Exploring a Self-Sustaining Heater without Strong Nuclear Radiation

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Abstract

The comparison between the new 3-parameter formula and the old 5-paramter formula for five major fusion cross-sections strongly confirms the selective resonant tunneling model which forms the physical basis of a self-sustaining heater without strong nuclear radiation. The development of condensed matter nuclear science is not contrary to all understanding gained of nuclear reactions in the last half century, but instead it improves our knowledge of the nuclear physics of resonant tunneling of the Coulomb barrier. The detection of neutrino emission from metal deuterides is proposed as a decisive step to further develop this model.

1. Introduction

Building a self-sustaining heater without strong nuclear radiation is the fundamental goal of the world-wide research into cold fusion, or condensed matter nuclear science (CMNS). After 19 year we have reached the stage of demonstration (Arata and Zhang's experiment[1]), correlation between the excess heat and the surface features (Violante et al. [2]). We still need an explanation of why there is no strong neutron emission or gamma radiation from CMNS experiments. The study on the nuclear fusion cross-section of the light nuclei just provided such an explanation.

Early in 1972, Duane[3] did a survey on the theory of the nuclear fusion of the light nuclei. He found that there was not enough experimental data to do a detailed study. However, based on the Breit-Wigner formula, he developed a 5-parameter formula to describe the available experimental data. He tried to reduce the number of the parameters, but he found that at least 5 parameters were necessary to fit the cross-sections for major fusion reactions. This 5-parameter formula was adopted in a Handbook of Plasma Formulary edited by Naval Research Laboratory (NRL) in 1978[4]. As a result, this 5-parameter formula has been widely cited in the plasma fusion community. In 1992, Bosch and Hale[5] developed a better 9-parameter formula based on the newly available experimental data and the R-matrix theory for nuclear reactions. Bosch and Hale pointed out that the 5-parameter formula was not correct at the low energy region, because it did not give the right dependence on energy. Nevertheless, this 5-parameter formula is still cited in the Plasma Formulary even in the new edition in 2007[6].

In 1999, an identity was derived for the nuclear fusion cross-section[7]. This new identity clearly showed the resonant effect using a complex quantity: W defined as the cotangent of the phase shift. When the real part of W equals 0, there will be a resonance. When the imaginary part of W equals (-1), the resonant effect will reach its maximum possible. This new identity explains why there is no neutron emission or gamma radiation accompanied with the "excess heat" in CMNS. We call it selective resonant tunneling theory. In 2008, it was found that the real part of W depended on the incident energy linearly, and the imaginary part of W was almost a constant. This immediately led to a 3-parameter formula for the fusion cross-section of the light nuclei. This new 3-parameter formula gives an even better fit with newly available experimental data than the 5-parameter formula does, because the astrophysical S-function in the 3-parameter formula includes a new term which is directly related to the selectivity of the resonant tunneling[8]. Therefore, the comparison with experimental data has confirmed the existence of the cold fusion phenomenon.

2. 3-parameter formula

The nuclear fusion cross-section may be written as [7]:

$$\sigma(E) = \frac{\pi}{k^2}\frac{(-4W_i)}{W_r^2 + (W_i - 1)^2} \tag{1}$$

if the S-partial wave is dominant. Here, W is related to the phase shift, δ , of the S-partial wave as $W \equiv Cot\delta$. When Coulomb field is applied to describe the repulsion between two charged reactant nuclei, W is the coefficient in the linear combination of the regular and irregular Coulomb wave functions. We have shown that the main dependence of W on energy is in the form of Gamow factor[7,8]:

$$W = \theta^2 w. \tag{2}$$

$$\theta \equiv \sqrt{\frac{Exp[\frac{2\pi}{ka_c}] - 1}{2\pi}}. \tag{3}$$

Here, k is the wave number of the interacting particle in the system of mass center; a_c is length of the Coulomb unit. w is defined as the reduced coefficient. $a_c \equiv \frac{4\pi\varepsilon_o\hbar^2}{Z_1 Z_2 e^2 \mu}$. $Z_1 e$ and $Z_2 e$ are the electrical charges of the colliding nuclei, respectively. $\hbar$ is the Planck constant divided by 2 π , μ is the reduce mass, ε_o is the dielectric constant of the vacuum. We found that the real part of this reduced coefficient, *w*, may be written as

$$w_r = C_1 + C_2 E, \tag{4}$$

The imaginary part of *w* may be approximated by a constant. Here, *E* is the kinetic energy of the incident particle in the laboratory system. Consequently, the fusion cross-section may be expressed as a function of 3 parameters (C_1,C_2,and w_i) only,

$$\sigma(E) = \frac{\pi}{k^2}\frac{1}{\theta^2}\frac{(-4w_i)}{w_r^2 + (w_i - \frac{1}{\theta^2})^2} = \frac{\pi}{k^2}\frac{1}{\theta^2}\frac{(-4w_i)}{(C_1 + C_2 E)^2 + (w_i - \frac{1}{\theta^2})^2} \tag{5}$$

The upper row of Fig. 1 shows the results of fitting this 3-parameter formula (5) to the experimental data for D+T, D+^{3}He, and D+D fusion reactions, respectively.

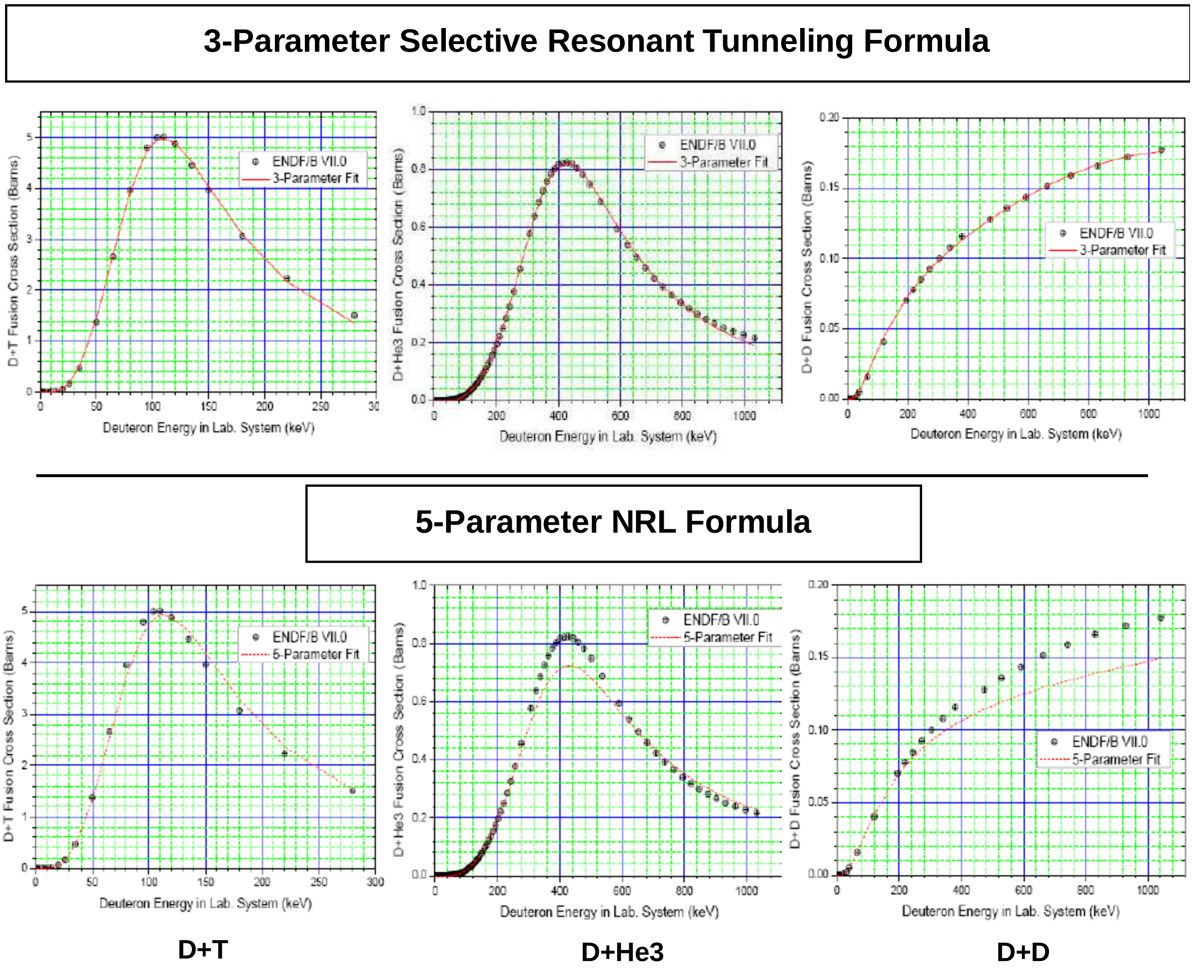

Figure 1. Selective resonant tunneling formula for D+T, D+^{3}He, and D+D

The upper row of Fig. 2 shows the results of fitting this 3-parameter formula (5) to the experimental data for T+T and T+^{3}He fusion. Table I gives the values of three parameters (C_1, C_2, and w_i) for each case. In these figures, the black points are the experimental data from The National Nuclear Data Center (ENDF/B VII.0 [9]). The solid lines are the results of calculation using 3-parameter formula (5). The dotted lines in the lower row of figure 1 and 2 are the results of calculation using the following 5-parameter NRL formula (6) with the parameters (A_1, A_2, A_3, A_4 and A_5) listed in that NRL Plasma Formulary[4,6].

$$\sigma(\boldsymbol{E}) = \frac{1}{\boldsymbol{E}}\left(\frac{1}{\exp[\frac{A_1}{\sqrt{\boldsymbol{E}}}]-1}\right)\left(A_5 + \frac{A_2}{(A_4 - A_3\boldsymbol{E})^2+1}\right) \tag{6}$$

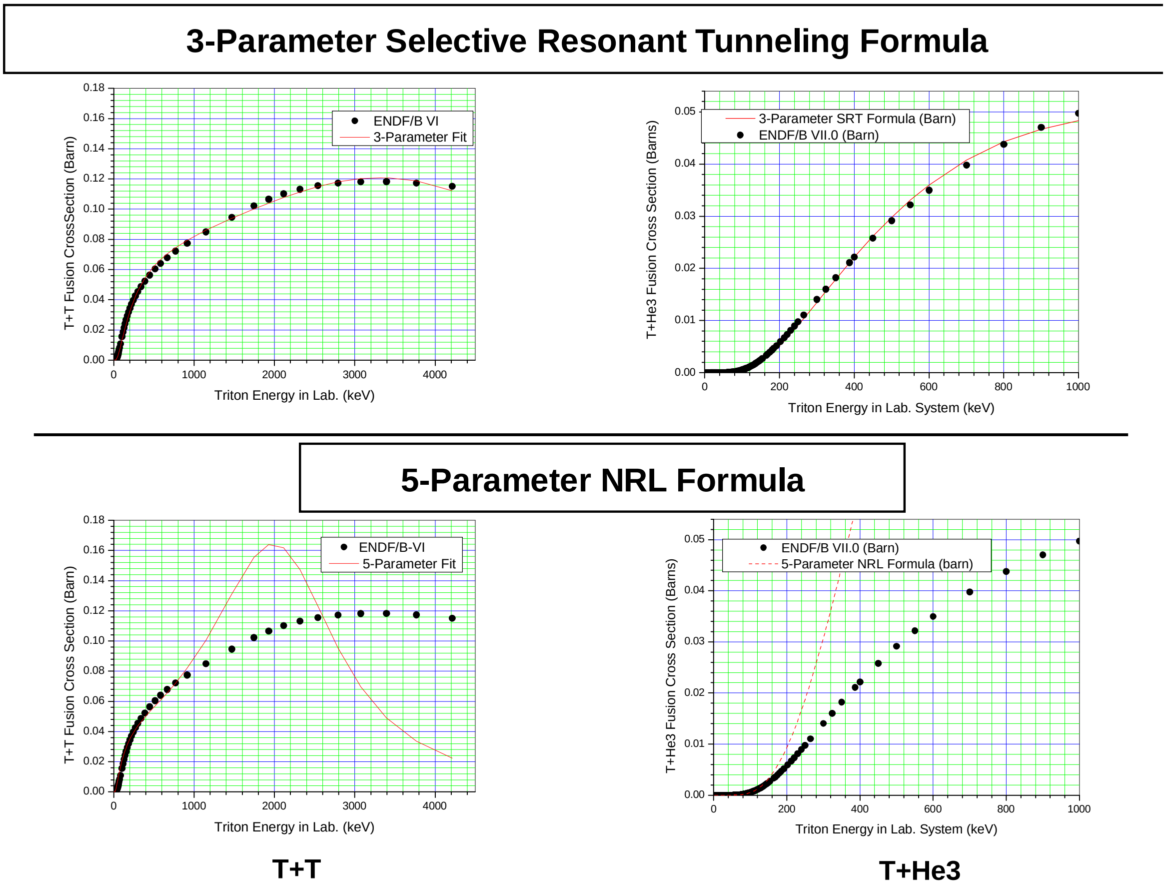

Figure 2. Selective resonant tunneling formula for T+T and T+^{3}He fusion.

Table I. PARAMETER LIST FOR 3-PARAMETER FORMULA

	D+T	D+^{3}He	D+D (p+T&n+^{3}He)	T+T	T+^{3}He
C_1	-0.54168	-1.13575	-60.2913	-36.7805	2.78836
C_2*	0.0055601	0.0030453	0.05068	0.00927803	0.000959464
w_i	-0.39189	-0.67162	-55.0122	-24.5337	-1.04059

*C_2 is in unit of (1/keV) when E in the Eq. (5) is the incident energy in the laboratory system in units of keV.

It is clear that the 5-parameter formula gives a comparable result only in the case of the D+T fusion. In all the other cases, NRL 5-parameter formula is not able to give the right position of the peak and the height of peak of the cross-section. On the other hand, this new 3-parameter formula is able to give the right position and the height of the peak of the cross sections, because this new 3-parameter formula includes a new term in its denominator with a strong energy dependence: i.e. $(w_i - \frac{1}{\theta^2})^2 = (w_i - \frac{2\pi}{Exp[\frac{2\pi}{ka_c}]-1})^2$.

3. A New Term in the Astrophysical S-function

The astrophysical S-function was introduced in astrophysics and nuclear physics in order to extract the geometric factor, $\frac{\pi}{k^2}$, and the Gamow factor, $\frac{1}{\theta^2}$ from the cross-section. It was thought that the remaining astrophysical S-function is supposed to be a **slowly** varying function to express the **INTRINSIC** nature of the nuclear state. In Duane's 5-parameter formula, only the $(A_4 - A_3\boldsymbol{E})^2$ term shows the resonant nature of the nuclear state. Bosch and Hale attempted to improve the energy-dependence of the astrophysical S-function using 2 polynomials with 9 parameters. In this 3-parameter formula, a new term has been introduced into the denominator of the astrophysical S-function. This new term depends on the energy as **rapidly** as the Gamow factor does. The comparison with the experimental data strongly confirmed that it is important to include this new energy-dependence in the denominator of the astrophysical S-function, and it is not simply an expression of the **INTRINSIC** nature of the nuclear state only(it includes a factor related to Coulomb field outside the nuclear potential well).

4. The Matching of the Channel Width of Energy

In order to see the physical meaning of this new term, we rewrite the cross-section in the form of Breit-Wigner formula.

$$\sigma(E) = \frac{\pi}{k^2}\frac{(\Gamma_a\Gamma_{in})}{(E-E_0)^2 + (\frac{\Gamma_a+\Gamma_{in}}{2})^2}; \quad \text{with} \quad \Gamma_{in} = \frac{2}{\theta^2 C_2}; \quad \Gamma_a = -\frac{2w_i}{C_2}; \quad E_0 = -\frac{C_1}{C_2}. \tag{7}$$

This new term is related to the incident channel width, $\Gamma_{in} = \frac{2}{\theta^2 C_2}$, and the parameter w_i is related to the absorption channel width, $\Gamma_a = -\frac{2w_i}{C_2}$. It is well known that the matching between the incident channel width and the absorption channel width is very important for the resonant tunneling process. When the incident energy, E, approaches the resonant energy, $E_0 = -\frac{C_1}{C_2}$, the cross-section has a peak. The height of the peak depends on the matching strongly. Only if the incident channel width matches the absorption channel width, $\Gamma_a \approx \Gamma_{in}$; then, cross-section of resonance reaches its maximum possible. Otherwise, even if there is a resonance, it might not be observable because of the mismatching between the incident channel width and the absorption channel width($\Gamma_a \ll \Gamma_{in}$ or $\Gamma_a \gg \Gamma_{in}$). In the case of condensed matter nuclear science, the incident energy is so low that the incident channel width, Γ_{in}, is very narrow. This means that the absorption channel width, Γ_a, must be very narrow in order to observe the resonant tunneling process. Therefore, only the long lifetime resonant state might appear as a result of resonant tunneling at low energy. The neutron emission or gamma radiation could not be the products of the resonant tunneling at low energy because their lifetimes of resonant state are too short to match the incident channel width (i.e. $\Gamma_a >> \Gamma_{in}$). Only the weak interaction process might be involved in low energy resonant tunneling of Coulomb barrier. This explains the cold fusion phenomenon — "excess heat" without commensurable neutron emission or gamma radiation. This is just the physical basis we have sought for 19 year in pursuit of a self-sustaining heater without strong nuclear radiation.

5. Hot Fusion Data Imply Existence of Cold Fusion Phenomena

If we use a spherical square-potential well to describe the nuclear interaction inside the nuclear potential well, the real part and the imaginary part of the potential depth and the radius of the potential well (U_{1r}, U_{1i}, and *a*) are just the 3 parameters related to these 3 parameters in our formula (C_1, C_2, and w_i). Hence, it is possible to use the hot fusion data to figure out the nuclear potential well. Once we have the nuclear potential well, it is possible to predict if there is a resonance when the incident energy is approaching zero (i.e. in the case of CMNS).

In mathematics, the resonance simply means the wave function reaches almost its maximum at the interface between the nuclear potential well and the Coulomb barrier, because this boundary condition of the wave function will make the amplitude of the wave function enhanced inside the nuclear potential well. Figure 3 shows the hot fusion data for the p+D → ^{3}He+γ fusion process.

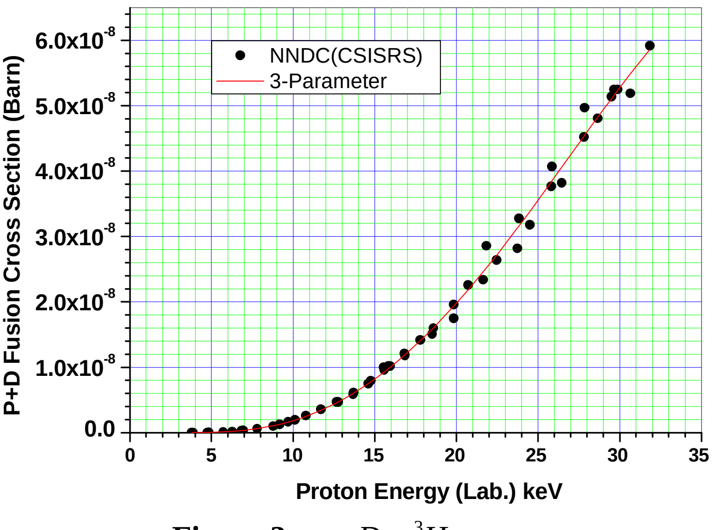

Figure 3. $p + D \rightarrow {}^3He + \gamma$

We may fit these hot fusion data using U_{1r}=-43.90 MeV, U_{1i}=-0.0233 eV, and a=3.9458×10^{-15} m, as shown in Fig. 4.

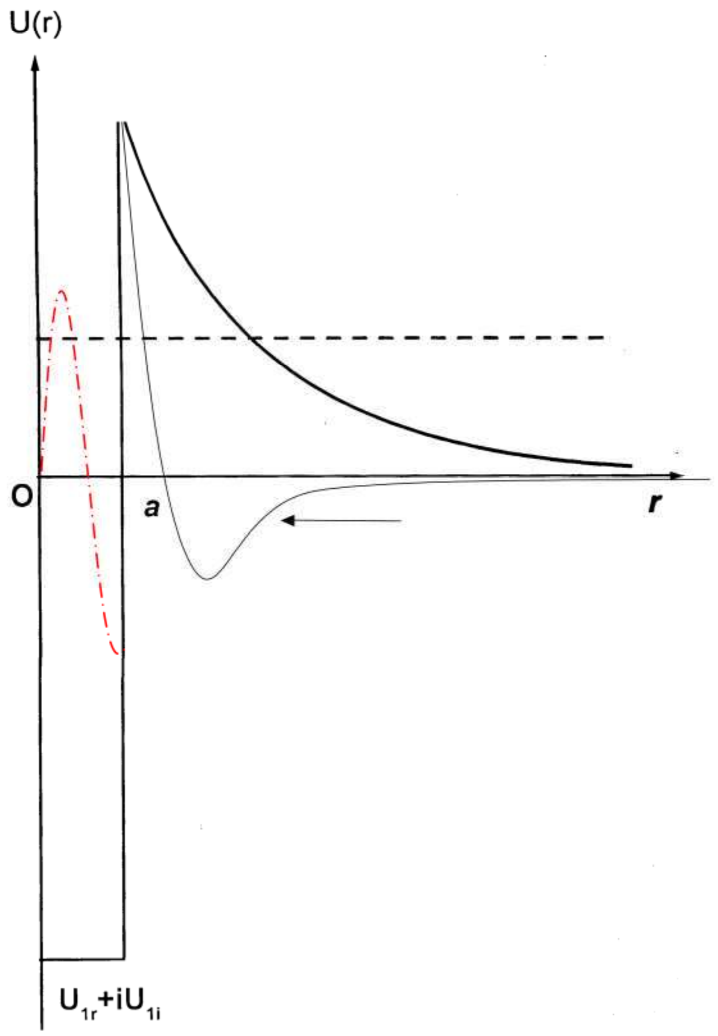

Figure 4. When Coulomb field is replaced by molecular well in a crystal, the nuclear potential is assumed unchanged

When the deuteron and proton are trapped in palladium crystal, the nuclear potential is supposed to be the same as that in the beam-target situation. Then we are able to calculate the phase of the wave function at the boundary between nuclear potential well and the molecular well in crystal (Fig. 4):

$$\mathrm{Re}[k_1 a] \equiv \mathrm{Re}[\sqrt{\frac{2\mu}{\hbar^2}(E - U_{1r} - iU_{1i})}\ a] \xrightarrow[E\to 0]{} 2.98 \times (\frac{\pi}{2}) \quad (8)$$

When the incident energy approaches zero, the phase of wave function just approaches 3π/2. This means that the wave function reaches almost the maximum at the interface between the nuclear potential well and the molecular well in crystal. (See the dot-dash-dot line for the wave function in Fig. 4). Hence, it predicts that the resonant tunneling may appear when deuteron and hydrogen are trapped inside the palladium crystal lattice.

The match between the incident channel width and the absorption channel width implied that the product of resonant tunneling in CMNS should be the product of a weak nuclear interaction. The calculation shows that K-capture of electrons by deuteron followed by a decay of triton is the possible candidate for this weak interaction[10]:

$$\begin{array}{l} p + d + e^- \rightarrow T + \nu \quad (5.474 MeV) \\ \qquad\qquad T \rightarrow {}^3He + e^- + \tilde{\nu} \quad (18\ keV) \\ \hline p + d \rightarrow {}^3He + \nu + \tilde{\nu} (5.492 MeV) \end{array} \tag{9}$$

The anomalous helium-3 and the triton in condensed matter nuclear processes are the experimental evidence [11] for this assumption. The recent successful repetition of 3 deuteron fusion reaction experiments at NRL provided an additional strong evidence of this long lifetime 2 deuteron resonant state in the titanium crystal as well[12].

6. Conclusions

(1) Nineteen years ago, some nuclear physicists alleged that the cold fusion phenomenon is contrary to all understanding gained of nuclear reactions in the last half century [13]. Indeed, after careful study of the nuclear physics accumulated in the last half century it is found that the hot fusion data themselves imply the existence of the cold fusion phenomenon.

(2) A 3-parameter formula is proposed to replace that 36 years old 5-parameter formula with better fit to experimental data:

$$\sigma(\boldsymbol{E}) = \frac{1}{\boldsymbol{E}} \left(\frac{1}{\exp[\frac{Z_a Z_b e^2}{2\varepsilon_0 \hbar}\sqrt{\frac{M_a}{2\boldsymbol{E}}}] - 1} \right) \left(\frac{-4 w_i (\frac{\pi\hbar}{\mu})^2 M_a}{(C_1 + C_2 \boldsymbol{E})^2 + (w_i - \frac{2\pi}{\exp[\frac{Z_a Z_b e^2}{2\varepsilon_0 \hbar}\sqrt{\frac{M_a}{2\boldsymbol{E}}}] - 1})^2} \right) \tag{10}$$

Here $\boldsymbol{E}$ is the incident energy in the laboratory system, (M_a, $Z_a e$) and (M_b, $Z_b e$) are the mass and electrical charge of the projectile and target, respectively. For convenience, we substitute all the constants in the formula, and leave only (m_a, Z_a) and (m_b, Z_b) in this unified formula as:

$$\sigma(E_{lab}) = \frac{-16389 w_i (m_a + m_b)^2}{m_a m_b^2 E_{lab}\left[Exp\left(\frac{31.4 Z_a Z_b}{\sqrt{\frac{E_{lab}}{m_a}}}\right)-1\right][(C_1 + C_2 E_{lab})^2 + (w_i - \frac{2\pi}{\left[Exp\left(\frac{31.4 Z_a Z_b}{\sqrt{\frac{E_{lab}}{m_a}}}\right)-1\right]})^2]} \quad (11)$$

Here, E_{lab} is the incident energy in the laboratory system in unit of keV. For deuteron incident, (m_a, Z_a)=(2,1), etc. (C_1, C_2, w_i) is from Table I and II.

(3) Detection of neutrino emission from the metal deuterides would be a critical step for the research of the condensed matter nuclear science because the selective resonant tunneling of Coulomb barrier at very low energy must be accompanied neutrino emission which is the necessary products of any weak interactions.

There are four possible sites for neutrino detection: DUSEL (South Dakota, USA), KamLand (Japan), Gran Sasso(Italy), and Da-Ya Bay (Canton, China). The positive results of neutrino detection from the metal deuterides would finally turn over the world view on CMNS research

Acknowledgments

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References

1. Arata, Y., and Zhang, Y-C., Proceedings of ICCF-14, Washington D.C., Aug. 10-15, 2008.
2. Violante,V. et al., Proceedings of ICCF-14, Washington D.C., Aug.10-15, 2008.
3. Duane, B. H., “Fusion cross section theory”, in annual Report on CTR Technology 1972(WOKENHAUER, W.C. Ed.), Rep.BNWL-1685, Battelle Pacific Northwest Laboratory, Richland, WA (1972).
4. Book, D. L., NRL Plasma Formulary, Naval Research Laboratory, Washington D.C. (Revised 1980) p.44.
5. Bosch, H. S., Hale, G. M., Nuclear Fusion **12** (1992) 611.
6. Huba, J. D., NRL Plasma Formulary, Naval Research Laboratory, Washington D.C. (Revised 2007) p.44.(Indeed there was another mistake in the citation of NRL Plasma Formulary. The reference [28] there “Rept.BNWL-1685 (Brookhaven National Laboratory, 1972) ” should be corrected as “Rept.BNWL-1685(Battelle Pacific Northwest Laboratory, 1972), p.76”. This mistake was pointed out early in 2002[14].)
7. Li, X. Z., Tian, J., Mei, M. Y., and Li, C. X., Phys. Rev. C **61** (2000) 024610.
8. Li, X. Z., Liu, B., Chen, S., Wei, Q. M., and Hora, H., Laser and Particle Beams **22** (2004) 469.

9. Chadwick, M. B., Oblozinsky, P., Herman, M., at al.,"ENDF/B-VII.0: Next Generation Evaluated Nuclear Data Library for Nuclear Science and Technology", Nuclear Data Sheets, vol. **107**, pp. 2931-3060, 2006.
10. Chen, S., Li, X. Z., “Tritium Production and Selective Resonant Tunneling Model”, Proceedings of ICCF-9, May 19-24, 2002, Beijing China, Ed. X. Z. Li, (Tsinghua Univ. Press), p.42
11. Mamyrin, B. A., Khbarin, L. V., and Yuderich, V. S., “Anomalously High Isotope Ratio $^{3}He/^{4}He$ in Technical-grade Metals and Semiconductors,” Sov. Phys. Dokl. **23**(8). Aug. 1978, p. 581.
12. Hubler, G. K., et al., private communication. August, 2008.
13. ERAB, *Report of the Cold Fusion Panel to the Energy Research Advisory Board*. November, 1989, Washington, DC. DOE/S-0073 DE90 005611
14. Li, X. Z., Fusion Sci. and Tech. **41** (2002) 63.