a wave and interacts with nuclei on the lattice points (lattice nuclei) through nuclear force. The interaction could be treated approximately by Fermi pseudo-potential (zero-radius potential)

$$V(r) = \frac{2\pi\hbar^2 b}{m}\frac{\delta(r)}{r^2} \qquad (1)$$

with b a non-dimensional parameter. The wave function of the neutron will be calculated with Wigner-Seitz method by solving an equation

$$\{-\frac{\hbar^2}{2mr^2}\frac{\mathrm{d}}{\mathrm{d}r}(r^2\frac{\mathrm{d}}{\mathrm{d}r}) + V(r)\}\psi(r) \;=\; E\psi(r) \tag{2}$$

subject to a boundary condition

$$(\frac{\partial\psi}{\partial r}) \;=\; 0, \qquad (\text{at } \; r \;=\; r_0) \tag{3}$$

where r_0 is the radius of the so-called s–sphere having the same volume as the atomic volume of the crystal.

To illustrate the essential point of this treatment, we have calculated the energy band structure of a neutron with mass m in the one dimensional Kronig-Penny lattice with lattice constant a and delta-function potential:

$$V(x) \;=\; -\frac{\hbar^2 P}{ma}\delta(x+na), \qquad (n \;=\; 0,\; \pm1,\; \pm2,\cdots) \tag{4}$$

where P is a constant proportional to the intensity of the attractive potential (width × depth). The energy E of the neutron with wave vector $\vec{k}$ in this crystal is determined by an equation[1)]

$$-P\frac{\sin\alpha a}{\alpha a} + \cos\alpha a \;=\; \cos ka \tag{5}$$

where $\alpha \;=\; (2mE/\hbar^2)^{1/2}$. Band structure of this energy spectrum is plotted in Fig. 1 in the reduced zone scheme ($-\pi \;\leq\; ka \;\leq \pi$)[2,3)]. The value of P is assumed arbitrarily as $3\pi/2$ which corresponds to a square well potential with depth 2×10^{6} eV and width 10^{-13} cm. Increase of the parameter P makes the width of the allowed band narrower. The energy of the edge of the lowest energy band is inversely proportional to the square of the lattice constant a^2 and is 2.04 × 10^{-2} eV for $a = 10^{-8}$ cm. It is interesting to notice that the minimum is at $ka \;=\; \pm\pi$ and the energy of this band edge is somewhat lower than the thermal energy at room temperature (300 K) for a lattice with lattice constant 2 ∼ 3 Å.

On the other hand, the wave function of the neutron in the band has a large amplitude at lattice points where are centers of the attractive potential.

So, the neutron in a crystal has an energy band structure with the lowest minimum at large k and localized probability amplitude at lattice nuclei.

3. Neutron Cooper Pair in Solid

It was shown above that neutrons interacting with nuclei on the lattice points (lattice nuclei) has an energy spectrum with band structure in a Kronig-Penny model with an attractive δ - function type potential (Fig. 1). When a solid has a sandwich structure with different lattice constants, a part of neutrons in a domain with large lattice constant is Bragg reflected at the boundary between small lattice constants and is trapped there.

As the neutron in the crystal lattice interacts with phonons, it is reasonable to assume that a trapped neutron interacts with other neutrons through neutron-phonon interaction as in the case of electrons in BCS theory of superconductivity.

As is well known in the theory of superconductivity, the Cooper pair was a key point to solve the historical problem. The calculation for the neutron Cooper pair in a situation where we are most interested in goes parallel to that for the electrons given in textbooks[4]. Difference is just in the distribution of particles on the energy levels except Coulomb repulsion between electrons; electrons are in degenerate Fermi distribution with definite Fermi energy while neutrons are in non-degenerate Boltzmann distribution because of its low density in our problem.

The model calculation of the neutron band given above shows that the minimum energy of the lowest band is at large $\vec{k}$. This situation facilitates to form neutron Cooper pair even if density of neutrons is very low. So, it is interesting to formulate the problem of neutron Cooper pair along the line well known in the theory of superconductivity.

With similar calculation to that given in the textbook[4], we can obtain an energy decrease Δ due to the neutron Cooper pair formation as follows:

$$\Delta = \frac{2\omega_D}{e^{1/\rho_m V} - 1}, \tag{6}$$

where ω_D is the Debye angular frequency of the crystal, ρ_m is the state density of the lowest neutron band at its bottom, V is a positive constant related with neutron-neutron interaction through neutron-phonon interaction. This is the binding energy of a neutron Cooper pair with respect to the bottom of the lowest band.

Thus we have found that for V positive (attractive interaction) the energy of the system becomes lower by making a pair of neutrons in the bottom of the lowest band, therefore , the one neutron band is unstable. This instability modifies the neutron band structure in an important way to stabilize the neutron against beta decay forming many pairs in the crystal and also inducing Bose condensation.

4. Neutron Affinity of an element — Neutron Life Time in Solids and a Role of Lithium in Electrolyte

It is known that a neutron in its free state decays into a proton with a decay constant $\lambda = 1/\tau = 1.5 \times 10^{-3}\ \mathrm{s}^{-1}$ and decay energy $\sim +\ 0.782$ MeV emitting an electron and a neutrino. The average life time τ of the neutron is, therefore, 11 minutes. On the other hand, the neutron in a deuteron interacting with a proton in it, for instance, is stable because the deuteron has lower energy than the state where there is two protons, an electron and a neutrino by an amount 1.44 MeV.

We have given a prediction[2] that the life time of a neutron in a neutron Bloch band interacting with lattice nuclei might be elongated by the same cause as that makes the neutron in the deuteron stable. To treat this problem physically, we made an assumption that the interaction of a neutron Bloch wave and lattice nuclei is approximated by a mean value of individual interaction of a neutron and each nucleus on the lattice point[5,6].

A neutron in a lattice of nuclei with mass ${}^{A}{}_{Z}M$ is stable if the neutron affinity $\eta \equiv -\Delta\varepsilon$

of the nucleus defined below is positive in this approximation, :

$$\eta \equiv -\Delta\epsilon \equiv -({}^{A+1}_{Z}M - {}^{A+1}_{Z+1}M)c^2.$$

Therefore, it is possible to say that the larger the neutron affinity of a nucleus interacting with a neutron, the more stable the neutron is against beta disintegration.

Then, for example, the stability of a neutron Bloch wave interacting with ${}^{106}{}_{46}$Pd nucleus is estimated by taking an energy difference $\Delta\epsilon$ of two states ${}^{107}{}_{46}$Pd and ${}^{107}{}_{47}$Ag.

The average value of $\Delta\epsilon$ over elements, i.e. the average neutron affinity of the elements $<\eta> = -<\Delta\epsilon>$, were calculated using natural abundances of the elements and tabulated in Table 1.

Using values of neutron affinity $<\eta> = -<\Delta\epsilon>$ given in Table 1, it is possible to calculate the corresponding value for compound materials showing Cold Fusion phenomenon. The calculated values are given in Table 2.

From the values of the neutron affinity $<\eta>$ given in Tables 1 and 2, it is possible to deduce a conclusion that the assumption about the stability of a neutron trapped in material is consistent with experimental results obtained hitherto in various materials i.e. materials with the large neutron affinity are preferable for cold fusion.

It is also interesting to investigate an experimental fact that Li is necessary to use in electrolysis from the point of the neutron affinity. As is seen from Table 1, the neutron affinity of Li is negative and its absolute value is tremendously large ($\sim$ 15). If there is a layer of Li or LiPd compound on a surface of Pd metal, neutron is reflected effectively at the boundary because of the large difference of neutron affinity of two materials forming the border. Therefore, the role of Li is possible to interpret confining neutrons in palladium metal effectively.

5. Neutron Mössbauer Effect

Another effect relevant with behavior of low energy neutrons in solid is the neutron Mössbauer effect.

The physical meaning of the Mössbauer effect had been discussed thoroughly and the essential points were formulated as described in text books[7,8].

When phonons are distributed according to the canonical distribution at temperature T, the probability f of recoilless emission of a particle from a nucleus is given as follows[6];

$$f = \exp\{-\frac{K^2}{3} < u^2 >_T\}, \tag{7}$$

where $-\vec{K}$ is the momentum of emitted particle and $\vec{u}$ is the displacement from equilibrium of the emitting nucleus with mass M. It should be noticed that this expression is independent of the mechanism taking place in the nucleus emitting the particle, i.e. photon, neutron, or other particles.

For a temperature T lower than the Debye temperature Θ of the crystal ($T \ll \Theta$),

$$\frac{1}{3}K^2 < u^2 >_T = \frac{3R}{2k_B\Theta}\{1 + \frac{2\pi^2}{3}(\frac{T}{\Theta})^2\}, \tag{8}$$

where $R = K^2/2M$ is the free atom recoil energy of the nucleus and k_B is Boltzmann constant.

Finally, we obtain an expression for the probability

$$f = \exp[-\frac{3R}{2k_B\Theta}\{1+\frac{2\pi^2}{3}(\frac{T}{\Theta})^2\}]. \tag{9}$$

Relevant quantities for several metals are given in Table 3.

A neutron with an energy, ε, can be absorbed and emitted by a nucleus in a lattice if the nucleus has a resonance absorption level at ε according to the Mössbauer mechanism similar to the recoilless absorption and emission of a photon by a nucleus in the crystal. A neutron with an energy, $\varepsilon_s = 5.33$ eV, has the same momentum as that of a photon with energy 100 keV which corresponds to the photon used in the Mössbauer resonance technique. Thus, the ordinary crystal can be bearable to the neutron Mössbauer effect for neutrons with energy less than few eV including thermal one (0.025 eV).

To estimate the probability of recoilless emission of a neutron, we will compare it with a standard probability of recoilless emission of a photon with energy $h\nu = 100$ keV from ^{57}Fe nucleus with mass M_s (denoting relevant standard quantities with suffix s). The probability Eq. (9) of recoilless emission of a thermal neutron from a nucleus with mass, M, is rewritten as follows:

$$f = f_s^{(R/R_s)}, \tag{10}$$

$$f_s = \exp[-\frac{3R_s}{2k_B\Theta}\{1+\frac{2\pi^2}{3}(\frac{T}{\Theta})^2\}]. \tag{11}$$

In the above equations, R_s is the recoil energy when a neutron with mass m_n and energy $\varepsilon_s = 5.33$ eV is emitted from ^{57}Fe nucleus in the free state; $R_s = m_n\varepsilon_s/M_s = 9.4 \times 10^{-2}$ eV (Table 3).

The numerical relation between f and f_s for the metals tabulated in Table 3 is

$$\ln f \simeq 10^{-3}\ln f_s. \tag{12}$$

This relation shows that f is very close to 1 for the ordinary situation where Eq. (8) is applicable. So, when one of these nuclei in a crystal emits or absorbs a neutron with energy of the order of or less than the thermal one, the process is essentially recoilless.

6. TNCF model of Cold Fusion

If we assume stable trapping of neutrons in a crystal as explained in previous sections, we could explain CF phenomenon from low reproducibility to various products in various materials[9~14] including systems with light water[15] consistently in TNCF model.

6 - 1. Fundamentals of TNCF model

A trapped neutron in a material containing hydrogen isotopes fuses with one of hydrogen isotopes to emit a high energy particle and a photon. The reaction works for CF phenomenon as a trigger ("trigger reaction");

$$\begin{aligned} n+p &= d\,(1.33\ \text{keV}) + \gamma\,(2.22\ \text{MeV}), &(13)\\ n+d &= t\,(6.98\ \text{keV}) + \gamma\,(6.25\ \text{MeV}), &(14)\end{aligned}$$

The produced high energy particles d or t in these trigger reactions can accelerate hydrogen isotopes in the material successively by elastic collisions or can fuse with them according to following reactions. The accelerated hydrogen isotope fuses together to generate particles and excess energy. ("breeding reactions");

$$\begin{aligned} p+d &= {}^{3}\text{He}\,(5.35\ \text{keV}) + \gamma\,(5.49\ \text{MeV}), &(15)\\ d+d &= {}^{3}\text{He}\,(0.82\ \text{MeV}) + n\,(2.45\ \text{MeV}), &(16)\\ &= t\,(1.01\ \text{MeV}) + p\,(3.02\ \text{MeV}), &(17)\\ &= {}^{4}\text{He}\,(76.0\ \text{keV}) + \gamma\,(23.8\ \text{MeV}), &(18)\\ t+d &= {}^{4}\text{He}\,(3.5\ \text{MeV}) + n\,(14.1\ \text{MeV}), &(19)\\ d+{}^{3}\text{He} &= {}^{4}\text{He}\,(3.67\ \text{MeV}) + p\,(14.7\ \text{MeV}), &(20)\end{aligned}$$

Those "breeding reactions" generate excess energy and reaction products, the amount of them depending on the situation in the material. The situation is determined by stochastic processes occurring in the sample and makes the reproducibility of the phenomenon very low.

Trigger reactions (13) and (14) work just to ignite following chain breeding reactions (15) $\sim$ (20) and therefore the numbers of events of trigger reactions might be small compared with those in the breeding reactions on the optimum situation. This makes the number of photons expected to come out from the reactions (13) and (14) so small that it is difficult to observe them.

There will be many reactions between trapped neutron and nuclei in a sample material resulting in nuclear transmutation. In simplest series of reactions, any element ${}^{A}{}_{Z}M$ in materials can be transformed into another element ${}^{A+1}{}_{Z+1}M$ by absorption of a neutron and a successive β decay:

$$ {}^{A}_{Z}M + n \rightarrow {}^{A+1}_{Z}M \rightarrow {}^{A+1}_{Z+1}M + e^{-} + \nu_e. \qquad (21)$$

6 - 2. Several facts on the role of background neutrons:

There are several experimental results on the role of low energy neutrons.

a. Null results without background neutrons.

There are many experimental results which show null result[16,17] without background neutron. Negativists against CF rest on these results along with low reproducibility to deny CF.

b. Effects of background neutron.

There are several results[18~21] showing that the background or artificial thermal neutron induces CF products.

6 - 3. Explanation of the low reproducibility of CF events by TNCF model

The condition to trap neutrons which induce trigger reactions (13) and (14) is dependent upon stochastic processes in the material[9]. The condition for effective occurence of chain breeding reactions (15) to (20) is also dependent upon stochastic processes in the material[10,11]. These stochastic processes are out of our control even if we set adjustable parameters at definite values. This is the origin of the low reproducibility of CF events though sincere efforts improved reproducibility very much[21~24].

6 - 4. Observation of high energy photons

In relation with observation of 2.22 and 6.25 MeV photons expected to be generated in trigger reactions, it is remarked that there are only a few data[24~28] observed them. These data were obtained in "dry experiment" (without water) except one "wet experiment" (in water)[25].

7. Conclusion

The physics of the low energy neutron has been developed in relation with the structural analysis of matter and control of the atomic pile. New features of behavior of neutrons in crystals presented in sections 2 to 5 in this paper give a profound field where the solid state - nuclear physics will flourish.

The change of life time of neutrons in solids discussed in Section 4 using the concept of neutron affinity has indirect support from an experiment in which the change of radioactivity of tritium in materials[29] was concluded.

The TNCF model is indirectly supported from well known facts that it is necessary sometimes to continue a process of deuteron occlusion for several months to get CF phenomenon[25,30]. This long term is considered usually necessary to elevate deuteron density. It is, however from our point of view, rather to pile up of background neutrons for the trigger reaction.

Though various new discoveries[21,31,32] in CF have been reported in a couple of years, it might be useful for the development of research to give an unified interpretation for fundamental results from one point of view.

There are many experimental results which show nuclear transmutation in solid[33~37]. These data could be explained with use of trapped neutrons explained in this paper.

The unified interpretation based on TNCF model given in this paper assumes a common mechanism for CF phenomenon observed in various materials. It is, of course, possible to assume differently that various mechanisms are responsible for various events observed in various materials.

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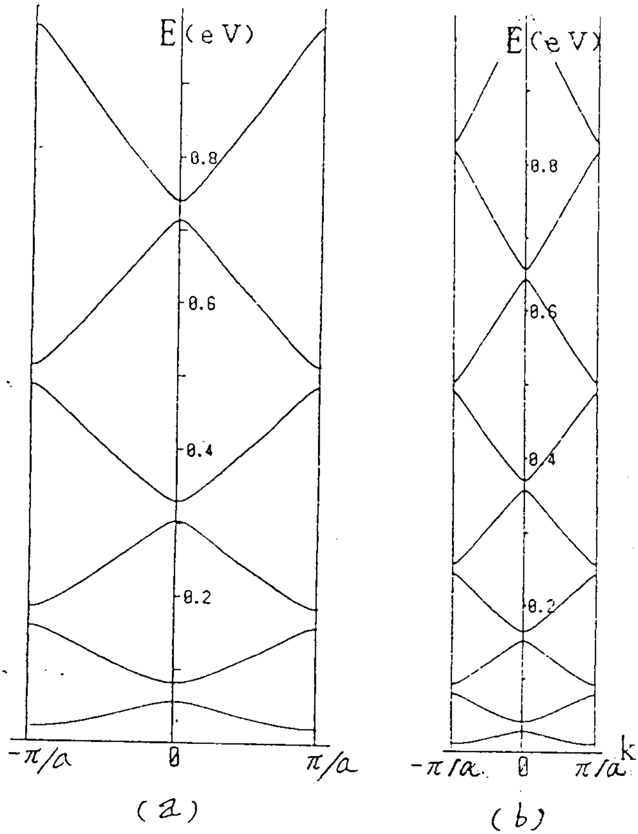

Fig. 1 Energy bands of low energy neutron in one-dimensional solid with lattice constant a. Kronig - Penny attractive potential with zero width limit is used. The parameter $P = 3\pi /2$, $a =$ (a) 10^{-8}, (b) $\sqrt{2} \times 10^{-8}$ cm.

Table 1: Average energy differences, $<\Delta\epsilon> \; = - \; <\eta>$ (MeV) of elements between two nuclear states interacting with neutron Bloch wave and with proton Bloch wave averaged over isotopes with natural abundance. *)The value for Li was calculated with an assumption $^{8}_{4}$Be = 2 $^{4}_{2}$He because of the absence of $^{8}_{4}$Be in nature.

$_{1}$H −2.224	$_{1}$D 0.0186									
$_{3}$Li 14.8*	$_{4}$Be 0.555	$_{5}$B 10.31	$_{6}$C −2.20	$_{7}$N −2.71	$_{8}$O −2.66	$_{9}$F 7.02				$_{10}$Ne −2.8
$_{11}$Na 5.51	$_{12}$Mg −3.484	$_{13}$Al 4.64	$_{14}$Si −4.71	$_{15}$P 1.71	$_{16}$S −5.32	$_{17}$Cl 1.74				$_{18}$Ar 2.46
$_{19}$K 1.462	$_{20}$Ca −6.302	$_{21}$Sc 2.37	$_{22}$Ti −0.959	$_{23}$V 3.97	$_{24}$Cr −0.707	$_{25}$Mn 3.70	$_{26}$Fe −1.01	$_{27}$Co 2.82	$_{28}$Ni −3.87	$_{29}$Cu 1.212
	$_{30}$Zn −1.77	$_{31}$Ga 2.58	$_{32}$Ge −0.055	$_{33}$As 2.97	$_{34}$Se 0.735	$_{35}$Br 2.54				$_{36}$Kr 0.850
$_{37}$Rb 2.75	$_{38}$Sr 0.780	$_{39}$Y 2.29	$_{40}$Zr −0.597	$_{41}$Nb 2.06	$_{42}$Mo −0.730	$_{43}$Tc	$_{44}$Ru −0.563	$_{45}$Rh 2.47	$_{46}$Pd −0.264	$_{47}$Ag 2.241
	$_{48}$Cd −0.0125	$_{49}$In 3.22	$_{50}$Sn −0.641	$_{51}$Sb 2.37	$_{52}$Te 1.17	$_{53}$I 2.12				$_{54}$Xe −0.6
$_{55}$Cs 1.99	$_{56}$Ba 1.22	LN	$_{72}$Hf −0.555	$_{73}$Ta 1.79	$_{74}$W 0.606	$_{75}$Re 1.734	$_{76}$Os 0.0474	$_{77}$Ir 1.952	$_{78}$Pt − 0.27	$_{79}$Au 1.38
	$_{80}$Hg −0.588	$_{81}$Tl 1.312	$_{82}$Pb − 0.912	$_{83}$Bi 1.16	$_{84}$Po	$_{85}$At				$_{86}$Rn
	$_{87}$Fr	$_{88}$Ra	$_{89}$Ac							
$_{57}$La 3.77	$_{58}$Ce 0.66	$_{59}$Pr 2.16	$_{60}$Nd −0.354	$_{61}$Pm	$_{62}$Sm −0.364	$_{63}$Eu 1.90	$_{64}$Gd −0.151	$_{65}$Tb 1.835	$_{66}$Dy −0.151	$_{67}$Ho 1.863
$_{68}$Er −0.350	$_{69}$Tm 0.969	$_{70}$Yb −0.152	$_{71}$Lu 1.17							
$_{90}$Th −1.239	$_{91}$Pa	$_{92}$U 1.285								

Table 2: Average energy differences $<\Delta\varepsilon> = - <\eta>$ of compounds between two nuclear states interacting with neutron Bloch wave and with proton Bloch wave averaged over isotopes with natural abundance:

Substance	$SrCeO_3$	$LaNi_5$	KD_2PO_4	$YBa_2Cu_3O_7$	$Na_{0.9}WO_3$
$<\Delta\varepsilon>$ (MeV)	-1.67	-1.633	-0.926	-0.788	-0.604

Table 3: Some constants of metals relevant with recoilless emission of neutron. The value of R in Eq.(2) is given for a emission of a neutron with thermal energy 0.025 eV and a constant defined in Eq.(4) $R_s = 9.4 \times 10^{-2}$ eV.

	Iron (Fe)	Titanium (Ti)	Nickel (Ni)	Palladium (Pd)
Θ (K)	355	413	430	275
$k_B\Theta$ (10^{-2} eV)	2.9	3.4	3.6	2.3
$R_s/k_B\Theta$	3.2	2.8	2.6	4.1
M/m_n	57	48	59	106
M_s/M	1	1.19	0.97	0.54
R ($\times 10^{-4}$ eV)	4.4	5.3	4.3	2.4
R/R_s ($\times 10^{-3}$)	4.7	5.6	4.6	2.5