



Research Article

# “Excess Heat” in Ni–H Systems and Selective Resonant Tunneling \*

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## Abstract

Selective resonant tunneling model is applied to Ni–H systems to explain the “excess heat” without strong neutron and gamma radiations. In combination with Bethe’s solar model of weak interaction, the reaction rate is estimated, and compared with experiments. An experimental test is further suggested.

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*Keywords:* Bethe’s solar model of weak interaction, Internal conversion electron, Resonant electron capture, Selective resonant tunneling

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## 1. Introduction

Excess heat in Ni–H systems was discovered in Piantelli’s biological experiments in a cryogenic environment [1], and in Mastromatteo’s chip of integrated circuits when electrical current was passing through the nickel foil in the hydrogen gas [2]. Thanks to Professor Focardi, my visits to Bologna University and Siena University were arranged to see their Ni–H systems for detecting excess heat and nuclear radiations in 1999 and 2000. Rossi’s demonstrations in 2011 motivated us to study the resonant tunneling [3–8] through Coulomb barrier with high charge number  $Z = 28$ . Although the resonant tunneling model is still valid to explain the excess heat without strong neutron and gamma radiation, it needs additional consideration to calculate the reaction rate for  $Z = 28$ .

The resonant tunneling model introduces three parameters:  $U_r$ ,  $U_i$ , and  $a_0$ , i.e. the real and imaginary part of nuclear potential well and its radius, respectively. The imaginary part,  $U_i$ , would be extremely small for a resonant tunneling with  $Z = 28$ , because  $U_i$  is supposed to be in the order of  $(1/\theta^2)$  in order to have a resonant tunneling. Here  $(1/\theta^2)$  is the Gamow penetration factor, an extremely small number for  $Z = 28$ . Indeed, it is not legitimate to use  $U_i$  for this case, because the weak interaction is dominant, and the imaginary part of nuclear potential is no longer a suitable tool for describing the weak interaction. The intermediate heavy boson makes the range of weak interaction much shorter

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than the range of strong interaction ( $a_0$ ). We have to calculate the overlapping of the initial wave function with the final wave function in order to estimate the reaction rate instead of using  $U_i$ .

## 2. Overlapping of Wave Functions

In Bethe's solar model [9], the overlapping of wave functions was calculated to estimate the fusion reaction rate for  $p + p \rightarrow d + e^+ + \text{neutrino}$ , because the weak interaction dominates. The cross-section of reaction,  $\sigma$ , is written as

$$\sigma = \frac{g f(W) \left| \int \Psi_f \Psi_i d\tau \right|^2}{v}. \quad (1)$$

Here,  $g$  is the coupling constant for weak interaction, which is about  $10^{-4}$  1/s,  $f(W)$  is a function of emitted  $\beta$ -particle's energy,  $W$  and  $v$  is the speed of incoming proton. The integration  $\int \Psi_f \Psi_i d\tau$  shows the overlapping of the initial wave function,  $\Psi_i$ , with the final wave function,  $\Psi_f$ . In Bethe's calculation,  $\Psi_i$  is the  $p + p$  elastic scattering wave function which is in a continuous state normalized to the incoming beam intensity, and  $\Psi_f$  is the  $n + p$  confined state wave function (i.e. deuteron) which is in a discrete state normalized in its confined region. The transition from  $p + p$  to  $n + p$  with positron emission implies that a proton is transformed into a neutron, and a positron is created. Both of these two processes need energy, which is provided by the binding energy of deuteron. There is no heavy electron involved at all. Hence, if  $n + {}^{58}\text{Ni}$  confined state would provide enough binding energy, the  $p + {}^{58}\text{Ni}$  might be transformed into  $n + {}^{58}\text{Ni}$  confined state in terms of electron capture as well:



We learned two points from Bethe's calculation: (??) the contribution from the overlapping of wave functions outside the nuclear potential well was much greater than the contribution from the overlapping of wave functions inside the nuclear potential well. Hence, the resonance of transition would appear when the overlapping of wave functions outside the nuclear potential well reaches a maximum; (??) in a hydrogen-storage metal (Ni-H system),  $p + {}^{58}\text{Ni}$  is in a confined state in lattice which is different from an incoming proton beam; hence, the initial wave function must be normalized in its confined region (including the lattice region) as well. The cross-section in Eq. (??) is supposed to be replaced by the probability of transition,  $T$ :

$$T \propto g \cdot \frac{\left| \int \Psi_f \Psi_i d\tau \right|^2}{\int |\Psi_f|^2 d\tau \cdot \int |\Psi_i|^2 d\tau}. \quad (3)$$

Searching the resonance means searching for the maximum of  $T$  in Eq. (3). Mathematical theorem says that the ratio of integrations in Eq. (3) would reach its maximum value 1, if and only if

$$\Psi_i = \text{Constant} \cdot \Psi_f, \quad (4)$$

$\Psi_f$  is a confined state of  $n + {}^{58}\text{Ni}$  or the excited  ${}^{59}\text{Ni}$ . The neutron wave function would extend to outside of the nuclear potential well (thick dashed curve in Fig. 1). It is an exponentially decaying wave function outside the nuclear well; hence, the resonance condition (??) requires an exponentially decaying wave function,  $\Psi_i$ , in the region under the Coulomb barrier (thick solid curve in Fig. 2). In other words, the irregular Coulomb wave function,  $G_0$ , must be dominant in this region.

Figure 2 shows  $p + {}^{58}\text{Ni}$  wave function in a down-shifted Coulomb field and a square nuclear potential well, when the wave function reaches almost the maximum on the boundary of the nuclear potential well. The resonance condition, Eq. (??), implies a similar logarithmic derivative for  $\Psi_i$  and  $\Psi_f$ . The logarithmic derivative of  $\Psi_f$  at the border of nuclear potential well is determined by the binding energy of  $n + {}^{58}\text{Ni}$  confined state. If this binding energy is too large

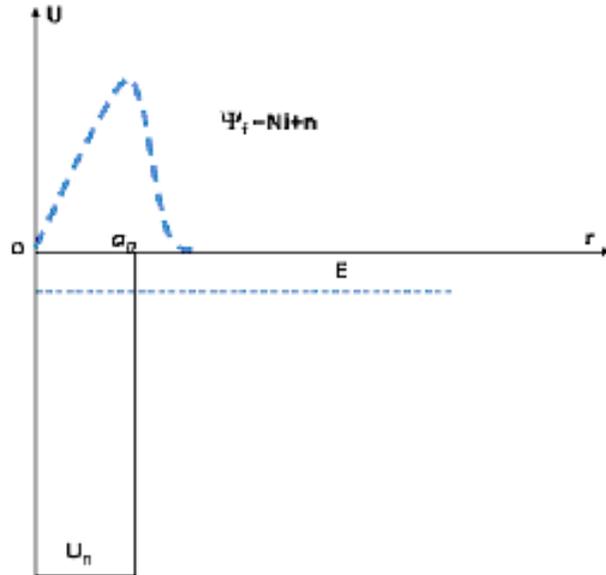


Figure 1.  $n + {}^{58}\text{Ni}$  wave function in a square nuclear potential well.

or too small, it might be not suitable to have a good overlapping in the integration of the numerator of Eq. (3), because

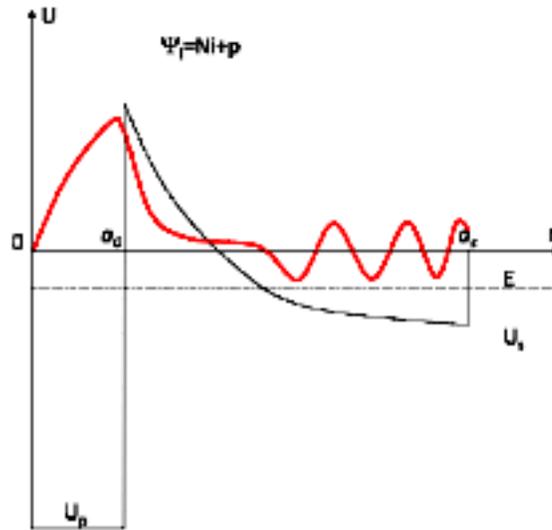


Figure 2.  $p + {}^{58}\text{Ni}$  wave function in a down-shifted Coulomb field and a square nuclear potential well, when the wave function reaches almost the maximum on the boundary of the nuclear potential well.

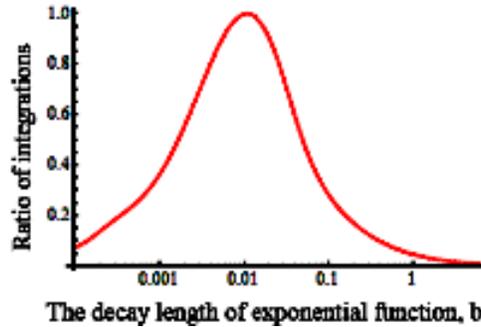


Figure 3. Qualitatively showing the maximum of overlapping was reached when binding energy of  $n + {}^{58}\text{Ni}$  is of order of MeV.

the logarithmic derivative of  $\Psi_f$  at the border of nuclear potential well has to be close to

$$\frac{1}{G_0} \cdot \left. \frac{\partial G_0}{\partial r} \right|_{r=a_0}.$$

Figure 3 shows the normalized overlapping of  $G_0[\eta, \rho]$  with an exponentially decaying function,  $\exp[-\rho/b]$ , varies with the decay length,  $b$ , which depends on the binding energy of  $n + {}^{58}\text{Ni}$  confined state.

In Fig. 2, the Coulomb potential is down-shifted by the electron-screening effect to form a potential well in lattice. The wave function in this lattice well is a combination of irregular Coulomb wave function,  $G_0$  and the regular Coulomb wave function,  $F_0$ ,  $\Psi_i = F_0 + K \cdot G_0$ . The coefficient of linear combination,  $K$ , would eventually determine the overlapping of the initial and final wave functions. Figure 4 shows that the normalized overlapping ratio of wave functions,  $R$ , for  $p + {}^{58}\text{Ni}$  may approach its maximum when  $K$  is greater than  $(10000/\theta)$ .

$$R = \frac{|\int \Psi_f \Psi_i d\tau|^2}{\int |\Psi_f|^2 d\tau \cdot \int |\Psi_i|^2 d\tau}. \quad (5)$$

It is evident that even if the Gamow factor is very small for the  $p + {}^{58}\text{Ni}$  system, it is still possible to reach the resonance by controlling the linear combination coefficient. Thus the probability of transition,  $T$ , in Eq. (3), would be in the order of  $10^{-5}/s$ , if and only if  $G_0$  is dominant at the interface between nuclear potential well and the Coulomb barrier in the initial wave function,  $\Psi_i$ .

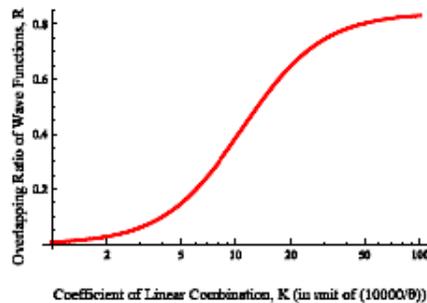


Figure 4. The overlapping of wave functions is a function of the linear combination coefficient,  $K$ .

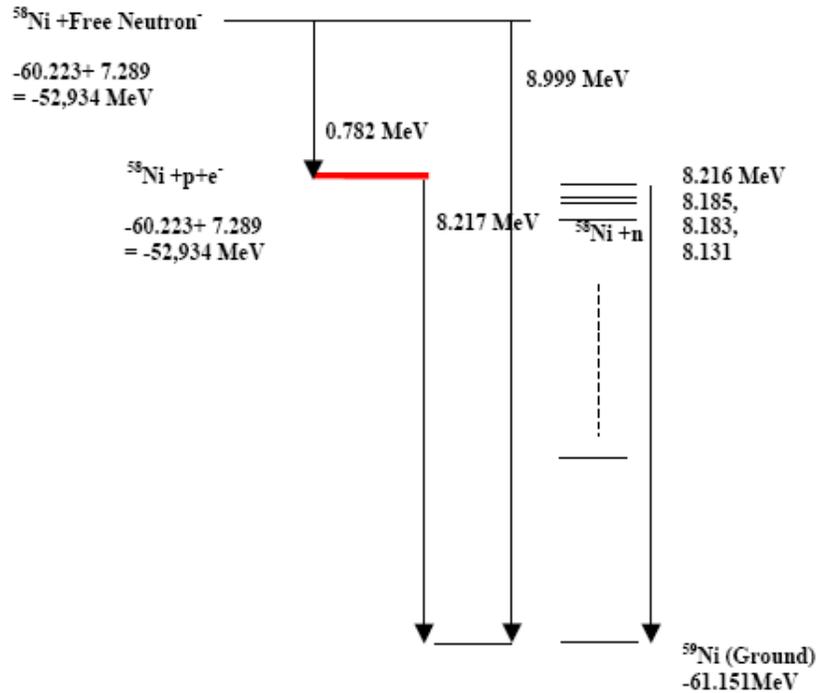
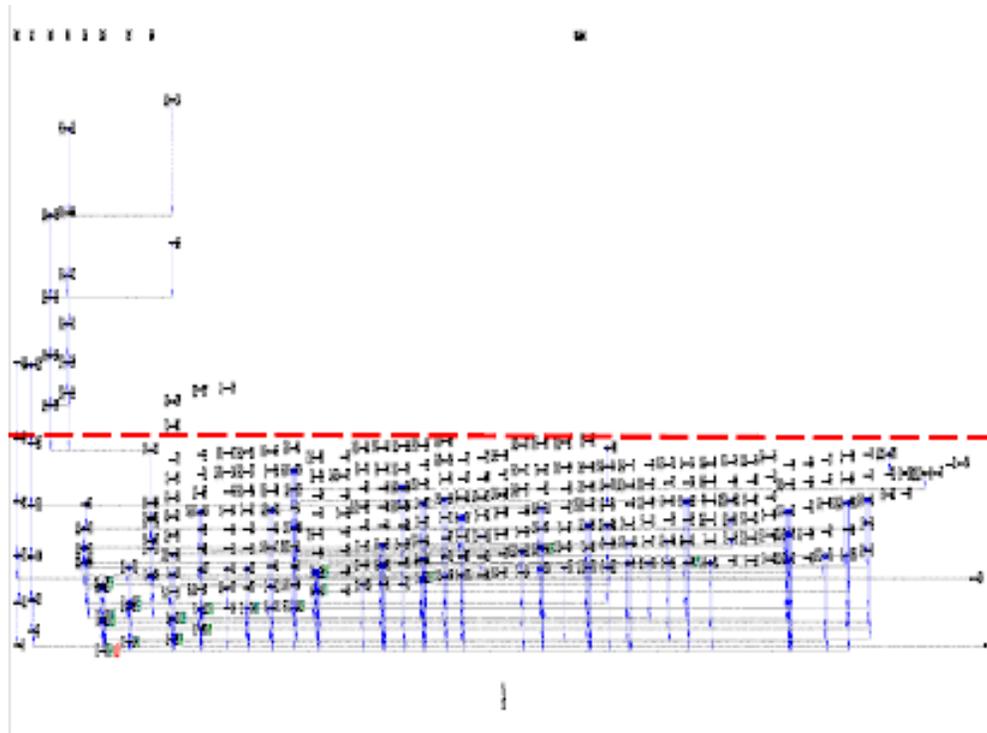


Figure 5.  $n + ^{58}\text{Ni}$  (top line) and  $p + ^{58}\text{Ni} + e^-$  states (thick line) on the  $^{59}\text{Ni}$  energy spectrum (right).

### 3. Energy Transfer

When  $p + ^{58}\text{Ni}$  forms a mother nuclear state for transition, it is important to discuss the daughter nuclear state of  $n + ^{58}\text{Ni}$ , because the energy spectrum of the daughter state determines the energy transfer from nuclear energy to lattice energy. If the energy is taken away by a neutrino during the transition, it is not good for heating the lattice, because neutrino would escape with its energy. Hence, it is important to have a  $n + ^{58}\text{Ni}$  confined state just between the  $p + ^{58}\text{Ni}$  confined state and ground state of  $^{59}\text{Ni}$  in order to reduce the escaping energy carried by the neutrino. Figure 5 shows the  $n + ^{58}\text{Ni}$  state and  $p + ^{58}\text{Ni} + e^-$  state on the  $^{59}\text{Ni}$  energy spectrum. For the lattice confined hydrogen in nickel,  $p + ^{58}\text{Ni}$  state is below the “ $^{58}\text{Ni} + \text{Free neutron}$ ” state by  $0.782 \text{ MeV}$ . Hence, the energy defect prohibits the transition from proton to free neutron. However, there is a series of excited states of  $^{59}\text{Ni}$ , which are just below  $p + ^{58}\text{Ni}$  state by keV to MeV. Indeed this binding energy assists the transition from a proton to a confined neutron. During this *resonant electron capture* process only about  $1 \text{ keV} - 1 \text{ MeV}$  is taken away by the neutrino, and most of excited energy still remains in the excited  $^{59}\text{Ni}$  nucleus. Now the question is how this energy ( $\sim 7 \text{ MeV}$ ) would be preferably transferred to the lattice during its de-excitation processes.

The de-excitation processes are in two categories: (1) releasing the energy to internal conversion electron; (2) emitting photon through gamma decay. If the energy is transferred to orbital electrons through internal conversion electron, it is good for heating the lattice. However, if the energy is taken by photons, and photons penetrate the nickel lattice; then, it is not good for heating the lattice, and causes the problem of radiation protection. They are the competing processes. The result of the competition is determined by the energy difference between two energy levels.



**Figure 6.** More than 276 energy levels are below the dashed line in  $^{59}\text{Ni}$  energy spectrum.

When the energy difference is getting smaller and smaller, the internal conversion electron dominates. That is, the orbital electrons would take away most of the de-excitation energy and heat the lattice eventually. Figure 6 shows the whole energy spectrum of  $^{59}\text{Ni}$ . The long thick dashed line shows the energy level of  $p + ^{58}\text{Ni}$  state. A lot of energy levels are below this dashed line (each short dash represents an energy level in Fig. 6). Roughly speaking, more than 276 energy levels are below that dashed line. It implies that the average difference between two neighboring energy levels is around 30 keV. Thus the internal conversion electrons would dominate the de-excitation process by a factor of up to  $10^5$ . This is shown in Fig. 7. The ratio of internal conversion probability to the gamma transition is depicted in Fig. 7 for K-orbital electrons. At the low energy, the internal conversion process dominates for all modes of gamma emission [10].

The electron capture or the internal conversion would capture or kick out an orbital electron and create a vacancy which would introduce the characteristic X-rays and Auger electrons. Table 1 shows the ionization energy for all the orbits of nickel and copper. They are all below 12 keV [11]. Now we may answer the question whether the nickel powder cylinder of diameter of 5 cm and the lead plate of 3 mm thickness are enough to reduce all the gamma radiations and the energetic electrons to the background level? [12] The dose of background radiation is about 1 mSv/year which corresponds to an energy flux density of 1–6 MeV/cm<sup>2</sup>/s of 30–60 keV photons (Fig. 8) [13]. However, 10 kW of heating power corresponds to an energy flux density of  $8 \times 10^{14}$  MeV/cm<sup>2</sup>/s on the surface of the copper tube of 5 cm diameter in the case of E-cat demonstration in 2011 if there was no attenuation of  $\gamma$  radiation. Hence, it is necessary to provide a reduction of the order of  $10^{14}$  in order to reach a background dose outside the E-cat device. The mass attenuation coefficient for 60 keV photon just provides such a reduction of the order of  $10^{14}$  (the dashed

line in Fig. 9 [14]). However, if the excited  $^{59}\text{Ni}$  de-excites to the ground state directly and emit a gamma photon with 8.216 MeV; then, the mass attenuation coefficient would be reduced by a factor of 40 or more in comparison with that of 30–60 keV photons (the dashed line in comparison with dotted line in Fig. 9). As a result, the 8.216 MeV photon would not leave the energy to lattice, and the radiation dose would be higher than the background in E-cat demonstrations

#### 4. Excess Power

When the weak interactions dominate the de-excited processes; then one might worry if it would give 10 kW power in a volume of  $85\text{ cm}^3$  [12]. Indeed the nickel ( $\sim 10\text{ mol}$ ) is more than enough. The resonant electron capture has a rate of  $10^{-5}$  per second in Eq. (3). It would provide a power of 10 MW if all of nickel nuclei are in the resonant electron capture process. In reality, the resonance happens only in the surface layer of  $10^{-8}\text{ m}$  ( $100\text{ \AA}$ ) thickness. If we do not use nickel powder, only  $10^{-6}$  of total nickel nuclei are involved. They are able to provide 10 W at most. However if we use the powder of diameter of  $10^{-5}\text{ m}$  ( $10\text{ }\mu\text{m}$ ); then, it would provide 10 kW of excess heat. This is just the size of the powder revealed in the patent.

The 10 kW E-cat is supposed to be in operation for half a year ( $\sim 10^7\text{ s}$ ). The number of nickel nuclei in resonance would decrease dramatically, because the total number of nickel nuclei in the surfaces of powder would decrease by e-fold after every  $10^5\text{ s}$ . We expect that the powder would split gradually during the process of absorbing and desorbing; then, a constant power of 10 kW might be maintained with the assistance of some wave fields.

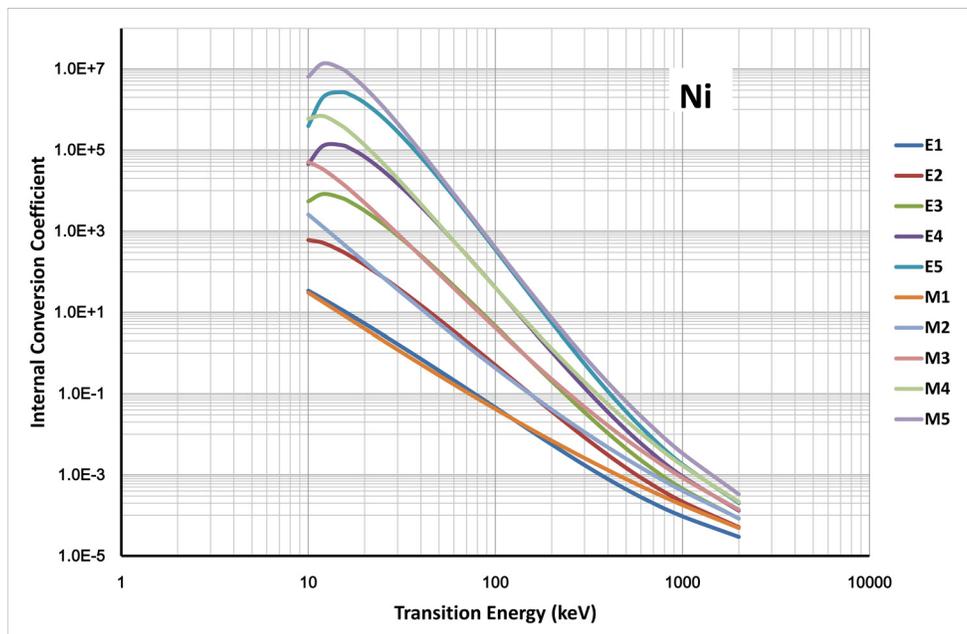
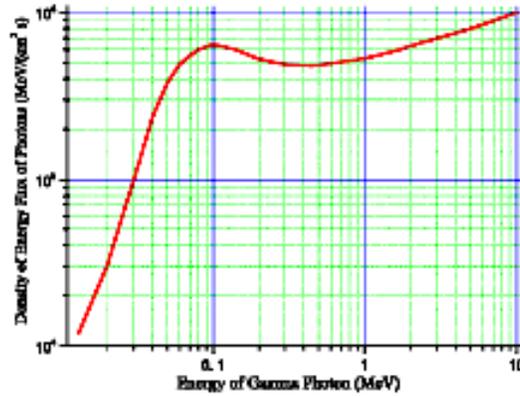


Figure 7. The internal conversion coefficient versus transition energy (in keV) for nickel.

**Table 1.** Ionization energies of atoms and atomic ions (in unit of eV)

Neutral atoms to +7 ions neutral		I	II	III	IV	V	VI	VII	VIII
Z	Element								
28	Ni	7.6398	18.16884	35.19	54.9	76.06	108	133	162
29	Cu	7.72638	20.2924	36.841	57.38	79.8	103	139	166
+ 8 Ions to + 15 ions		IX	X	XI	XII	XIII	XIV	XV	XVI
Z	Element								
28	Ni	193	224.6	321.0	352	384	430	464	499
29	Cu	199	232	265.3	369	401	435	484	520
+ 16 Ions to + 23 ions		XVII	XVIII	XIX	XX	XXI	XXII	XXIII	XXIV
Z	Element								
28	Ni	571.08	607.06	1541	1648	1756	1894	2011	2131
29	Cu	557	633	670.588	1697	1804	1916	2060	2182
+ 24 Ions to + 29 ions		XXV	XXVI	XXVII	XXVIII	XXIX			
Z	Element								
28	Ni	2295	2399.2	10288.8	10775.40				
29	Cu	2308	2478	2587.5	11062.38	11567.617			



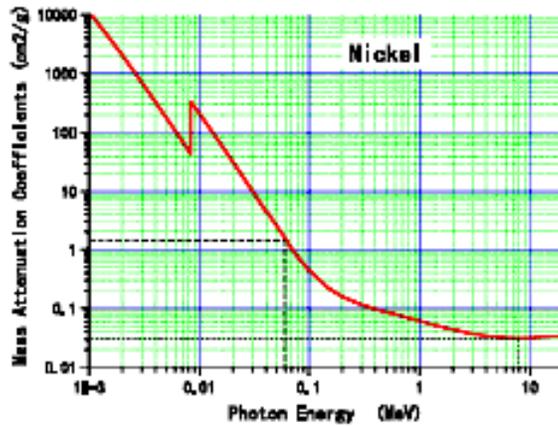
**Figure 8.** The energy flux density of gamma radiation versus photon energy for 1 Roentgen/hour dose in air. (1 Roentgen/hour is about 76212 mSv/year).

### 5. Eigen Equation

In Fig. 2 the lattice potential well is approximated by a down-shifted Coulomb field in an electron screening sphere. The wave function of proton in this potential well is a linear combination of irregular and regular Coulomb wave functions:  $F_0 + KG_0$ . The coefficient of linear combination,  $K$ , is determined by the eigen equations (6) and (7). Here,

$$k_1 = \sqrt{\frac{2\mu(E - U_p)}{\hbar^2}},$$

$\mu$  is the reduced mass for  $p + {}^{58}\text{Ni}$  system;  $E$  and  $U_p$  are the energy and nuclear potential of  $p + {}^{58}\text{Ni}$  system, respectively,  $\hbar$  is the Planck constant divided by  $2\pi$ ,  $\eta = 1/(ka_c)$  and  $\rho = kr$  are Coulomb variables with



**Figure 9.** The necessary mass attenuation coefficient to reduce the gamma radiation dose to the background level.

$$k = \sqrt{\frac{2\mu(E - U_s)}{\hbar^2}} \quad \text{and} \quad a_c = \frac{4\pi\epsilon_0\hbar^2}{Ze^2\mu}, \quad \epsilon_0 = 8.8542 \times 10^{-12} \text{ F/m};$$

$U_s$  is the depth of the lattice potential well for p +  $^{58}\text{Ni}$  system;  $a_s$  is the radius of the electron screening sphere.

$$\frac{F_0[\eta, \rho_0]}{G_0[\eta, \rho_0]} \cdot \frac{\frac{\rho_0}{F_0[\eta, \rho_0]} \cdot \frac{\partial F_0[\eta, \rho]}{\partial \rho} \Big|_{\rho=\rho_0} - k_1 a_0 \cot[k_1 a_0]}{\frac{\rho_0}{G_0[\eta, \rho_0]} \cdot \frac{\partial G_0[\eta, \rho]}{\partial \rho} \Big|_{\rho=\rho_0} - k_1 a_0 \cot[k_1 a_0]} = \frac{F_0[\eta, \rho_s]}{G_0[\eta, \rho_s]} \cdot \frac{\frac{\rho_s}{F_0[\eta, \rho_s]} \cdot \frac{\partial F_0[\eta, \rho]}{\partial \rho} \Big|_{\rho=\rho_s} + \beta a_s}{\frac{\rho_s}{G_0[\eta, \rho_s]} \cdot \frac{\partial G_0[\eta, \rho]}{\partial \rho} \Big|_{\rho=\rho_s} + \beta a_s}, \quad (6)$$

$$K = -\frac{F_0[\eta, \rho_0]}{G_0[\eta, \rho_0]} \cdot \frac{\frac{\rho_0}{F_0[\eta, \rho_0]} \cdot \frac{\partial F_0[\eta, \rho]}{\partial \rho} \Big|_{\rho=\rho_0} - k_1 a_0 \cot[k_1 a_0]}{\frac{\rho_0}{G_0[\eta, \rho_0]} \cdot \frac{\partial G_0[\eta, \rho]}{\partial \rho} \Big|_{\rho=\rho_0} - k_1 a_0 \cot[k_1 a_0]}. \quad (7)$$

$$\rho_0 = ka_0, \quad \rho_s = ka_s, \quad \text{and} \quad \beta = \sqrt{\frac{2\mu(-E)}{\hbar^2}}$$

Equation (6) determines the eigen value of energy  $E$ , and Eq. (7) determines the coefficient,  $K$ , of the linear combination. In general,

$$\frac{F_0[\eta, \rho_0]}{G_0[\eta, \rho_0]} \sim \frac{2\pi\eta}{\exp[2\pi\eta] - 1} = \frac{1}{\theta^2} \ll 1.$$

It makes  $K \sim (1/\theta)^2$ . In order to meet the resonance condition in Fig. 4, the denominator in Eq. (7) must satisfy

$$\left( \frac{\rho_0}{G_0[\eta, \rho_0]} \cdot \frac{\partial G_0[\eta, \rho]}{\partial \rho} \Big|_{\rho=\rho_0} - k_1 a_0 \cot[k_1 a_0] \right) \ll 1/10000 \theta. \quad (8)$$

This is the boundary condition for the p +  $^{58}\text{Ni}$  wave function at  $r = a_0$ . Equation (??) corresponds to its smooth connection to an irregular Coulomb wave function,  $G_0[\eta, \rho_0]$ , in the lattice well. That is the necessary condition for a resonance, because it makes the good overlapping with an exponentially decaying n +  $^{58}\text{Ni}$  wave function (Figs. 3 and 4). Equation (??) is indeed a relation between  $U_r$  and  $a_0$  when  $U_i \rightarrow 0$ . We may suggest that an experimental test on this relation should be performed.

## 6. Experimental Test

In the above-mentioned sections, all discussions are based on a fundamental assumption, i.e. there is a resonance in the p +  $^{58}\text{Ni}$  system near the zero energy. This resonance allows proton to penetrate Coulomb barrier, and pick up the weak interaction only among various interactions – selective resonant tunneling. If we have a set of good data for p +  $^{58}\text{Ni}$  non-elastic scattering; then, we might use the 3-parameter formula [6]

$$\sigma_r = \frac{\pi}{k^2} \cdot \frac{1}{\theta^2} \frac{-4w_i}{w_i^2 + (w_i - \frac{1}{\theta^2})^2} \quad (9)$$

to fit this set of data in order to find the real and imaginary part of nuclear potential well and its radius, respectively ( i.e.  $U_r$ ,  $U_i$ , and  $a_0$ ) because  $w_r$  and  $w_i$  depend on these three parameters only. We have successfully applied this method to the  $p+{}^6\text{Li} \rightarrow {}^3\text{He} + {}^4\text{He}$  fusion reaction data [8], and showed that  $U_r, U_i$ , and  $a_0$  satisfy the resonance condition (??). Unfortunately, there is no such data set for  $p + {}^{58}\text{Ni}$  at low energy. The only available low-energy data for  $p + {}^{58}\text{Ni}$  is the  $p+{}^{58}\text{Ni} \rightarrow {}^{59}\text{Cu} + \gamma$  data published in 1977 [10], which is not accurate enough to find this fit. Hence, a better experiment for  $p + {}^{58}\text{Ni}$  system is desirable to confirm this resonance.

In addition, we may detect the neutrino emission from the resonant electron capture process. The mono-energetic neutrino might make this difficult test a little easier [15].

## 7. Conclusion

A resonant electron capture model is proposed to explain the “excess heat” in Ni–H system without strong neutron and gamma radiation. It has four main features:

- (1) Proton penetrates the Coulomb barrier of  ${}^{58}\text{Ni}$  in terms of selective resonant tunneling; hence, the resultant resonance state should be a  $p + {}^{58}\text{Ni}$  state with no strong neutron or gamma emission. Only the state governed by the weak interaction would be created as a mother nucleus.
- (2) The  $p + {}^{58}\text{Ni}$  state would transit to  $n + {}^{58}\text{Ni}$  confined state in terms of electron capture processes  $p + {}^{58}\text{Ni} + e^- \rightarrow {}^{59}\text{Ni}^* + \text{neutrino}$  with the neutrino emission. The neutrino would take away part of the binding energy if the newly created  ${}^{59}\text{Ni}^*$  state is still in an excited state of  ${}^{59}\text{Ni}$ . The de-excitation of this  ${}^{59}\text{Ni}^*$  state would provide the observed “excess heat” in Ni–H system.
- (3) The internal conversion electron process would dominate the de-excitation, because  ${}^{59}\text{Ni}^*$  state is submerged in a sea of energy levels of excited  ${}^{59}\text{Ni}$  state. The energy difference between two neighboring levels is around 30–60 keV, the internal conversion electron process would win over the gamma decay in the competition (this is consistent with Defkalion and E-cat measurements published during or after ICCF-17).
- (4) In a word, proton is transformed into a neutron to gain the binding energy from  $(p + {}^{58}\text{Ni})$  to  $(n + {}^{58}\text{Ni})$ . The energy level of  $(p + {}^{58}\text{Ni})$  system near zero energy plays a key role. It may be verified in a beam-target experiment.

## Notes

- (1) The assumption of resonance level might be verified by  $d + (d + d)$  reaction as well, when low-energy data is not accurate enough to determine the boundary condition of nuclear potential well for  $(d + d)^*$  state.
- (2) The probability in resonance would be greatly enhanced when we consider the transition from energy band of proton in lattice and the dynamic feed-back mechanism.
- (3) F. Piantelli and W. Collis *Some results from the Nichenergy Laboratory. 10th Int. Workshop on Anomalies in Hydrogen Loaded Metals*, 10–14 April 2012, Certosa di Pontignano, Loc. Pontignano, 53010 Vagliagli, Siena – Italia, described the potential well in the lattice as well.

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