Excitation transfer: New results, some applications

P L Hagelstein

Motivation

- Interested in understanding new physics involved in excess heat production in F&P experiment
- Interpretation of excess heat as involving nuclear origin, but without energetic nuclear radiation
- Cannot use conventional nuclear diagnostics to study mechanism
- Need other kinds of experiments...
- ...that focus on mechanisms in isolation
- Phonon-nuclear coupling proposed as important interaction
- Now some experimental evidence that supports it
- Consistent with our approach to excess heat models
- Implication of much larger family of effects than just excess heat

Overview of (general) models

- Start with phonon-nuclear coupling
- Since no energetic lattice phonons, excitation transfer is lowest-order physical process
- Propose excitation transfer responsible for some low-energy nuclear emissions from F&P experiments
- Many excitation transfer reactions leads to up-conversion, down-conversion
- Propose up-conversion for collimated x-ray emission experiments
- Subdivision (one deexcitation → multiple lower energy excitations)
- Propose subdivision and down-conversion to explain excess heat
- Toolbox to address many anomalies

Phonon-nuclear interaction

Phonon-nuclear interaction

- Possibility of boost correction of nuclear interaction noted by Breit (1937)
- Nuclear interaction modified in moving frame compared to rest frame…
- … so oscillations or accelerations can couple to internal nuclear transitions
- Effect known in the literature for other applications (but not for coupling with phonons)

Relativistic problem

Relativistic Hamiltonian: $H = \sum_j \boldsymbol{\alpha}_j \cdot c\mathbf{p}_j + \sum_j \beta_j mc^2 + \sum_{j<k} V_{jk}(\mathbf{r}_k - \mathbf{r}_j)$

Incomplete F-W rotation: $H' = e^{iS}\left(H - i\hbar\frac{\partial}{\partial t}\right)e^{-iS}, \ S = -i\frac{1}{2Mc^2}\sum_j \beta_j \boldsymbol{\alpha}_j \cdot c\mathbf{P}$

$$H' \rightarrow \boxed{\frac{|\mathbf{P}|^2}{2M}} + \boxed{\sum_j \boldsymbol{\alpha}_j \cdot c\boldsymbol{\pi}_j + \sum_j \beta_j mc^2 + \sum_{j<k} V_{jk}(\xi_k - \xi_j)} + \boxed{\sum_j \mathbf{a}_j \cdot c\mathbf{P}}$$

nucleus as a particle internal nuclear model coupling nucleus as a particle

internal nuclear structure

$$\hat{H}' = \boxed{\frac{|\hat{\mathbf{P}}|^2}{2M}} + \boxed{\sum_j \beta_j mc^2 + \sum_j \boldsymbol{\alpha}_j \cdot c\hat{\boldsymbol{\pi}}_j + \sum_{j<k} \hat{V}_{jk}}$$
$$+ \left\{ \sum_j \beta_j \frac{\hat{\boldsymbol{\pi}}_j}{M} + \frac{1}{2Mc} \sum_{j<k} \left[\left(\beta_j \boldsymbol{\alpha}_j + \beta_k \boldsymbol{\alpha}_k \right), \hat{V}_{jk} \right] \right\} \cdot \hat{\mathbf{P}}$$

coupling between center of mass motion and internal nuclear degrees of freedom

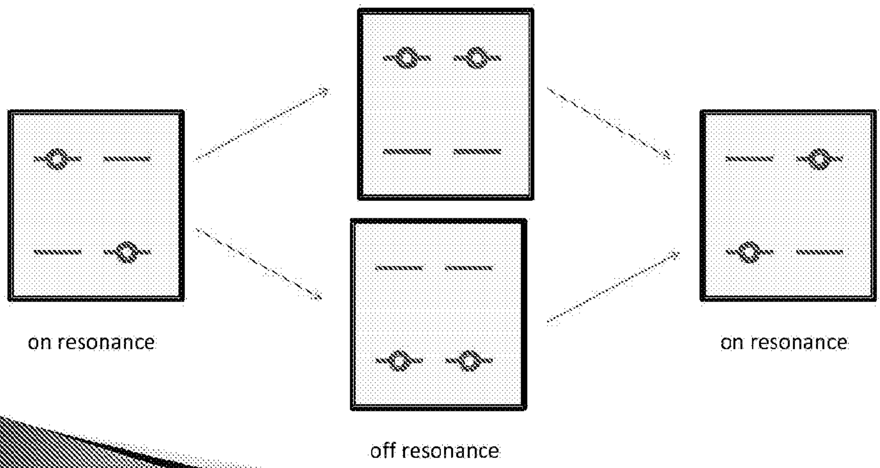
P L Hagelstein, J Cond. Mat. Nucl. Sci. **20** 139 (2016)

Excitation transfer

Excitation transfer

- Excitation transfer proposed around 1930 in connection with energy exchange in biomolecules...
- ... widely used in biophysics these days
- Transfer of excitation from one quantum system to another
- Transfer of electronic excitation known and observed in experiment
- Proposal in our work for phonon-mediated nuclear excitation transfer
- Recent experiments support mechanism

Excitation transfer



Simple model, weak coupling

$$Ec_1 = (\Delta E + (n+\frac{1}{2})\hbar\omega_0)c_1 + V_{12}c_2 + V_{13}c_3 + V_{14}c_4 + V_{15}c_5$$

$$Ec_2 = (n-1+\frac{1}{2})\hbar\omega_0 c_2 + V_{21}c_1 + V_{26}c_6$$

$$Ec_3 = (n+1+\frac{1}{2})\hbar\omega_0 c_3 + V_{31}c_1 + V_{36}c_6$$

$$Ec_4 = (2\Delta E + (n-1+\frac{1}{2})\hbar\omega_0)c_4 + V_{41}c_1 + V_{46}c_6$$

$$Ec_5 = (2\Delta E + (n+1+\frac{1}{2})\hbar\omega_0)c_5 + V_{51}c_1 + V_{56}c_6$$

$$Ec_6 = (\Delta E + (n+\frac{1}{2})\hbar\omega_0)c_6 + V_{62}c_2 + V_{63}c_3 + V_{64}c_4 + V_{65}c_5$$

$$E\begin{pmatrix} c_1 \\ c_6 \end{pmatrix} = \begin{pmatrix} H_{11} & V_{16} \\ V_{61} & H_{66} \end{pmatrix}\begin{pmatrix} c_1 \\ c_6 \end{pmatrix}$$

$$V_{16} = V_{61}^* = \frac{V_{12}V_{26} - V_{15}V_{56}}{\Delta E + \hbar\omega_0} + \frac{V_{13}V_{36} - V_{14}V_{46}}{\Delta E - \hbar\omega_0}$$

$$\begin{aligned} V_{16} &= \frac{V_0^2\left(n-(n+1)\right)}{\Delta E + \hbar\omega_0} + \frac{V_0^2\left((n+1)-n\right)}{\Delta E - \hbar\omega_0} \\ &= -\frac{V_0^2}{\Delta E + \hbar\omega_0} + \frac{V_0^2}{\Delta E - \hbar\omega_0} \\ &\approx -\frac{V_0^2}{\Delta E}(1-\frac{\hbar\omega_0}{\Delta E}) + \frac{V_0^2}{\Delta E}(1+\frac{\hbar\omega_0}{\Delta E}) = \frac{2V_0^2\hbar\omega_0}{\Delta E^2} \end{aligned}$$

$$V_{16} = V_{61} \approx \frac{2V_0^2\hbar\omega_0}{\Delta E^2}$$

Phonon energy

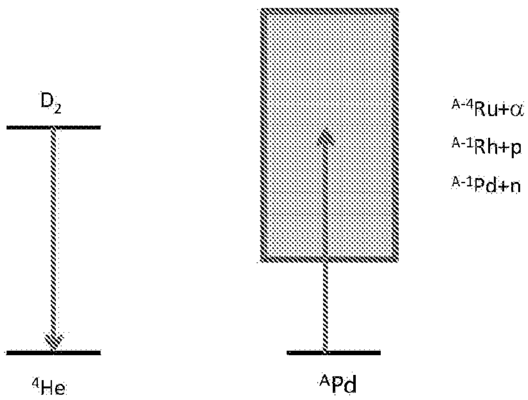
Nuclear transition energy

Thinking

- Quantum mechanical effect
- Intermediate states off of resonance
- Need at least 2 phonon exchange interactions for nuclear excitation transfer
- Overall effect is to move the excitation from one nucleus to another
- Destructive interference reduces indirect interaction strength
- Faster for lower energy nuclear transition
- Faster if phonon energy is high

Applications

Low-level energetic α, n emission



P L Hagelstein, Proc ICCF9

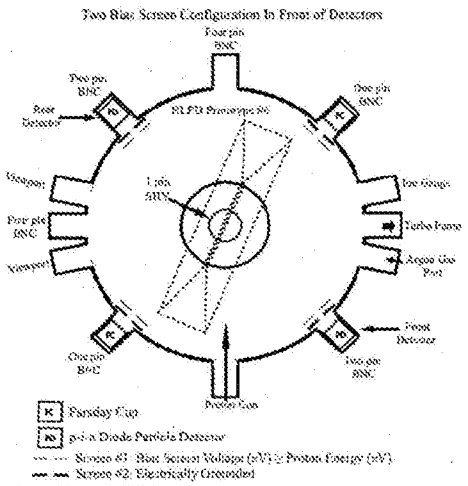
Thinking

- Transfer of $D_2/^4He$ (24 MeV) energy to disintegrate Pd nucleus
- Would produce low-level energetic alphas (observations reported by Chambers et al, Lipson et al, others)
- Would produce low-level energetic neutrons (observations reported by Roussetki et al, by Mosier-Boss et al)

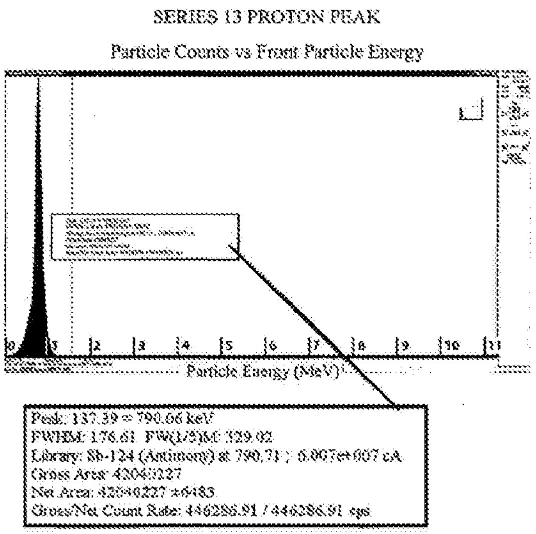
Experiment of Lipinski and Lipinski

- Claimed observations of very large enhancement of $p(^7Li,\alpha)\alpha$ fusion reaction cross section at low (sub keV) energy
- Interpreted as due to gravitational resonance effect
- Data shows very strong proton signal at 0.79 MeV
- Results from 25 different experimental series discussed in two patent applications (2009,2014)
- We will focus on series 13 experiment and results

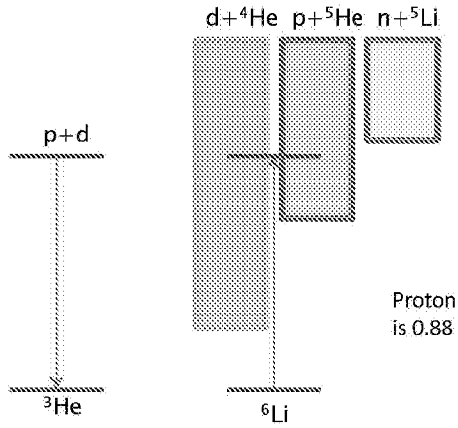
Lipinski and Lipinski experiment



Proton signal

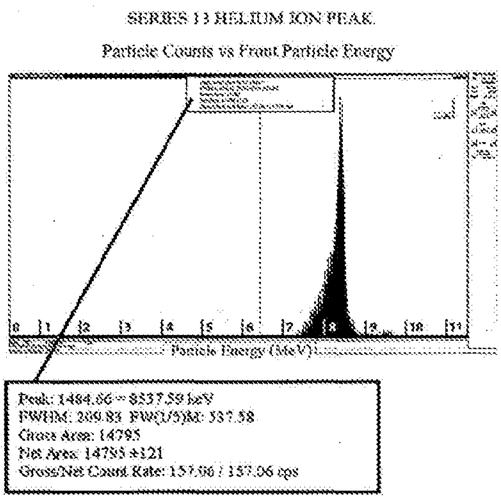


Incoherent excitation transfer



Proton energy including recoil is 0.88 MeV

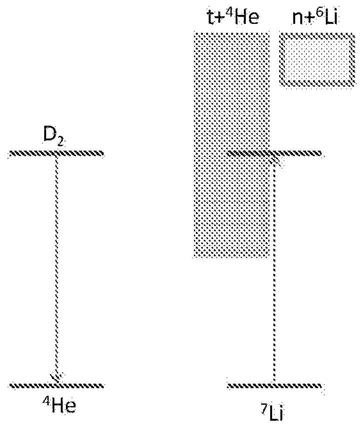
Alpha signal



Interpretations

- Lipinski and Lipinski interpret this peak as due to (anomalous) p(^{7}Li,α)α + 17.34 MeV due to sub-keV proton beam
- Energy of ejected alpha is 8.67 MeV
- We considered the same reaction as potentially a result of 0.79 MeV protons
- ...but the fusion cross section is too low by O(100)
- Also considered the ejected alpha as perhaps due to incoherent excitation transfer reaction

Incoherent excitation transfer

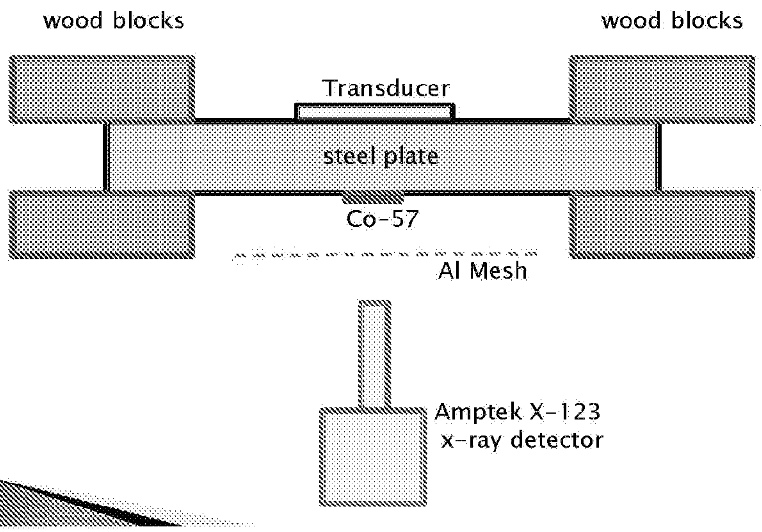


alpha energy including recoil is 9.13 MeV

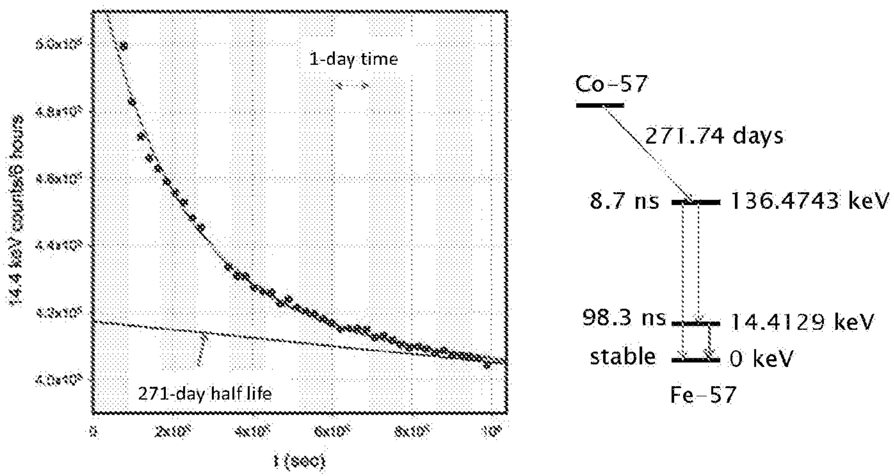
Thinking

- Experiment of Lipinski and Lipinski is important if correct
- Fusion not expected with protons below 1 keV
- Effort at MIT to confirm
- Inventors attribute effect to gravity resonance effect between p and ^7Li
- 0.79 MeV proton signal attributed to "backscatter"
- We contemplate that 0.79 MeV proton signal might be a result of incoherent excitation transfer reaction from HD/^3He
- ...and 8.54 MeV a signal might a result of incoherent excitation transfer reaction from D_2/^4He

Experiment



Metzler et al, J Cond Mat Nuclear Science 27 (2018) 46-96



Thinking

- Set up the experiment to look for excitation transfer due to MHz phonon exchange
- But no obvious response to MHz vibrations
- Instead saw a response connected to creep
- Interpretation: delocalization of excitation of 14.4 keV state due to phonon-mediated non-resonant excitation transfer
- Also evidence for angular anisotropy of 122 keV, 136 keV gammas
- Interpretation: phase correlation of 136 keV state due to phonon-mediated resonant excitation transfer

Basic model predictions for E1, M1 transitions

Modeling

- Have developed a formalism for coupling phonons and nuclei

$$H = \sum_k \hbar\omega_k a_k^\dagger a_k + \sum_j \mathbf{M}_j c^2 + \sum_j \mathbf{a}_j \cdot c\mathbf{P}_j$$

with

$$\mathbf{P}_j = \sum_k \frac{\partial \mathbf{P}_j}{\partial a_k} a_k + \sum_k \frac{\partial \mathbf{P}_j}{\partial a_k^\dagger} a_k^\dagger$$

- Time to exercise the model!
- Phonon-nuclear coupling to nuclear electric dipole and related nuclear transitions
- Simplest for E1 (electric dipole) nuclear transitions
- More complicated for M1 (magnetic dipole) and E2 (electric quadrupole) transitions

E1 transitions, resonant case

$$\left(\hat V (E - \hat H_0)^{-1} \hat V\right)_{\text{resonant}} \rightarrow \frac{Mc^2}{(\Delta E)^2} \sum_{j<j'} \sum_{m_0} \sum_{m_1} \sum_{m_0'} \sum_{m_1'} \left(|J_0 m_0\rangle\langle J_1 m_1|\right)_j \left(|J_1 m_1'\rangle\langle J_0 m_0'|\right)_{j'}$$

$$\langle J_0 m_0|\mathbf{a}_j|J_1 m_1\rangle \cdot \left[\frac{1}{N}\sum_{\mathbf{k},\sigma} (\hbar\omega_{\mathbf{k},\sigma})^2 \mathbf{u}_{\mathbf{k},\sigma}\mathbf{u}_{\mathbf{k},\sigma} \cos\left(\mathbf{k}\cdot(\mathbf{R}_{j'}^{(0)} - \mathbf{R}_j^{(0)})\right)\right] \cdot \langle J_1 m_1'|\mathbf{a}_{j'}|J_0 m_0'\rangle$$

$$+\frac{Mc^2}{(\Delta E)^2} \sum_{j<j'} \sum_{m_0} \sum_{m_1} \sum_{m_0'} \sum_{m_1'} \left(|J_1 m_1\rangle\langle J_0 m_0|\right)_j \left(|J_0 m_0'\rangle\langle J_1 m_1'|\right)_{j'}$$

$$\langle J_1 m_1|\mathbf{a}_j|J_0 m_0\rangle \cdot \left[\frac{1}{N}\sum_{\mathbf{k},\sigma} (\hbar\omega_{\mathbf{k},\sigma})^2 \mathbf{u}_{\mathbf{k},\sigma}\mathbf{u}_{\mathbf{k},\sigma} \cos\left(\mathbf{k}\cdot(\mathbf{R}_{j'}^{(0)} - \mathbf{R}_j^{(0)})\right)\right] \cdot \langle J_0 m_0'|\mathbf{a}_{j'}|J_1 m_1'\rangle \}$$

M1 transitions, 1-mode, resonant case

$$
\begin{aligned}
&\left(\hat{V}(E-\hat{H}_0)^{-1}\hat{V}(E-\hat{H}_0)^{-1}\hat{V}(E-\hat{H}_0)^{-1}\hat{V}\right)_{\text{resonant}} \to \\
&\frac{(Mc^2)^2}{4N}\sum_{J_2}\sum_{J_2'}\frac{\begin{pmatrix}(E_1-E_0)^2-2(E_1-E_0)[(E_2-E_0)+(E_2'-E_0)] \\ +2[(E_2-E_0)^2+(E_2-E_0)(E_2'-E_0)+(E_2'-E_0)^2]\end{pmatrix}}{(E_2-E_0)(E_2'-E_0)(E_1-E_2)(E_1-E_2')(E_2+E_2'-E_0-E_1)} \\
&\sum_{j}\sum_{j'}\sum_{m_0}\sum_{m_1}\sum_{m_2}\sum_{m_0'}\sum_{m_1'}\sum_{m_2'}\left(|J_0m_0\rangle\langle J_1m_1|\right)_j\left(|J_1m_1'\rangle\langle J_0m_0'|\right)_{j'} \\
&\sum_{\alpha}\sum_{\beta}\sum_{\gamma}\sum_{\delta}(\langle J_0m_0|a_j|J_2m_2\rangle)_\alpha(\langle J_2m_2|a_j|J_1m_1\rangle)_\beta(\langle J_1m_1'|a_{j'}|J_2'm_2'\rangle)_\gamma(\langle J_2'm_2'|a_{j'}|J_0m_0'\rangle)_\delta \\
&\left[\frac{1}{N}\sum_{\mathbf{k},\sigma}(\hbar\omega_{\mathbf{k},\sigma})^2(\mathbf{u}_{\mathbf{k},\sigma})_\alpha(\mathbf{u}_{\mathbf{k},\sigma})_\beta(\mathbf{u}_{\mathbf{k},\sigma})_\gamma(\mathbf{u}_{\mathbf{k},\sigma})_\delta\cos\left(2\mathbf{k}(\mathbf{R}_j^{(0)}-\mathbf{R}_{j'}^{(0)})\right)\right] \\
&+i\frac{(Mc^2)^2}{2N}\sum_{J_2}\sum_{J_2'}\frac{(2E_2-E_0-E_1)(2E_2'-E_0-E_1)}{(E_1-E_0)(E_2-E_0)(E_2'-E_0)(E_2-E_1)(E_2'-E_1)} \\
&\sum_{j}\sum_{j'}\sum_{m_0}\sum_{m_1}\sum_{m_2}\sum_{m_0'}\sum_{m_1'}\sum_{m_2'}\left(|J_0m_0\rangle\langle J_1m_1|\right)_j\left(|J_1m_1'\rangle\langle J_0m_0'|\right)_{j'} \\
&\sum_{\alpha}\sum_{\beta}\sum_{\gamma}\sum_{\delta}(\langle J_0m_0|a_j|J_2m_2\rangle)_\alpha(\langle J_2m_2|a_j|J_1m_1\rangle)_\beta(\langle J_1m_1'|a_{j'}|J_2'm_2'\rangle)_\gamma(\langle J_2'm_2'|a_{j'}|J_0m_0'\rangle)_\delta \\
&\left[\frac{1}{N}\sum_{\mathbf{k},\sigma}(\hbar\omega_{\mathbf{k},\sigma})^3(\mathbf{u}_{\mathbf{k},\sigma})_\alpha(\mathbf{u}_{\mathbf{k},\sigma})_\beta(\mathbf{u}_{\mathbf{k},\sigma})_\gamma(\mathbf{u}_{\mathbf{k},\sigma})_\delta\tau_{\mathbf{k},\sigma}\sin\left(2\mathbf{k}(\mathbf{R}_j^{(0)}-\mathbf{R}_{j'}^{(0)})\right)\right].
\end{aligned}
$$

Thinking

- OK, have mechanism…
- Have experimental results…
- Can exercise formalism to make predictions…

- However, theory off by orders of magnitude from experiment

Add loss…

Loss

- In 2002 we noticed that augmenting spin-boson models with asymmetric loss could dramatically increase rates for up-conversion, down-conversion
- Would also expect modification of excitation transfer rates with loss

E1 transitions, loss, resonant case

$$
\left(\hat{V}(E-\hat{H}_0)^{-1}\hat{V}\right)_{m_0 m_1 m_0' m_1'} \rightarrow
$$

$$
-i\frac{\hbar}{2}(\gamma_{00}+\gamma_{11}-\gamma_{01}-\gamma_{10})\frac{Mc^2}{2(\Delta E)^2}\sum_{j<j'}\sum_{m_0}\sum_{m_1}\sum_{m_0'}\sum_{m_1'}\Big(|J_0 m_0\rangle\langle J_1 m_1|\Big)_j\Big(|J_1 m_1'\rangle\langle J_0 m_0'|\Big)_{j'}
$$

$$
\langle J_0 m_0|\mathbf{a}_j|J_1 m_1\rangle\cdot\left[\frac{1}{N}\sum_{\mathbf{k},\sigma}(\hbar\omega_{\mathbf{k},\sigma})^2\mathbf{u}_{\mathbf{k},\sigma}\mathbf{u}_{\mathbf{k},\sigma}(2\bar{n}_{\mathbf{k},\sigma}+1)\cos\left(\mathbf{k}\cdot(\mathbf{R}_j^{(0)}-\mathbf{R}_{j'}^{(0)})\right)\right]\cdot\langle J_1 m_1'|\mathbf{a}_{j'}|J_0 m_0'\rangle
$$

$$
-i\frac{\hbar}{2}(\gamma_{00}+\gamma_{11}-\gamma_{01}-\gamma_{10})\frac{Mc^2}{2(\Delta E)^2}\sum_{j<j'}\sum_{m_0}\sum_{m_1}\sum_{m_0'}\sum_{m_1'}\Big(|J_1 m_1\rangle\langle J_0 m_0|\Big)_j\Big(|J_0 m_0'\rangle\langle J_1 m_1'|\Big)_{j'}
$$

$$
\langle J_1 m_1|\mathbf{a}_j|J_0 m_0\rangle\cdot\left[\frac{1}{N}\sum_{\mathbf{k},\sigma}(\hbar\omega_{\mathbf{k},\sigma})^2\mathbf{u}_{\mathbf{k},\sigma}\mathbf{u}_{\mathbf{k},\sigma}(2\bar{n}_{\mathbf{k},\sigma}+1)\cos\left(\mathbf{k}\cdot(\mathbf{R}_j^{(0)}-\mathbf{R}_{j'}^{(0)})\right)\right]\cdot\langle J_0 m_0'|\mathbf{a}_{j'}|J_1 m_1'\rangle\Big\}.
$$

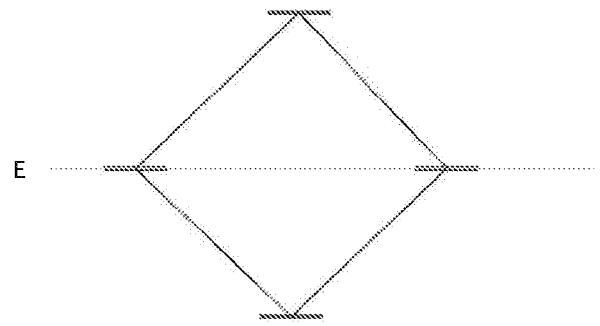
Thinking

- Dramatic increase in indirect coupling when (asymmetric) loss important
- Large effect also for M1 transitions
- Models close to experiment qualitatively
  - See resonant excitation transfer effect for close nuclei
  - See non-resonant delocalization effect for distant nuclei

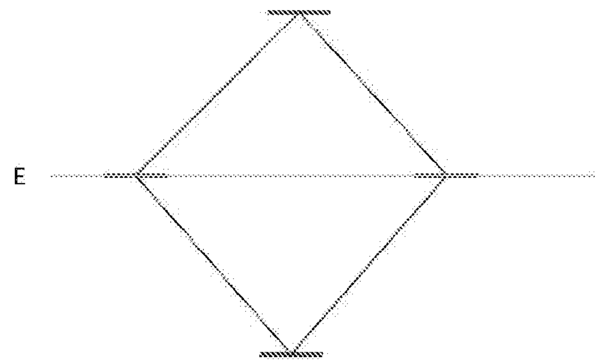
- However, predicted effect much smaller than effect observed

Basis state shifts off of resonance

Cancellation without off-res shift



Less cancellation with shift



Basis state energy shift off of resonance

- Noticed that this might provide a possible resolution to the problem in 2018
- Papers in the literature discuss modification of nuclear interaction off of resonance…
- … but no systematic quantification of the amount of shift expected
- So, need to develop excitation transfer formula that take effect into account
- Need to quantify energy shifts off of resonance

E1 transitions, shifts, resonant case

$$\left(\hat{V}(E-\hat{H}_0)^{-1}\hat{V}\right)_{coherent}$$

$$\rightarrow \sum_{j}\sum_{j'}\sum_{m_0}\sum_{m_1}\sum_{m_0'}\sum_{m_1'}\sum_{\mathbf{k},\sigma}\frac{Me^2\hbar\omega_{\mathbf{k},\sigma}}{2N}$$

$$\Big\{|J_0m_0\rangle\langle J_0m_0|\mathbf{u}_{\mathbf{k},\sigma}\cdot\mathbf{a}_j|J_1m_1\rangle\langle J_1m_1||J_1m_1'\rangle\langle J_1m_1'|\mathbf{u}_{\mathbf{k},\sigma}\cdot\mathbf{a}_{j'}|J_0m_0'\rangle\langle J_0m_0'|$$

$$\frac{E_{00}+E_{11}-2E_{10}}{(E_{10}-E_{00})(E_{11}-E_{10})}(2n_{\mathbf{k},\sigma}+1)\cos[\mathbf{k}\cdot(\mathbf{R}_j^{(0)}-\mathbf{R}_{j'}^{(0)})]$$

$$+|J_1m_1\rangle\langle J_1m_1|\mathbf{u}_{\mathbf{k},\sigma}\cdot\mathbf{a}_j|J_0m_0\rangle\langle J_0m_0||J_0m_0'\rangle\langle J_0m_0'|\mathbf{u}_{\mathbf{k},\sigma}\cdot\mathbf{a}_{j'}|J_1m_1'\rangle\langle J_1m_1'|$$

$$\frac{E_{00}+E_{11}-2E_{10}}{(E_{10}-E_{00})(E_{11}-E_{10})}(2n_{\mathbf{k},\sigma}+1)\cos[\mathbf{k}\cdot(\mathbf{R}_j^{(0)}-\mathbf{R}_{j'}^{(0)})]\Big\}.$$

M1 transitions, 1-mode, resonant case

$$\left(\hat{V}(E-\hat{H}_0)^{-1}\hat{V}(E-\hat{H}_0)^{-1}\hat{V}(E-\hat{H}_0)^{-1}\hat{V}\right)_{resonant}\rightarrow T_{a0}+T_{a1}+T_{a2}+T_c$$

$$T_{a0}=\frac{(Me^2)^2}{4N}\sum_{J_2}\sum_{J_2'}\left(\frac{2}{(E_{10}-E_{00})(E_{10}-E_{20})(E_{10}-E_{2'0})}+\frac{2}{(E_{10}-E_{11})(E_{10}-E_{21})(E_{10}-E_{2'1})}\right.$$

$$\left.+\frac{1}{(E_{10}-E_{20})(E_{10}-E_{2'0})(E_{10}-E_{2'2})}+\frac{1}{(E_{10}-E_{21})(E_{10}-E_{2'1})(E_{10}-E_{2'2})}\right)$$

$$\sum_{j}\sum_{j'}\sum_{m_0}\sum_{m_1}\sum_{m_2}\sum_{m_0'}\sum_{m_1'}\sum_{m_2'}\Big(|J_0m_0\rangle\langle J_1m_1|\Big)_j\Big(|J_1m_1'\rangle\langle J_0m_0'|\Big)_{j'}$$

$$\sum_{\alpha}\sum_{\beta}\sum_{\gamma}\sum_{\delta}\langle J_0m_0|a_j|J_2m_2\rangle_\alpha\langle J_2m_2|a_j|J_1m_1\rangle_\beta\langle J_1m_1'|a_{j'}|J_2'm_2'\rangle_\gamma\langle J_2'm_2'|a_{j'}|J_0m_0'\rangle_\delta$$

$$\left[\frac{1}{N}\sum_{\mathbf{k},\sigma}(\hbar\omega_{\mathbf{k},\sigma})^2(\mathbf{u}_{\mathbf{k},\sigma})_\alpha(\mathbf{u}_{\mathbf{k},\sigma})_\beta(\mathbf{u}_{\mathbf{k},\sigma})_\gamma(\mathbf{u}_{\mathbf{k},\sigma})_\delta\cos\Big(2\mathbf{k}(\mathbf{R}_j^{(0)}-\mathbf{R}_{j'}^{(0)})\Big)\right]$$

Thinking

- Even larger increases in indirect coupling rate…
- … if the energy shift off of resonance are greater than the loss rates
- So, need to develop estimates for the shifts
- This version of the model just might connect with experiment!

- Note that if so, would not need loss for up-conversion and down-conversion models

Deuteron off of resonance

Deuteron

- Many models for the deuteron available
- Calculation of the nuclear force off of resonance from scratch in the chiral effective field theory model is lots of work…
- Start with a simpler calculation
- Not so difficult to calculate extension of single-pion exchange contribution off of resonance
- This would get the long-range contribution
- Should be the dominant contribution to the shift for the deuteron
- Why not just add the increment to an existing model for the deuteron…

One-pion exchange

Relativistic one-pion exchange interaction off of resonance

$$V_{12} = -\frac{f^2}{\mu_\pi^2}(\tau_2 \cdot \tau_1)(\beta\gamma^{(5)})_2(\beta\gamma^{(5)})_1 \frac{1}{2}\int \frac{e^{i\mathbf{k}\cdot(\mathbf{r}_2-\mathbf{r}_1)}}{\hbar\omega_{\mathbf{k}}(E_{off}-\hbar\omega_{\mathbf{k}})}\frac{d^3\mathbf{k}}{(2\pi)^3} + (1 \leftrightarrow 2)$$

$$= -\frac{f^2}{\mu_\pi^2}(\tau_2 \cdot \tau_1)(\beta\gamma^{(5)})_2(\beta\gamma^{(5)})_1 \frac{1}{2\pi^2|\mathbf{r}_2-\mathbf{r}_1|}\int_0^\infty \frac{k\sin\left(k|\mathbf{r}_2-\mathbf{r}_1|\right)}{\hbar\omega_k(E_{off}-\hbar\omega_k)}dk$$

Pseudo-scalar and pseudo-vector interactions result in the same contribution for the one-pion exchange contribution

$$\int_0^\infty \frac{k\sin\left(k|\mathbf{r}_2-\mathbf{r}_1|\right)}{\hbar\omega_k(E_{off}-\hbar\omega_k)}dk = \int_0^\infty \frac{k\sin\left(k|\mathbf{r}_2-\mathbf{r}_1|\right)}{\sqrt{(\mu c^2)^2+\hbar^2c^2k^2}(E_{off}-\sqrt{(\mu c^2)^2+\hbar^2c^2k^2})}dk$$

$$= -\sum_i C_i \int_0^\infty \frac{k\sin\left(k|\mathbf{r}_2-\mathbf{r}_1|\right)}{(\mu_i c^2)^2+\hbar^2c^2k^2}dk \qquad \text{(fitting)}$$

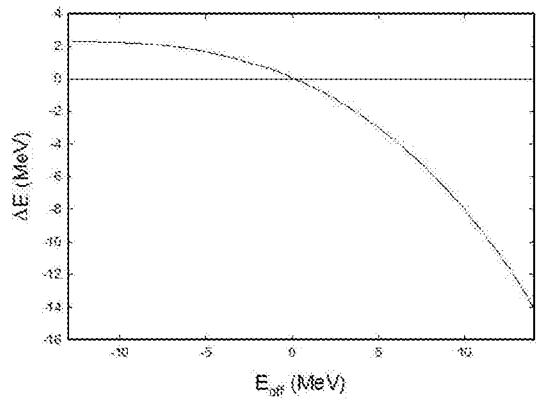
Deuteron model

Modification of the Hamada-Johnston model

$$\hat{H} = \frac{|\hat{\mathbf{p}}|^2}{M} \underbrace{+V_C + V_T\hat{S}_{12} + V_{LS}\hat{\mathbf{L}}\cdot\hat{\mathbf{S}} + V_{LL}\mathbf{L}_{12}}_{\text{Hamada-Johnston potential}} + \underbrace{\Delta V_C + \Delta V_T\hat{S}_{12}}_{\text{off-resonant correction}}$$

kinetic energy, reduced mass Is M/2

Deuteron binding energy shift



Thinking

- Big shift of the deuteron binding energy off of resonance
- Shift is nonlinear as a function of the off resonant energy…
- … which is important since the increase in excitation transfer rate depends on second derivative
- Still need shifts for other nuclei
- But looks like this approach is going to work!

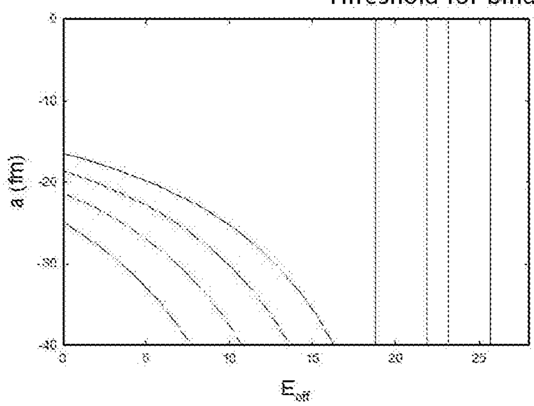
Dineutron off of resonance

Dineutron

- Deuteron problem important since it is simplest
- But no experiments expect with deuterons off of resonance
- Story is different for dineutron
- Iwamura experiment shows mass increases
- Multiple-neutron transfer a possible explanation
- But ... dineutron is not bound (same for multi-neutron clusters)
- Dineutron would be bound off of resonance
- Possible to use same approach to evaluate dineutron binding off of resonance

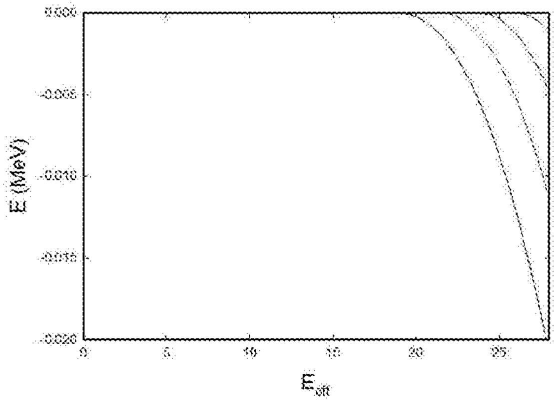
Dineutron scattering length

Threshold for binding



Use hard core radius as a parameter: 0.343, 0.342, 0.341,0.340

Dineutron binding energy



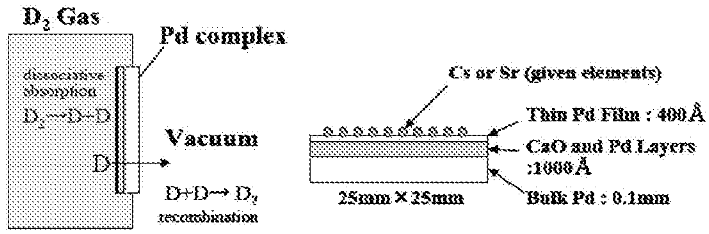
Use hard core radius as a parameter: 0.343, 0.342, 0.341,0.340

Thinking

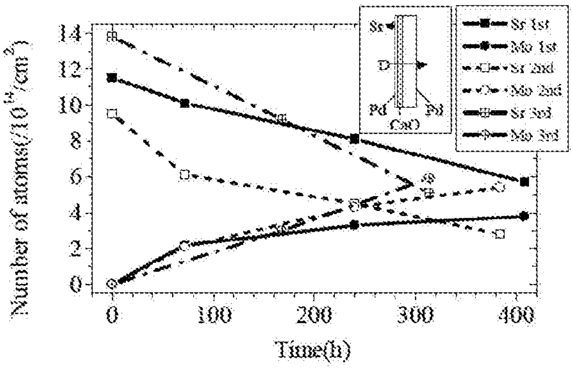
- Dineutron can be bound off of resonance…
- … as long as the off-resonant energy large enough
- Would expect multi-neutron clusters to be bound also far off of resonance
- Means that we might expect multi-neutron exchange to be possible off of resonance
- Perhaps an explanation for Iwamura transmutation experiment

Iwamura transmutation experiment

Iwamura 2003 transmutation exp't

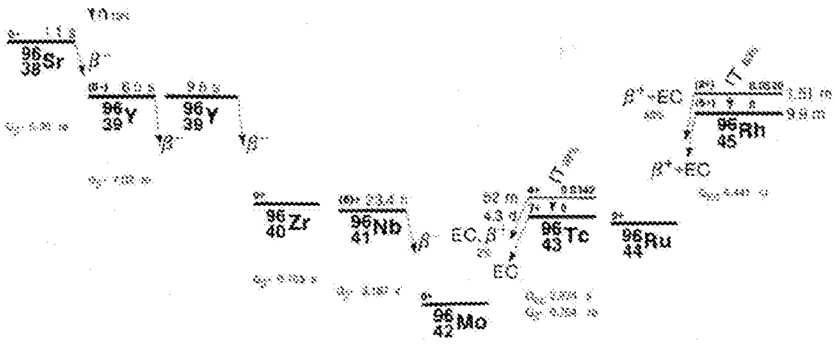


Y Iwamura, T Itoh, M Sakano and S Kuribayashi Proc ICCF10 (2003)



Off-resonant neutron cluster transfer

$^{110}Pd + ^{88}Sr \rightarrow (^{102}Pd + ^{8}n + ^{88}Sr)_{virtual} \rightarrow ^{102}Pd + ^{96}Sr$



Thinking

- 8-neutron cluster on resonance not bound
- Nuclear potential much stronger off of resonance
- Dineutron bound at about +25 MeV off-resonance
- Would expect 8 neutron cluster to be bound with +20-35 MeV off of resonance (need a calculation)
- Possible in connection with single or multiple D_2/^{4}He excitation transfer coherent process

More thinking

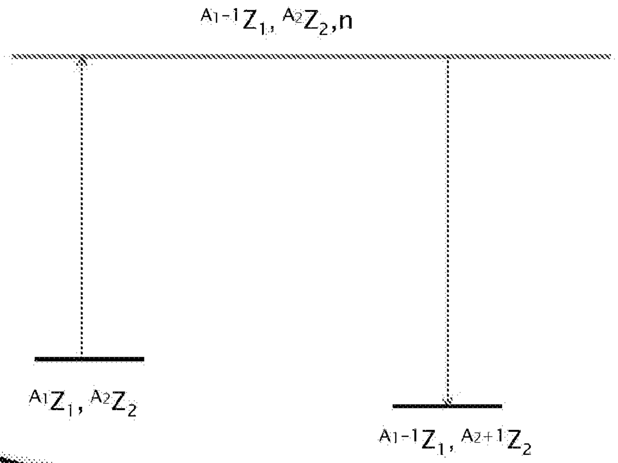
- If true, then similar exp't with restricted Pd isotopes would transfer a smaller neutron cluster
- If true, may be possible to see beta decay products (or rule out proposed mechanism if decay products not present)

Phonon-mediated neutron transfer

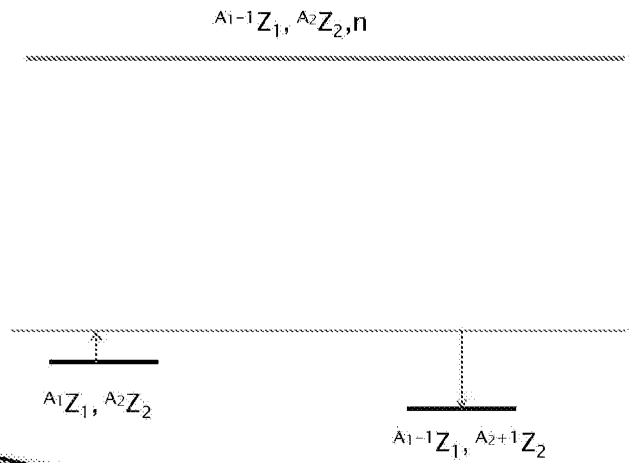
Single-neutron transfer

- Proposed in the 1990s by Hagelstein
- Analysis of the time did not support possibility
- Revisit in light of phonon-nuclear interaction
- Phonon-induced neutron transfer mechanism
- Resonant transfer probably expected, but may not be a good way to detect
- Off-resonant neutron transfer could make new nuclei
- If you make radioactive nuclei, then much easier to detect
- If it works, opens the possibility for eliminating some radioactive nuclei as an application

Resonant neutron transfer



Off-resonant neutron transfer



Thinking

- Looks good as a mechanism
- Would like candidates that minimize energy mismatch between initial and final states
- To analyze, download isotopic mass table
- Computer code to sort through all possible neutron transfer reactions
- Look for nuclei pairs where a new unstable nucleus is made

Results

stable	stable	stable	unstable	$T_{1/2}$	$\lvert\Delta E\rvert$ (keV)
Hf-179	Hf-178	Ar-40	Ar-41	110 min	0.04
Lu-176	Lu-175	Te-126	Te-127	9.35 h	0.28
Hf-178	Hf-177	Pd-102	Pd-103	17.0 d	0.56
Er-167	Er-166	Xe-132	Xe-133	5.25 d	0.57
Kr-83	Kr-84	Sm-144	Sm-143	8.75 min	0.59
Gd-155	Gd-154	Xe-132	Xe-133	5.25 d	0.57
Os-187	Os-188	Ho-165	Ho-164	28.8 min	0.65
Er-167	Er-168	Ir-193	Ir-192	73.8 d	0.65
Hf-177	Hf-176	Tb-159	Tb-160	72.3 d	0.75

Thinking

- Candidates available with relatively small overall mass defects
- Lowest one is:

$$^{179}\text{Hf}+^{40}\text{Ar} \rightarrow (^{178}\text{Hf}+\text{n}+^{40}\text{Ar})_{\text{virtual}} \rightarrow {}^{178}\text{Hf}+^{41}\text{Ar} + \delta\text{E}$$

- Perhaps try it out with Ar ion beam on Hf sample, look for radioactive ^{41}Ar
- Others could be done with either alloys, co-deposited material, or perhaps evaporations along with stress (similar to excitation transfer experiments)

Conclusions

Conclusions

- Excitation transfer models analyzed, but straightforward predictions too low to connect with experiment
- Loss helps, but not enough to fix things
- Off-resonance energy shifts proposed last year to address problem
- First computation of deuteron binding energy off of resonance – calculate big shift, and strong nonlinearity
- We expect this version of the model to connect with experiment
- Proposal for phonon-mediated single neutron transfer reactions...
- ... could test by making and detecting short-lived unstable nuclei
- Expect dineutron stabilization off of resonance
- Proposal for multi-neutron cluster exchange off of resonance where cluster can be bound