PHONON-MEDIATED OFF-RESONANT NEUTRON TRANSFER

TECHNICAL FIELD

[0001] The present invention relates generally to off-resonant neutron transfer, and more specifically to phonon-mediated, off-resonant neutron transfer.

BACKGROUND

[0002] Off-resonant neutron transfer reactions as a possible mechanism were introduced in the 1990s as a possible route to circumvent the Coulomb barrier in an effort to account for anomalies seen in the Fleischmann-Pons experiment.

[0003] The present disclosure relates to improved systems and methods of off-resonant neutron transfer.

SUMMARY

[0004] This summary is provided to introduce in a simplified form concepts that are further described in the following detailed descriptions. This summary is not intended to identify key features or essential features of the claimed subject matter, nor is it to be construed as limiting the scope of the claimed subject matter.

[0005] Disclosed herein is a method of moving neutrons from a first nucleus to a neighboring nucleus, including using a source of THz phonons on one side of a thin sample, and preferentially moving transferred neutrons from the one side to a second side.

[0006] According to one or more embodiments, the first nucleus is Fe-57.

[0007] According to one or more embodiments, the neighboring nucleus is Fe-56.

[0008] According to one or more embodiments, a method of transferring a neutron from one isotope of a first element to a different isotope includes, using phonon-mediated, off-resonant neutron transfer.

[0009] According to one or more embodiments, the different isotope is an isotope of the first element.

[0010] According to one or more embodiments, the different isotope is an isotope of a second element, wherein the first element and the second element are not the same element.

[0011] According to one or more embodiments, the method includes detecting neutron transfer using nuclear magnetic resonance (NMR) spectroscopy.

[0012] According to one or more embodiments, the method includes detecting neutron transfer using neutron activation analysis (NAA).

[0013] According to one or more embodiments, a method of neutron transfer includes, transferring a neutron onto a stable isotope, wherein a daughter with one more neutron is unstable, and verifying the transferring step by looking for an emitted beta, characteristic x-ray, gamma, or alpa.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The foregoing, as well as the following Detailed Description of preferred embodiments, is better understood when read in conjunction with the appended drawings. For the purposes of illustration, there is shown in the drawings exemplary embodiments; however, the presently disclosed subject matter is not limited to the specific methods and instrumentalities disclosed.

[0015] The embodiments illustrated, described, and discussed herein are illustrative of the present invention. As these embodiments of the present invention are described with reference to illustrations, various modifications or adaptations of the methods and or specific structures described may become apparent to those skilled in the art. It will be appreciated that modifications and variations are covered by the above teachings and within the scope of the appended claims without departing from the spirit and intended scope thereof. All such modifications, adaptations, or variations that rely upon the teachings of the present invention, and through which these teachings have advanced the art, are considered to be within the spirit and scope of the present invention. Hence, these descriptions and drawings should not be considered in a limiting sense, as it is understood that the present invention is in no way limited to only the embodiments illustrated.

[0016] Figure 1 illustrates an exemplary isotope table, according to one or more embodiments of the presently disclosed subject matter.

[0017] Particular embodiments of the presently disclosed subject matter are described in detail in Appendix A attached hereto.

DETAILED DESCRIPTION

[0018] These descriptions are presented with sufficient details to provide an understanding of one or more particular embodiments of broader inventive subject matters. These descriptions expound upon and exemplify particular features of those particular embodiments without limiting the inventive subject matters to the explicitly described embodiments and features. Considerations in view of these descriptions will likely give rise to additional and similar embodiments and features without departing from the scope of the inventive subject matters. Although the term “step” may be expressly used or implied relating to features of processes or methods, no implication is made of any particular order or sequence among such expressed or implied steps unless an order or sequence is explicitly stated.

[0019] Any dimensions expressed or implied in the drawings and these descriptions are provided for exemplary purposes. Thus, not all embodiments within the scope of the drawings and these descriptions are made according to such exemplary dimensions. The drawings are not made necessarily to scale. Thus, not all embodiments within the scope of the drawings and these descriptions are made according to the apparent scale of the drawings with regard to relative dimensions in the drawings. However, for each drawing, at least one embodiment is made according to the apparent relative scale of the drawing.

[0020] Unless defined otherwise, all technical and scientific terms used herein have the same meaning as commonly understood to one of ordinary skill in the art to which the presently disclosed subject matter pertains. Although any methods, devices, and materials similar or equivalent to those described herein can be used in the practice or testing of the presently disclosed subject matter, representative methods, devices, and materials are now described.

[0021] Following long-standing patent law convention, the terms "a", "an", and "the" refer to "one or more" when used in the subject specification, including the claims. Thus, for example, reference to "a device" can include a plurality of such devices, and so forth.

[0022] Unless otherwise indicated, all numbers expressing quantities of components, conditions, and so forth used in the specification and claims are to be understood as being modified in all instances by the term "about". Accordingly, unless indicated to the contrary, the numerical parameters set forth in the instant specification and attached claims are approximations that can vary depending upon the desired properties sought to be obtained by the presently disclosed subject matter.

[0023] As used herein, the term "about", when referring to a value or to an amount of mass, weight, time, volume, concentration, and/or percentage can encompass variations of, in some embodiments +/-20%, in some embodiments +/-10%, in some embodiments +/-5%, in some embodiments +/-1%, in some embodiments +/-0.5%, and in some embodiments +/-0.1%, from the specified amount, as such variations are appropriate in the presently disclosed subject matter.

INTRODUCTION

[0024] Off-resonant neutron transfer reactions as a possible mechanism were introduced in the 1990s as a possible route to circumvent the Coulomb barrier in an effort to account for anomalies seen in the Fleischmann-Pons experiment.

[0025] After analyzing the mechanism, it was found that severe cancellation would be expected in general, and that the only way that delocalization of an off-resonant neutron might occur was through coupling to Bragg states.

[0026] In one or more embodiments, electron capture on hydrogen may lead to neutrons via inverse beta decay, where delocalization might occur through coupling to the low-energy Bragg states. This requires the existence of a substantial population of MeV electrons, which are known not to be present due to an absence of either commensurate characteristic x-ray radiation or Bremsstrahlung.

[0027] In one or more embodiments, exists a (phonon-mediated) resonant neutron transfer mechanism, in which up-conversion may supply the energy needed for a neutron to be promoted to continuum states, including Bragg states. A large coherent neutron transfer rate may be expected under such conditions, since each step of the process could be on resonance. Arranging for sufficient energy exchange, to promote a bound neutron to a Bragg state, is on the order of 6-7 MeV, and restrictive conditions are needed to observe the process.

PHONON-MEDIATED OFF-RESONANT TRANSFER

[0028] According to one or more embodiments, the approach may be extended to the off-resonant case. The exchange of only a single phonon can provide for off-resonant coupling of a bound neutron to a Bragg state, which is special since although neutrons also couple to other continuum states, the destructive interference associated with normal continuum states would preclude delocalization.

[0029] To transfer a neutron at one lattice site, to one at another lattice site, it would require some degree of crystal order so that neutron reflections can occur to make the Bragg states look different than other free neutron states. At the other end, a single neutron exchange can allow for a neutron to transition back to a nucleus equivalent to the one that it came from. In this case there exists the possibility of an off-resonant neutron transfer -- referring to the neutron being off of resonance when separated from the nucleus of origin -- to an equivalent nucleus so that energy is conserved. This kind of process occurs in the presence of vibrations. It is expected that THz vibrations would be favored in each individual phonon exchange.

POTENTIAL APPLICATION FOR ISOTOPE SEPARATION

[0030] Moving neutrons from one nucleus, say Fe-57, to a neighboring nucleus, say initially Fe-56, can be difficult to detect. However, in a specially configured experiment it may be possible.

[0031] According to one or more embodiments, an isotope separation kind of application is possible in which a source of THz phonons on one side of a thin sample are used for a preferential movement of transferred neutrons to the other side. For example, starting with a natural iron sample with a random mix of Fe-56 and about 2% of Fe-57, may result with the Fe-57 enriched on one side of the sample.

TRANSFER FROM ONE NUCLEUS TO PRODUCE AN INEQUIVALENT ISOTOPE

[0032] In order to demonstrate the effect in a laboratory test, what is needed is for a directional excitation transfer process to be detectable in an isotope separation type of experiment. Ideally a highly sensitive experiment, in which new isotopes are made not present initially in the sample in significant amounts. In one or more embodiments, phonon-mediated off-resonant neutron transfer may be used to move a neutron from one isotope of one element to a different isotope of the same element, or to a different isotope of a different element. Detection of neutron transfer may be done using NMR or neutron activation analysis, both of which have the potential to be very sensitive to be able to see a small number of new isotopes.

PRODUCING AN UNSTABLE ISOTOPE

[0033] According to one or more embodiments, a further improvement in sensitivity is possible by transferring a neutron onto a stable isotope such that the daughter with one more neutron is unstable. This can be verified by looking for an emitted beta, characteristic x-ray, gamma or alpha. Such nuclear diagnostics can be even more sensitive. For example, in the case of gamma spectroscopy it is possible to develop unambiguous spectral and time-history evidence to identify and verify that the neutron transfer has taken place.

MINIMIZATION OF THE MASS DIFFERENCE

[0034] In both of the approaches just discussed, it is clear that there will be a mass difference between the initial and final states. The off-resonant neutron transfer process may be expressed as:

$$^{A1}Z_1 + {}^{A2}Z_2 \text{ --> } ({}^{(A1-1)}Z_1 + n_{Bragg} + {}^{A2}Z_2)_{\text{off-resonant}} \text{ --> } {}^{(A1-1)}Z_1 + {}^{(A2+1)}Z_2 + \delta E$$

Equation 1

[0035] The mass of the initial isotopes will in general be different than the mass of the final isotopes, with the difference in mass energy noted as δE here. If the lattice is able to either dissipate or provide the energy mismatch, then the process will proceed according to the associated Golden Rule rate. If too much energy needs to be provided, then the process will not occur.

[0036] In one or more embodiments, candidate sets of isotopes are examined to see which ones have the minimum mass difference for a neutron transfer process. For this analysis includes obtaining an isotope table file, and putting together some code to sort through all possible combinations to see which transitions result in the smallest mass defect. Some of the sets with the lowest energy difference are listed in Figure 1 below.

stable	stable	stable	unstable	$T_{1/2}$	$\|\Delta E\|$(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

Figure 1

[0037] Notably, the candidate with the lowest energy involves on the order of 40 eV for a mass difference. In this case the energy needs to be supplied to make unstable Ar-41.

INCOHERENT DISSIPATION OF A MASS EXCESS

[0038] For off-resonant neutron transfer processes in which the transfer is exothermic, it is expected that secondary coupling would be available to transfer energy to an electron, so that the mass energy defect could be dissipated. In this case the neutron transfer process would result in the production of some energy as heat along with the isotope changes. In one or more embodiments, some of the electron kinetic energy may be captured so that the nuclear mass energy could be converted to electrical energy.

MAKING UP THE MASS DIFFERENCE

[0039] When the off-resonant neutron transfer process is endothermic, then energy would need to be supplied in order to make the transfers occur. In this case one approach is to make use of up-converted energy from a coupled phonon-nuclear system to make up the energy difference. In this case, the overall neutron transfer process could be coherent, which would result in an accelerated rate (this could also be used in the case of a mass excess).

[0040] A coupled phonon-nuclear system of the type under consideration includes a solid or liquid that contains lots of isotopes with a low-energy excited state (such as Hg-201 which has an excited state at 1.5 keV, or Fe-57 which has an excited state at 14.4 keV), and that is vibrated. If the vibrations are THz vibrations then the greatest energy exchange is expected. Collimated x-ray emission have been interpreted in the Karabut experiment, Kornilova experiment, and Ivlev experiment in terms of this kind of up-conversion. The models for up-conversion predict down-conversion as well, so that the PdD and NiH/D systems both down-convert for excess heat production, but could up-convert for this kind of application.

[0041] This approach triggers the Fukai effect of D_2 / H_2 loading at the super abundant vacancy level, high loading into a triggerable reaction ready state. According to one or more embodiments of the presently disclosed subject matter, loading nano Pd and other metals most likely produces Fukai phase. This was unknown prior to this disclosure.

[0042] Fukai phase is related to in situ x-ray diffraction on Pd hydride under 5 GPa of hydrogen pressure which causes lattice contraction in 2-3 h at 700-800 °C due to vacancy formation. Two-phase separation into PdH and a vacancy-ordered phase of Cu_3Au structure (Pd_3VacH_4) occurs on subsequent cooling. After recovery to ambient conditions and removal of hydrogen, the vacancy concentration in Pd metal is determined, by measuring density and lattice parameter changes, to be 18 ± 3 at.%. This procedure provides a method of introducing superabundant vacancies in metals.

POTENTIAL APPLICATIONS

[0043] Applications of interest include additional experiments that provide a demonstration of the effect under discussion. For example, with the use of an ion gun to bombard a Hf target with Ar ions, it is possible to produce radioactive Ar-41, assuming that there are impurity isotopes in the Hf with low energy nuclear transitions. If not, then Hg, or Ta, or Fe or some other additive may be added to help with the up-conversion.

[0044] According to one or more embodiments of the presently disclosed subject matter, phonon-mediated off-resonant neutron transfer reactions may be used to make unstable isotopes for scientific applications.

[0045] Another potential application with big implications is in the area of radioactive waste remediation. A single neutron transfer requires stable isotopes one mass unit above and below, which restricts possible targets for elimination. For example, the elimination of I-129 through a single neutron transfer process is made difficult since neither I-128 nor I-130 are stable. On the other hand, Co-60 is a candidate since Co-59 is stable. In this case, there are relatively low energy mass defects in the case of ^{83}Kr/^{82}Kr (210 eV), ^{99}Ru/^{98}Ru (240 eV) and ^{174}Yb/^{173}Yb.

[0046] The present invention may be carried out in other specific ways than those herein set forth without departing from the scope and essential characteristics of the invention. The present embodiments are, therefore, to be considered in all respects as illustrative and not restrictive, and all changes coming within the meaning and equivalency range of the appended claims are intended to be embraced therein.

[0047] Particular embodiments and features have been described with reference to the drawings. It is to be understood that these descriptions are not limited to any single embodiment or any particular set of features, and that similar embodiments and features may arise or modifications and additions may be made without departing from the scope of these descriptions and the spirit of the appended claims.

[0048] These and other changes can be made to the disclosure in light of the above Detailed Description. While the above description describes certain embodiments of the disclosure, and describes the best mode contemplated, no matter how detailed the above appears in text, the teachings can be practiced in many ways. Details of the system may vary considerably in its implementation details, while still being encompassed by the subject matter disclosed herein. As noted above, particular terminology used when describing certain features or aspects of the disclosure should not be taken to imply that the terminology is being redefined herein to be restricted to any specific characteristics, features, or aspects of the disclosure with which that terminology is associated. In general, the terms used in the following claims should not be construed to limit the disclosure to the specific embodiments disclosed in the specification, unless the above Detailed Description section explicitly defines such terms. Accordingly, the actual scope of the disclosure encompasses not only the disclosed embodiments, but also all equivalent ways of practicing or implementing the disclosure under the claims.

CLAIMS

1. A method of moving neutrons from a first nucleus to a neighboring nucleus, comprising:

   using a source of THz phonons on one side of a thin sample; and

   preferentially moving transferred neutrons from the one side to a second side.

2. The method of claim 1, wherein the first nucleus is Fe-57.

3. The method of claim 1, wherein the neighboring nucleus is Fe-56.

4. A method of transferring a neutron from one isotope of a first element to a different isotope, comprising, using phonon-mediated, off-resonant neutron transfer.

5. The method of claim 4, wherein the different isotope is an isotope of the first element.

6. The method of claim 4, wherein the different isotope is an isotope of a second element, wherein the first element and second element are not the same element.

7. The method of claim 4, further comprising detecting neutron transfer using nuclear magnetic resonance (NMR) spectroscopy.

8. The method of claim 4, further comprising detecting neutron transfer using neutron activation analysis (NAA).

9. A method of neutron transfer, comprising:

transferring a neutron onto a stable isotope, wherein a daughter with one more neutron is unstable; and

verifying the transferring step by looking for an emitted beta, characteristic x-ray, gamma, or alpa.

ABSTRACT

The subject matter disclosed herein includes a method of moving neutrons from a first nucleus to a neighboring nucleus, comprising using a source of THz phonons on one side of a thin sample, and preferentially moving transferred neutrons from the one side to a second side.

Excitation transfer: New results, some applications

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

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

$$H' \to \frac{|\mathbf{P}|^2}{2M} + \sum_j \boldsymbol{\alpha}_j \cdot c\boldsymbol{\pi}_j + \sum_j \beta_j mc^2 + \sum_{j<k} V_{jk}\left(\boldsymbol{\xi}_k - \boldsymbol{\xi}_j\right) + \sum_j \mathbf{a}_j \cdot c\mathbf{P}$$

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

internal nuclear structure

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

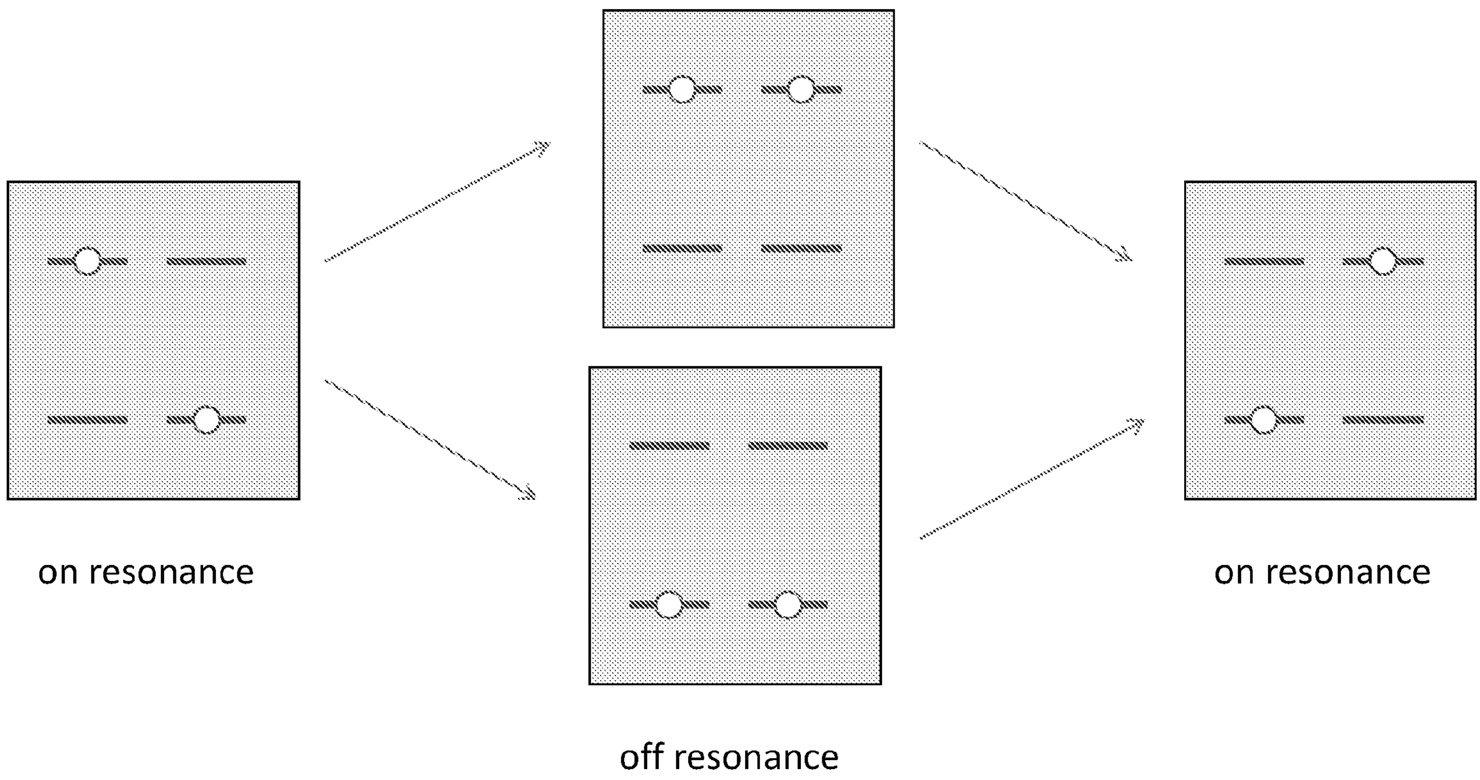
coupling between center of mass motion and internal nuclear degrees of freedom

Excitation transfer

Excitation transfer

- Excitation transfer proposed around 1930 in connection with energy exchange in biomolecules, 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 ($\hbar\omega_0$)

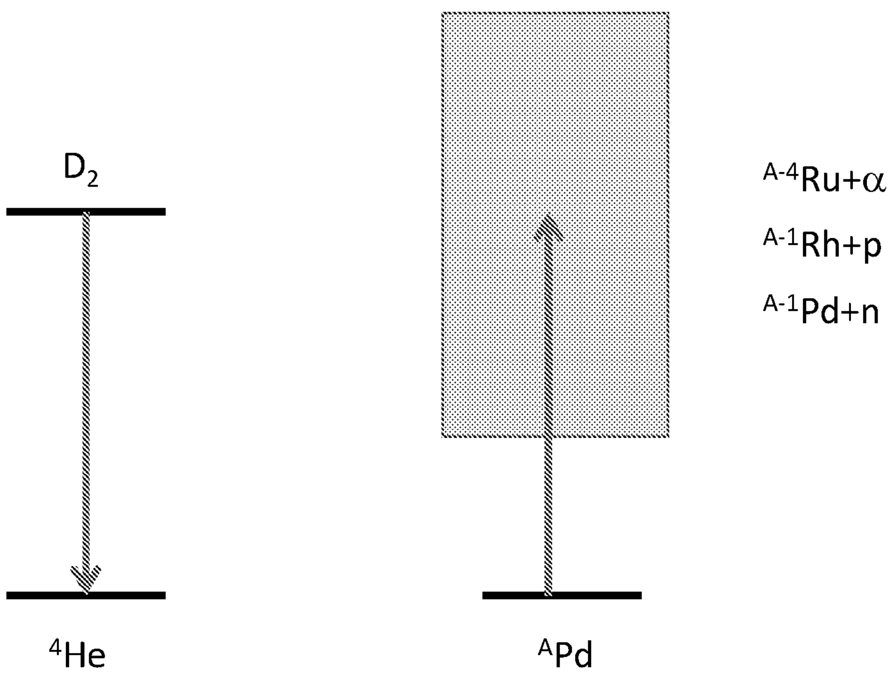
Nuclear transition energy (ΔE)

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



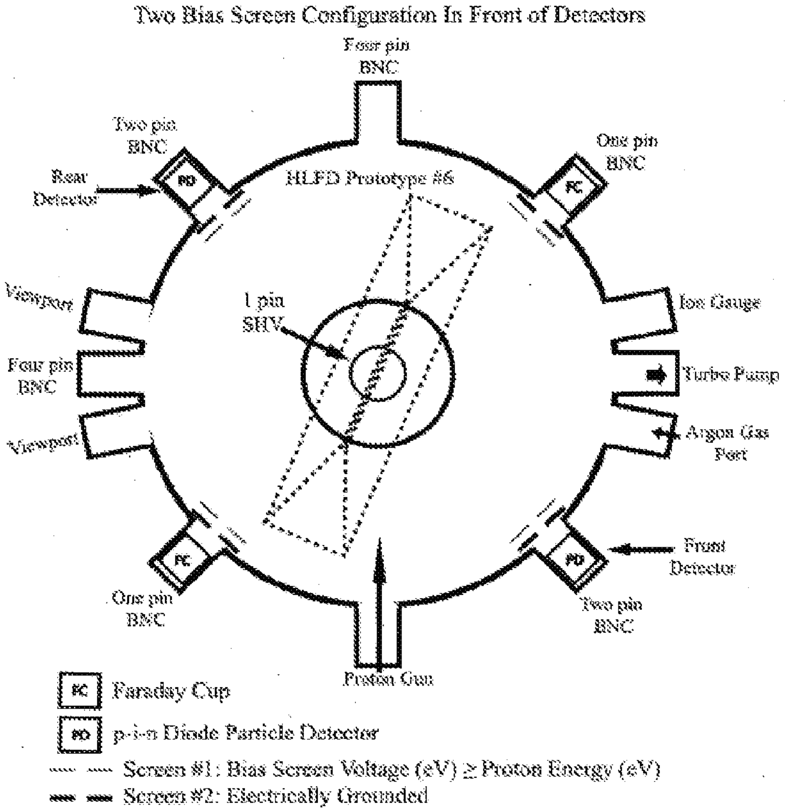
Thinking

- Transfer of $D_2/^4He$ (24 MeV) energy to disintegrate Pd nucleus
- Would produce low-level energetic alphas
- Would produce low-level energetic neutrons

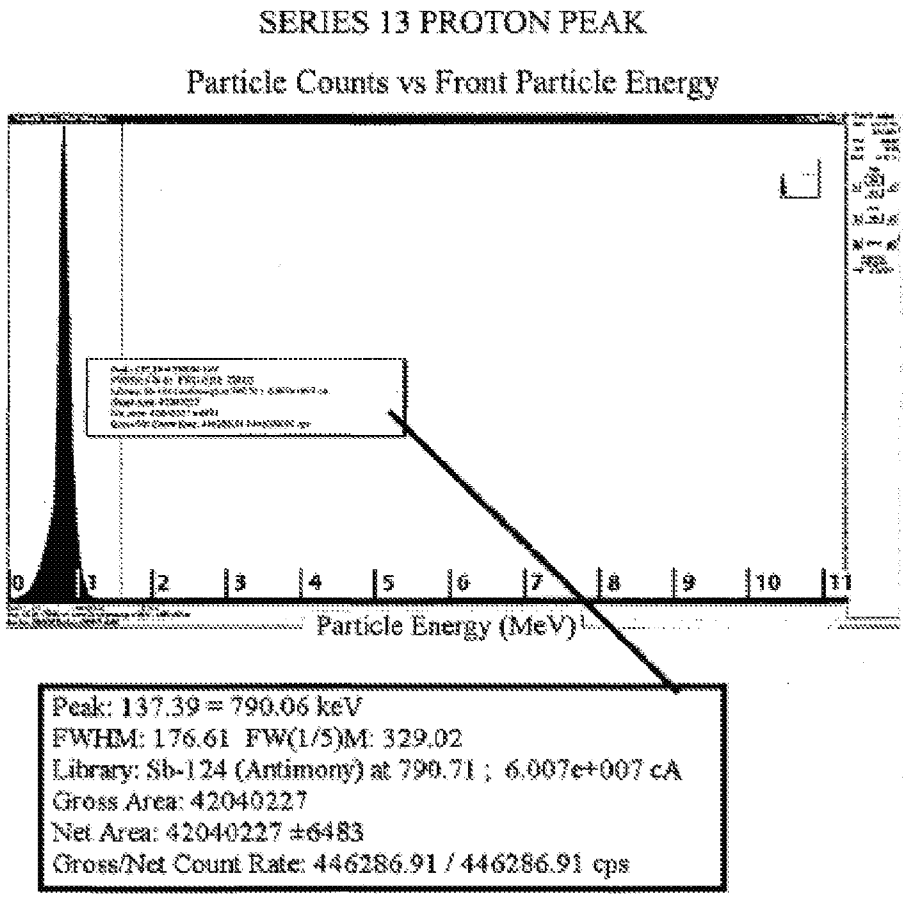
Experiment of Lipinski and Lipinski

- 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)
- Focus on series 13 experiment and results

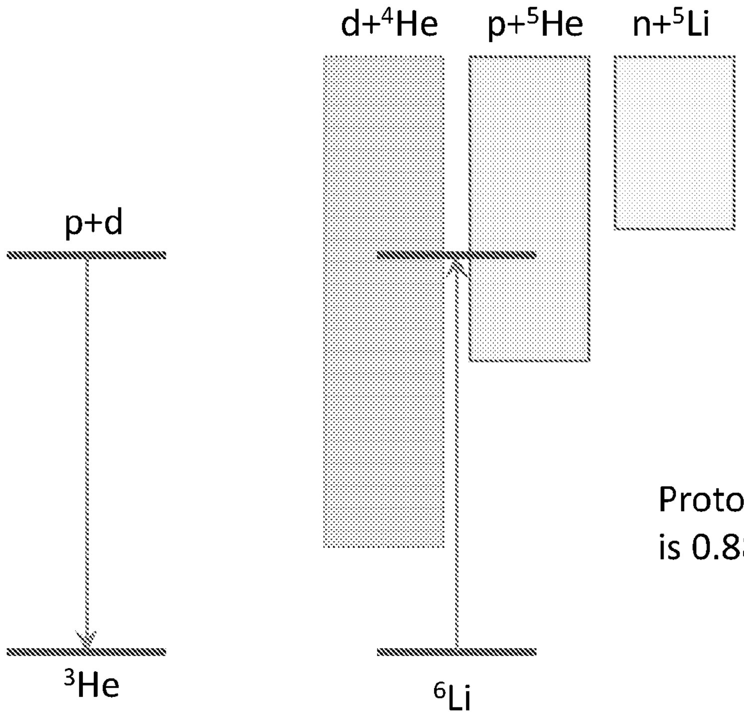
Lipinski and Lipinski experiment



Proton signal



Incoherent excitation transfer

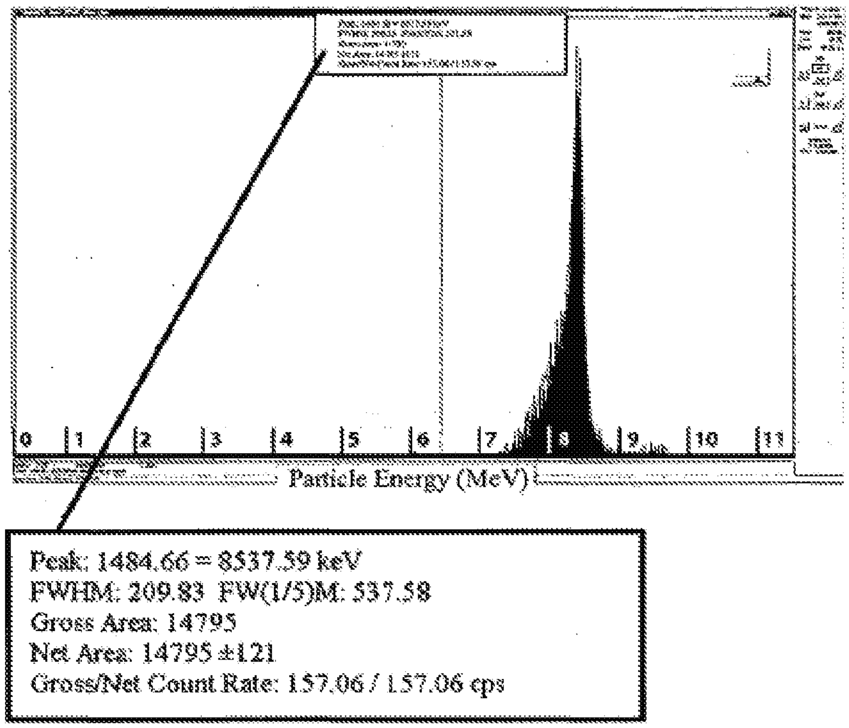


Proton energy including recoil is 0.88 MeV

Alpha signal

SERIES 13 HELIUM ION PEAK

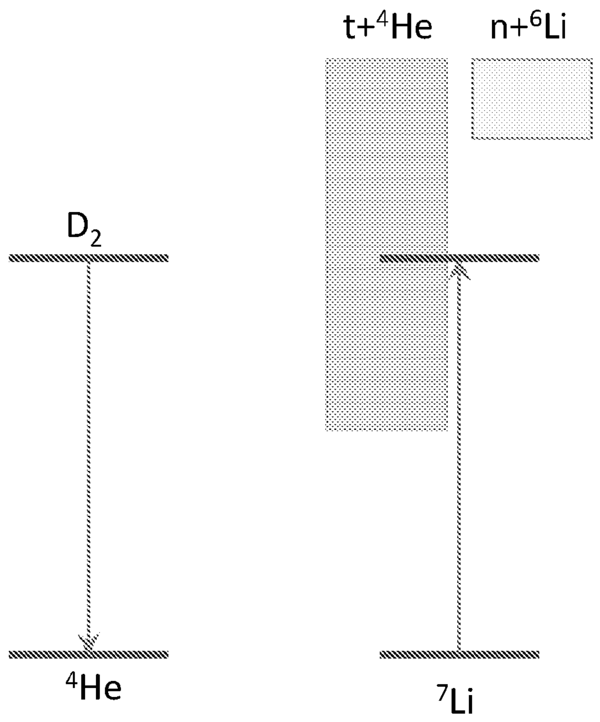
Particle Counts vs Front Particle Energy



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
- The same reaction considered 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

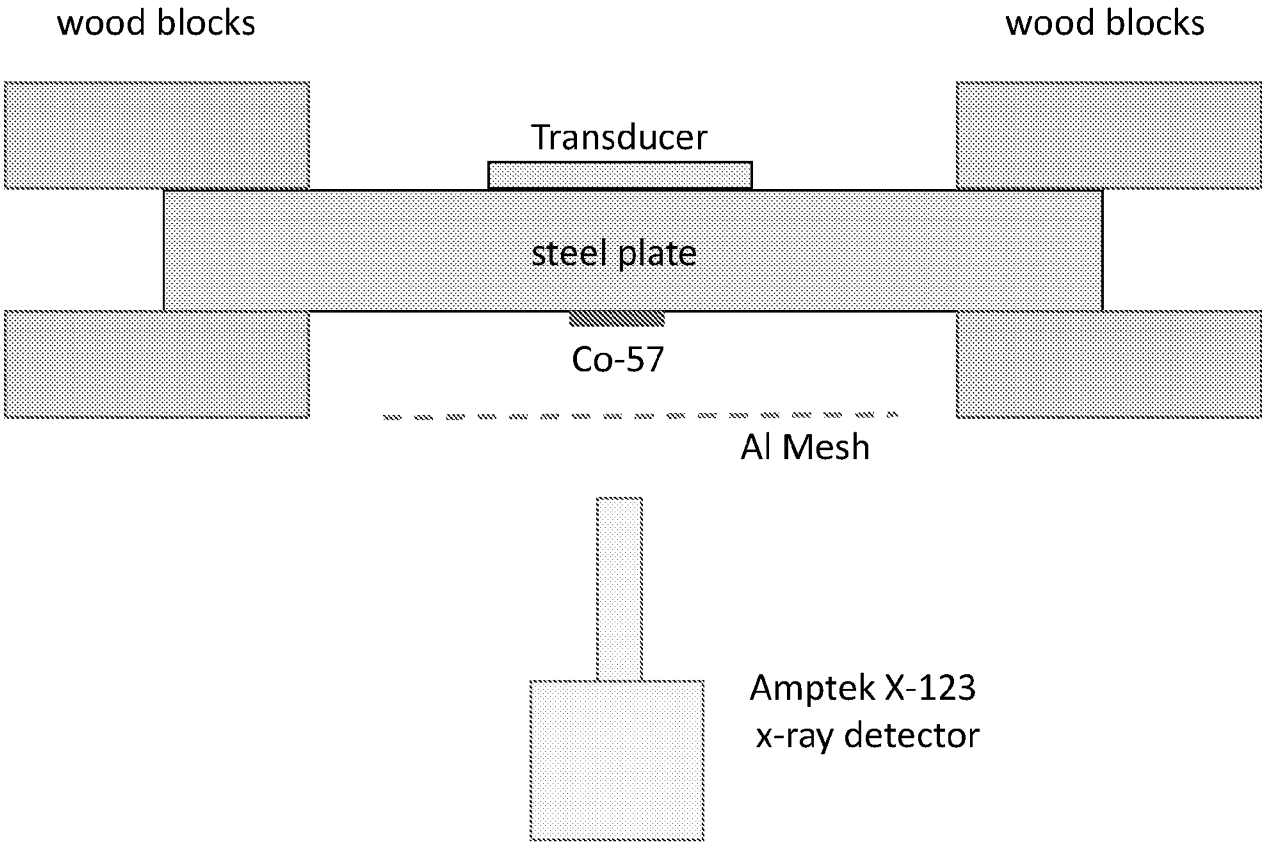


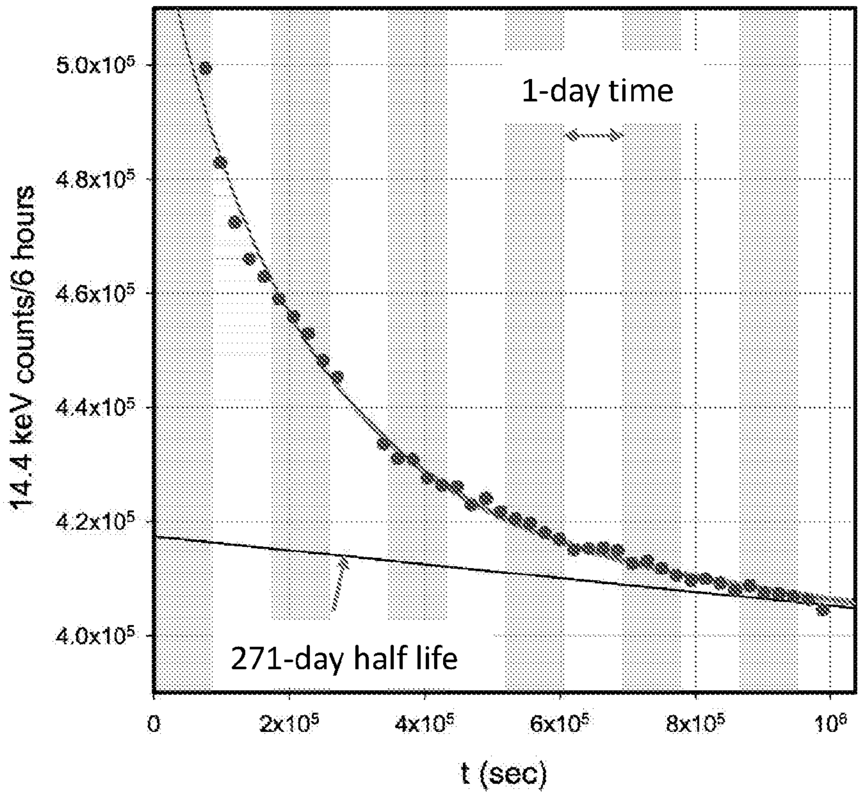
alpha energy including recoil
is 9.13 MeV

Thinking

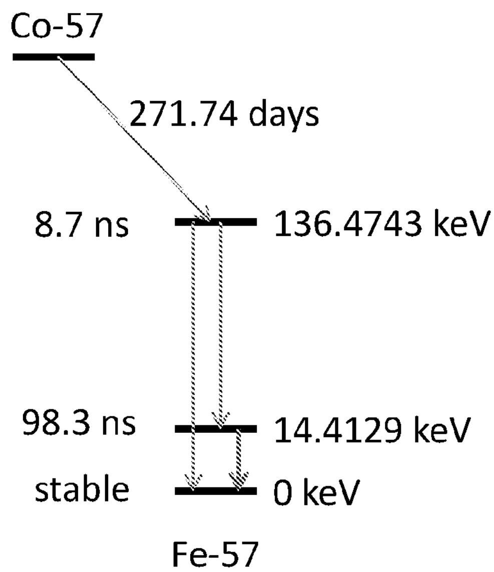
- Fusion not expected with protons below 1 keV
- Inventors attribute effect to gravity resonance effect between p and ^{7}Li
- 0.79 MeV proton signal attributed to "backscatter"
- Contemplated that 0.79 MeV proton signal might be a result of incoherent excitation transfer reaction from HD/^{3}He, and 8.54 MeV a signal might a result of incoherent excitation transfer reaction from D_2/^{4}He

Experiment


wood blocks
wood blocks
Transducer
steel plate
Co-57
Al Mesh
Amptek X-123
x-ray detector



1-day time
271-day half life
14.4 keV counts/6 hours
t (sec)
5.0x10^5
4.8x10^5
4.6x10^5
4.4x10^5
4.2x10^5
4.0x10^5
0
2x10^5
4x10^5
6x10^5
8x10^5
10^6



Co-57
271.74 days
8.7 ns
136.4743 keV
98.3 ns
14.4129 keV
stable
0 keV
Fe-57

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

$$\left(\hat{V}(E-\hat{H}_0)^{-1}\hat{V}\right)_{\text{resonant}} \rightarrow \frac{Mc^2}{(\Delta E)^2}\sum_{j<j'}\sum_{m_0}\sum_{m_1}\sum_{m_0'}\sum_{m_1'}\left(|J_0m_0\rangle\langle J_1m_1|\right)_j\left(|J_1m_1'\rangle\langle J_0m_0'|\right)_{j'}$$

$$\langle J_0m_0|\mathbf{a}_j|J_1m_1\rangle\cdot\left[\frac{1}{N}\sum_{\mathbf{k},\sigma}(\hbar\omega_{\mathbf{k},\sigma})^2\mathbf{u}_{\mathbf{k},\sigma}\mathbf{u}_{\mathbf{k},\sigma}\cos\left(\mathbf{k}\cdot(\mathbf{R}_{j'}^{(0)}-\mathbf{R}_j^{(0)})\right)\right]\cdot\langle J_1m_1'|\mathbf{a}_{j'}|J_0m_0'\rangle$$

$$+\frac{Mc^2}{(\Delta E)^2}\sum_{j<j'}\sum_{m_0}\sum_{m_1}\sum_{m_0'}\sum_{m_1'}\left(|J_1m_1\rangle\langle J_0m_0|\right)_j\left(|J_0m_0'\rangle\langle J_1m_1'|\right)_{j'}$$

$$\langle J_1m_1|\mathbf{a}_j|J_0m_0\rangle\cdot\left[\frac{1}{N}\sum_{\mathbf{k},\sigma}(\hbar\omega_{\mathbf{k},\sigma})^2\mathbf{u}_{\mathbf{k},\sigma}\mathbf{u}_{\mathbf{k},\sigma}\cos\left(\mathbf{k}\cdot(\mathbf{R}_{j'}^{(0)}-\mathbf{R}_j^{(0)})\right)\right]\cdot\langle J_0m_0'|\mathbf{a}_{j'}|J_1m_1'\rangle\Bigg\}$$

M1 transitions, 1-mode, resonant case

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

$$
\frac{(Mc^2)^2}{4N}\sum_{J_2}\sum_{J_2'}\frac{\begin{pmatrix} (E_1-E_0)^2-3(E_1-E_0)[(E_2-E_0)+(E_2'-E_0)] \\ +2[(E_2-E_0)^2+(E_2-E_0)(E_2'-E_0)+(E_2'-E_0)^2] \end{pmatrix}}{(E_2-E_0)(E_2'-E_0)(E_1-E_2)(E_1-E_2')(E_2+E_2'-E_0-E_1)}
$$

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

$$
\sum_{\alpha}\sum_{\beta}\sum_{\gamma}\sum_{\delta}(\langle J_0m_0|\mathbf{a}_j|J_2m_2\rangle)_\alpha(\langle J_2m_2|\mathbf{a}_j|J_1m_1\rangle)_\beta(\langle J_1m_1'|\mathbf{a}_{j'}|J_2'm_2'\rangle)_\gamma(\langle J_2'm_2'|\mathbf{a}_{j'}|J_0m_0'\rangle)_\delta
$$

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

$$
+i\frac{(Mc^2)^2}{2N}\sum_{J_2}\sum_{J_2'}\frac{(2E_2-E_0-E_1)(2E_2'-E_0-E_1)}{(E_1-E_0)(E_2-E_0)(E_2'-E_0)(E_2-E_1)(E_2'-E_1)}
$$

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

$$
\sum_{\alpha}\sum_{\beta}\sum_{\gamma}\sum_{\delta}(\langle J_0m_0|\mathbf{a}_j|J_2m_2\rangle)_\alpha(\langle J_2m_2|\mathbf{a}_j|J_1m_1\rangle)_\beta(\langle J_1m_1'|\mathbf{a}_{j'}|J_2'm_2'\rangle)_\gamma(\langle J_2'm_2'|\mathbf{a}_{j'}|J_0m_0'\rangle)_\delta
$$

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

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

- Augmenting spin-boson models with asymmetric loss could dramatically increase rates for up-conversion, down-conversion
- Expect modification of excitation transfer rates with loss

E1 transitions, loss, resonant case

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

$$-i\frac{\hbar}{2}(\gamma_{00}+\gamma_{11}-\gamma_{01}-\gamma_{10})\frac{Mc^2}{2(\Delta E)^2}\sum_{j<j'}\sum_{m_0}\sum_{m_1}\sum_{m_0'}\sum_{m_1'}\left(|J_0m_0\rangle\langle J_1m_1|\right)_j\left(|J_1m_1'\rangle\langle J_0m_0'|\right)_{j'}$$

$$\langle J_0m_0|\mathbf{a}_j|J_1m_1\rangle\cdot\left[\frac{1}{N}\sum_{\mathbf{k},\sigma}(\hbar\omega_{\mathbf{k},\sigma})^2\mathbf{u}_{\mathbf{k},\sigma}\mathbf{u}_{\mathbf{k},\sigma}(2\hat{n}_{\mathbf{k},\sigma}+1)\cos\left(\mathbf{k}\cdot(\mathbf{R}_{j'}^{(0)}-\mathbf{R}_j^{(0)})\right)\right]\cdot\langle J_1m_1'|\mathbf{a}_{j'}|J_0m_0'\rangle$$

$$-i\frac{\hbar}{2}(\gamma_{00}+\gamma_{11}-\gamma_{01}-\gamma_{10})\frac{Mc^2}{2(\Delta E)^2}\sum_{j<j'}\sum_{m_0}\sum_{m_1}\sum_{m_0'}\sum_{m_1'}\left(|J_1m_1\rangle\langle J_0m_0|\right)_j\left(|J_0m_0'\rangle\langle J_1m_1'|\right)_{j'}$$

$$\langle J_1m_1|\mathbf{a}_j|J_0m_0\rangle\cdot\left[\frac{1}{N}\sum_{\mathbf{k},\sigma}(\hbar\omega_{\mathbf{k},\sigma})^2\mathbf{u}_{\mathbf{k},\sigma}\mathbf{u}_{\mathbf{k},\sigma}(2\hat{n}_{\mathbf{k},\sigma}+1)\cos\left(\mathbf{k}\cdot(\mathbf{R}_{j'}^{(0)}-\mathbf{R}_j^{(0)})\right)\right]\cdot\langle J_0m_0'|\mathbf{a}_{j'}|J_1m_1'\rangle\Big\}.$$

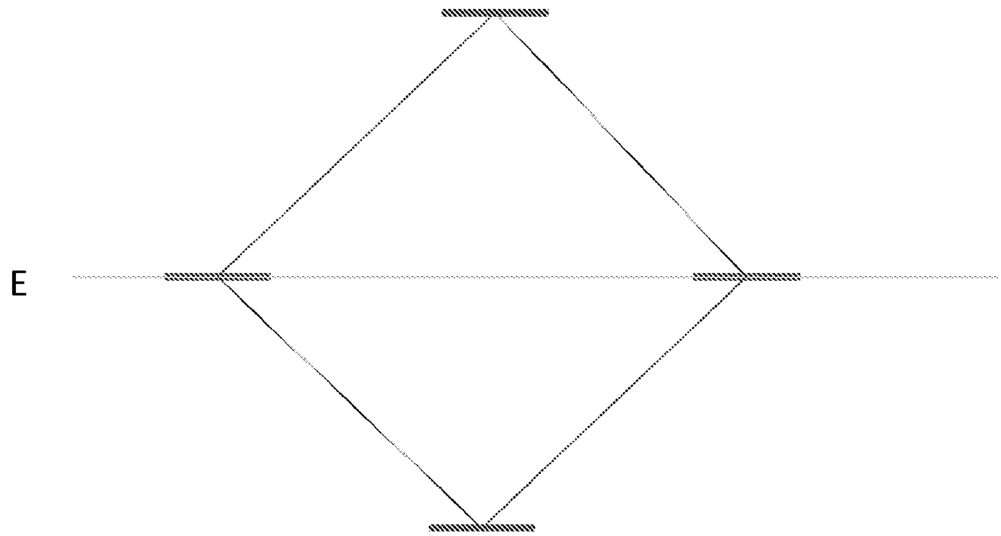
Thinking

- 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

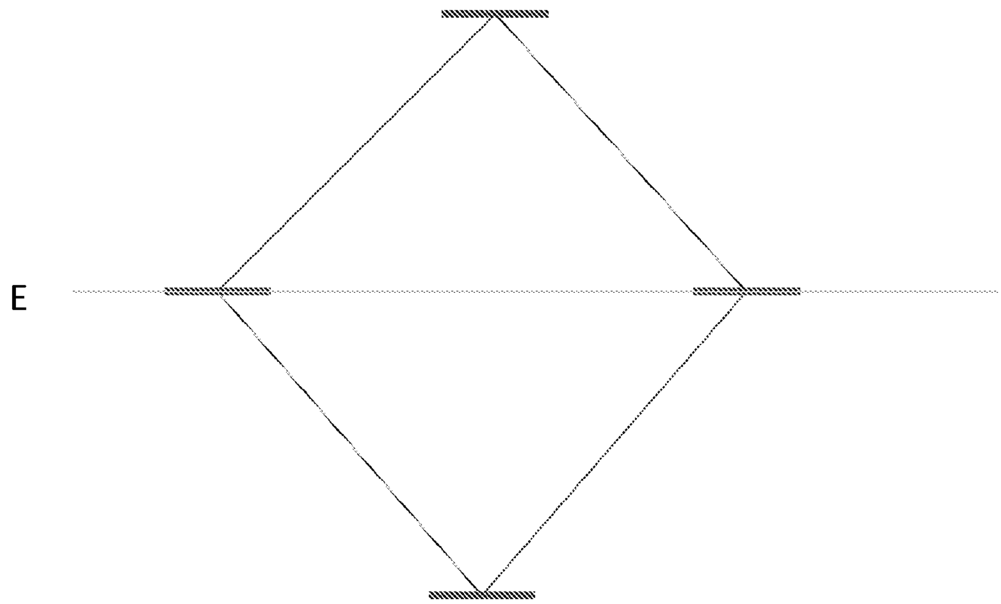
- Predicted effect much smaller than effect observed

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

$$
\begin{aligned}
&\left(\hat{V}(E-\hat{H}_0)^{-1}\hat{V}\right)_{\text{resonant}} \\
&\to \sum_{j}\sum_{j'}\sum_{m_0}\sum_{m_1}\sum_{m_0'}\sum_{m_1'}\sum_{\mathbf{k},\sigma}\frac{Mc^2\hbar\omega_{\mathbf{k},\sigma}}{2N} \\
&\Big\{|J_0m_0\rangle\langle J_0m_0|\mathbf{u}_{\mathbf{k},\sigma}\cdot\mathbf{a}_j|J_1m_1\rangle\langle J_1m_1||J_1m_1'\rangle\langle J_1m_1'|\mathbf{u}_{\mathbf{k},\sigma}\cdot\mathbf{a}_{j'}|J_0m_0'\rangle\langle J_0m_0'| \\
&\frac{E_{00}+E_{11}-2E_{10}}{(E_{10}-E_{00})(E_{11}-E_{10})}(2\hat{n}_{\mathbf{k},\sigma}+1)\cos[\mathbf{k}\cdot(\mathbf{R}_{j'}^{(0)}-\mathbf{R}_{j}^{(0)})] \\
&+|J_1m_1\rangle\langle J_1m_1|\mathbf{u}_{\mathbf{k},\sigma}\cdot\mathbf{a}_j|J_0m_0\rangle\langle J_0m_0||J_0m_0'\rangle\langle J_0m_0'|\mathbf{u}_{\mathbf{k},\sigma}\cdot\mathbf{a}_{j'}|J_1m_1'\rangle\langle J_1m_1'| \\
&\frac{E_{00}+E_{11}-2E_{10}}{(E_{10}-E_{00})(E_{11}-E_{10})}(2\hat{n}_{\mathbf{k},\sigma}+1)\cos[\mathbf{k}\cdot(\mathbf{R}_{j'}^{(0)}-\mathbf{R}_{j}^{(0)})]\Big\},
\end{aligned}
$$

M1 transitions, 1-mode, resonant case

$$\left(\hat{V}(E-\hat{H}_0)^{-1}\hat{V}(E-\hat{H}_0)^{-1}\hat{V}(E-\hat{H}_0)^{-1}\hat{V}\right)_{\text{resonant}} \to T_{c0}+T_{c1}+T_{c2}+T_{s1}$$

$$\begin{aligned}
T_{c0} = &\frac{(Mc^2)^2}{4N}\sum_{J_2}\sum_{J_2'}\left(\frac{2}{(E_{10}-E_{00})(E_{10}-E_{20})(E_{10}-E_{2'0})}+\frac{2}{(E_{10}-E_{11})(E_{10}-E_{21})(E_{10}-E_{2'1})}\right.\\
&\left.+\frac{1}{(E_{10}-E_{20})(E_{10}-E_{2'0})(E_{10}-E_{2'2})}+\frac{1}{(E_{10}-E_{21})(E_{10}-E_{2'1})(E_{10}-E_{2'2})}\right)\\
&\sum_{j}\sum_{j'}\sum_{m_0}\sum_{m_1}\sum_{m_2}\sum_{m_0'}\sum_{m_1'}\sum_{m_2'}\Big(|J_0m_0\rangle\langle J_1m_1|\Big)_j\Big(|J_1m_1'\rangle\langle J_0m_0'|\Big)_{j'}\\
&\sum_{\alpha}\sum_{\beta}\sum_{\gamma}\sum_{\delta}(\langle J_0m_0|\mathbf{a}_j|J_2m_2\rangle)_\alpha(\langle J_2m_2|\mathbf{a}_j|J_1m_1\rangle)_\beta(\langle J_1m_1'|\mathbf{a}_{j'}|J_2'm_2'\rangle)_\gamma(\langle J_2'm_2'|\mathbf{a}_{j'}|J_0m_0'\rangle)_\delta\\
&\left[\frac{1}{N}\sum_{\mathbf{k},\sigma}(\hbar\omega_{\mathbf{k},\sigma})^2(\mathbf{u}_{\mathbf{k},\sigma})_\alpha(\mathbf{u}_{\mathbf{k},\sigma})_\beta(\mathbf{u}_{\mathbf{k},\sigma})_\gamma(\mathbf{u}_{\mathbf{k},\sigma})_\delta\cos\Big(2\mathbf{k}(\mathbf{R}_{j'}^{(0)}-\mathbf{R}_j^{(0)})\Big)\right]
\end{aligned}$$

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
- Just add the increment to an existing model for the deuteron

One-pion exchange

Relativistic one-pion exchange interaction off of resonance

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

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

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

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

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

Deuteron model

Modification of the Hamada-Johnston model

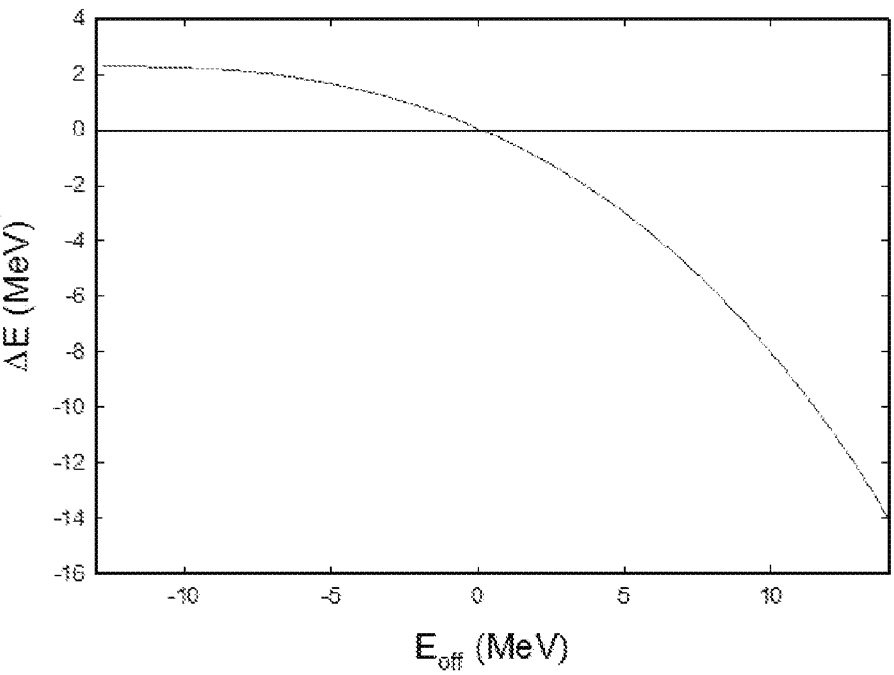
$$\hat{H} = \frac{|\hat{\mathbf{p}}|^2}{M} + \underbrace{V_C + V_T \hat{S}_{12} + V_{LS}\hat{\mathbf{L}}\cdot\hat{\mathbf{S}} + V_{LL}\mathbf{L}_{12}}_{\text{Hamada-Johnston potential}} + \underbrace{\Delta V_C + \Delta V_T \hat{S}_{12}}_{\text{off-resonant correction}}$$

kinetic energy, reduced mass Is M/2

Hamada-Johnston potential

off-resonant correction

Deuteron binding energy shift



Thinking

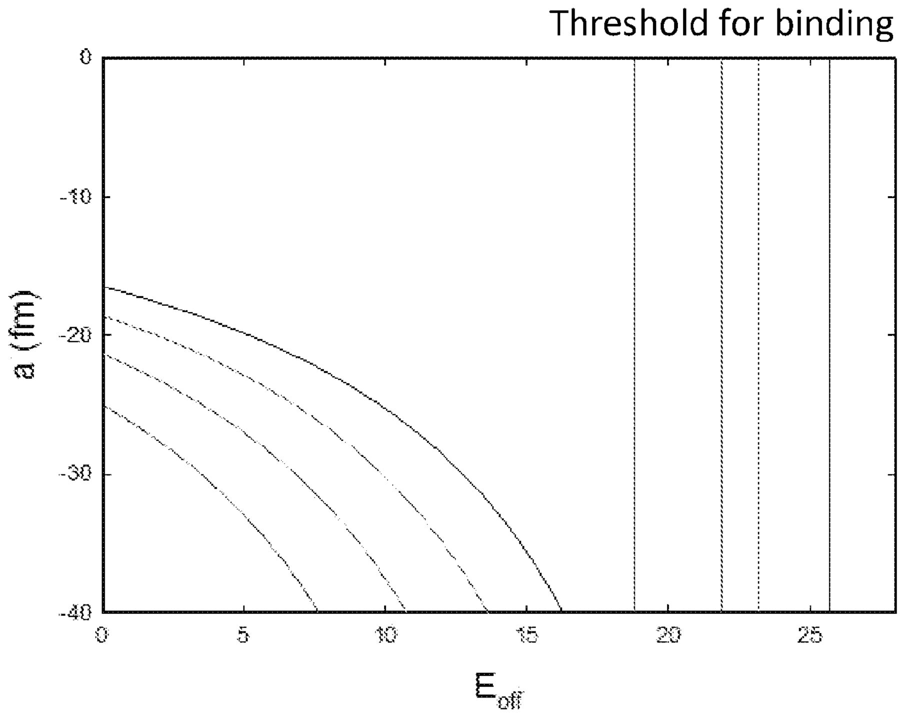
- Big shift of the deuteron binding energy off of resonance
- Shift is nonlinear as a function of the off resonant energy which is important since the increase in excitation transfer rate depends on second derivative
- Still need shifts for other nuclei
- This approach works

Dineutron off of resonance

Dineutron

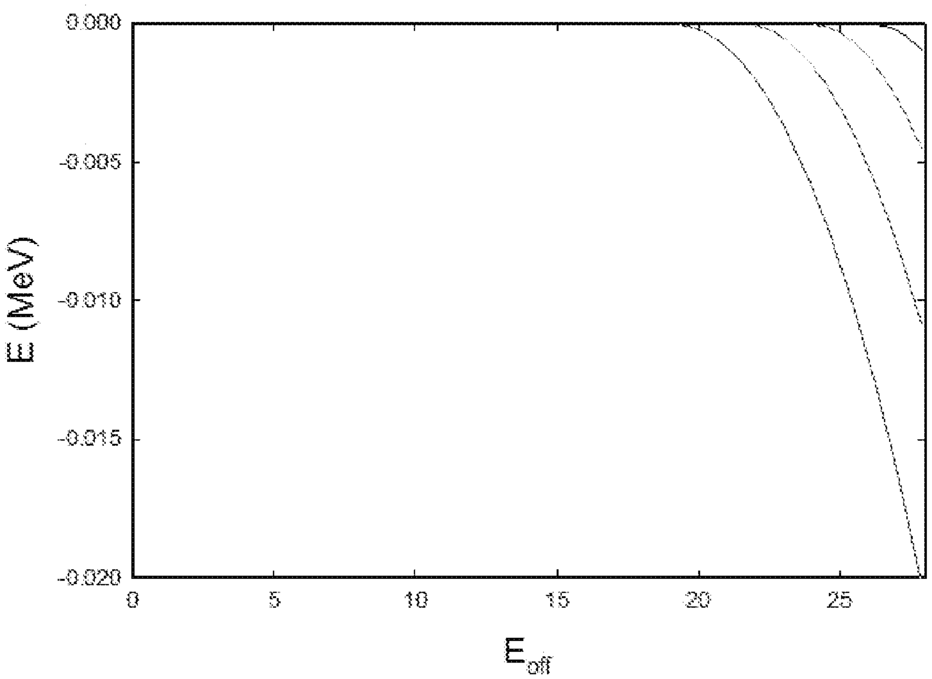
- Deuteron problem important since it is simplest
- But no experiments expect with deuterons off of resonance
- Story is different for dineutron
- Iwamura experiment shows mass increases
- Multiple-neutron transfer a possible explanation
- But dineutron is not bound (same for multi-neutron clusters)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

Dineutron scattering length



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

Dineutron binding energy



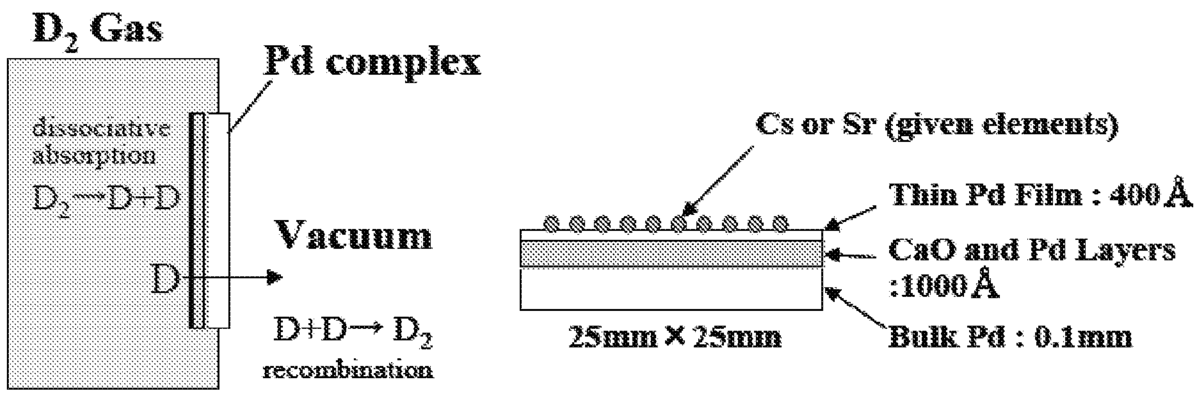
Use hard core radius as a parameter: 0.343, 0.342, 0.341,0.340

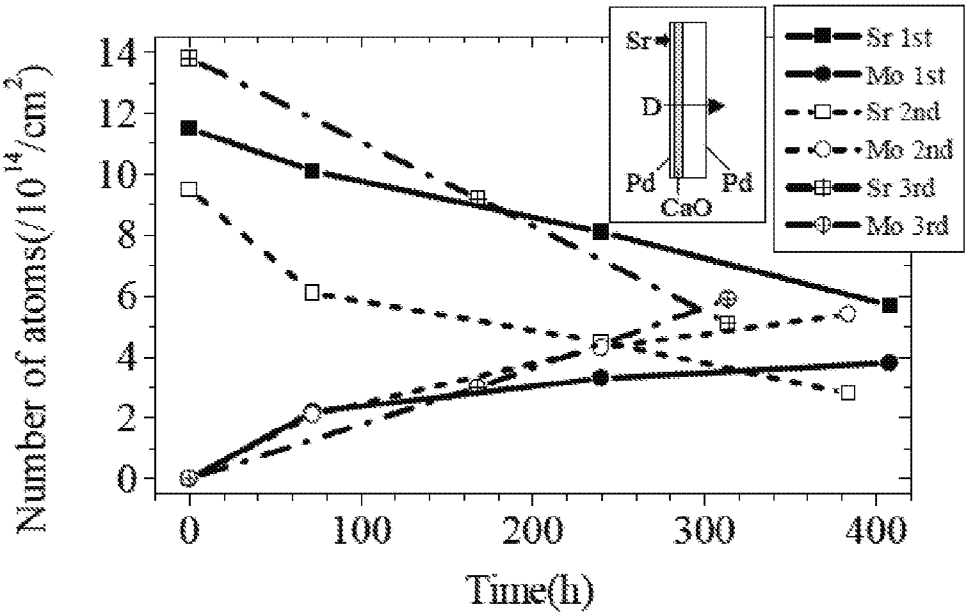
Thinking

- 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 multi-neutron exchange to be possible off of resonance
- Perhaps an explanation for Iwamura transmutation experiment

transmutation experiment

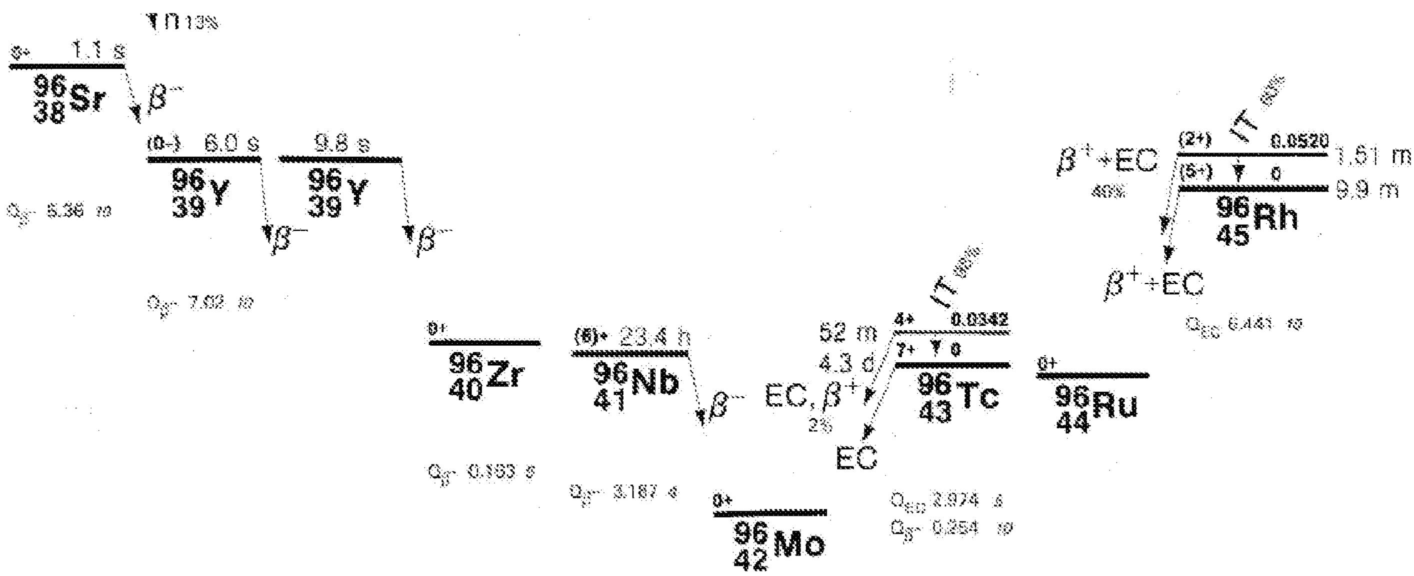
transmutation exp't




Sr
D
Pd
Pd
CaO
Sr 1st
Mo 1st
Sr 2nd
Mo 2nd
Sr 3rd
Mo 3rd
Number of atoms(/10^14/cm^2)
0
2
4
6
8
10
12
14
0
100
200
300
400
Time(h)

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 $D_2/^4He$ excitation transfer coherent process

More thinking

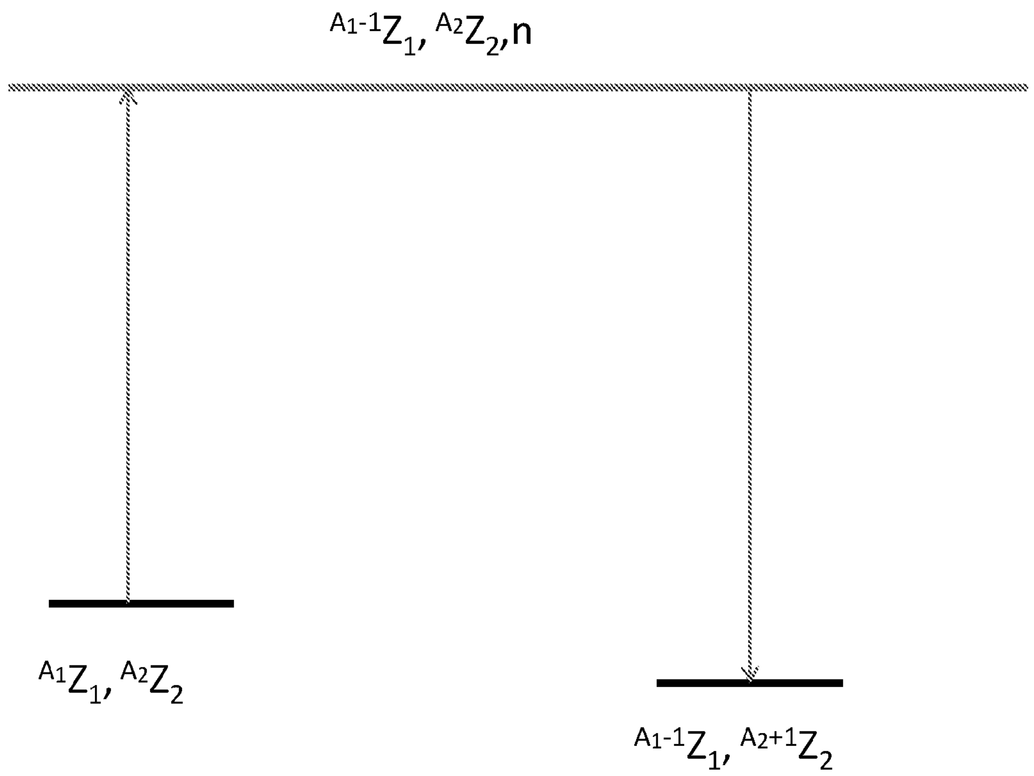
- Similar experiment with restricted Pd isotopes transfers a smaller neutron cluster
- Possible to see beta decay products (or rule out proposed mechanism if decay products not present)

Phonon-mediated neutron transfer

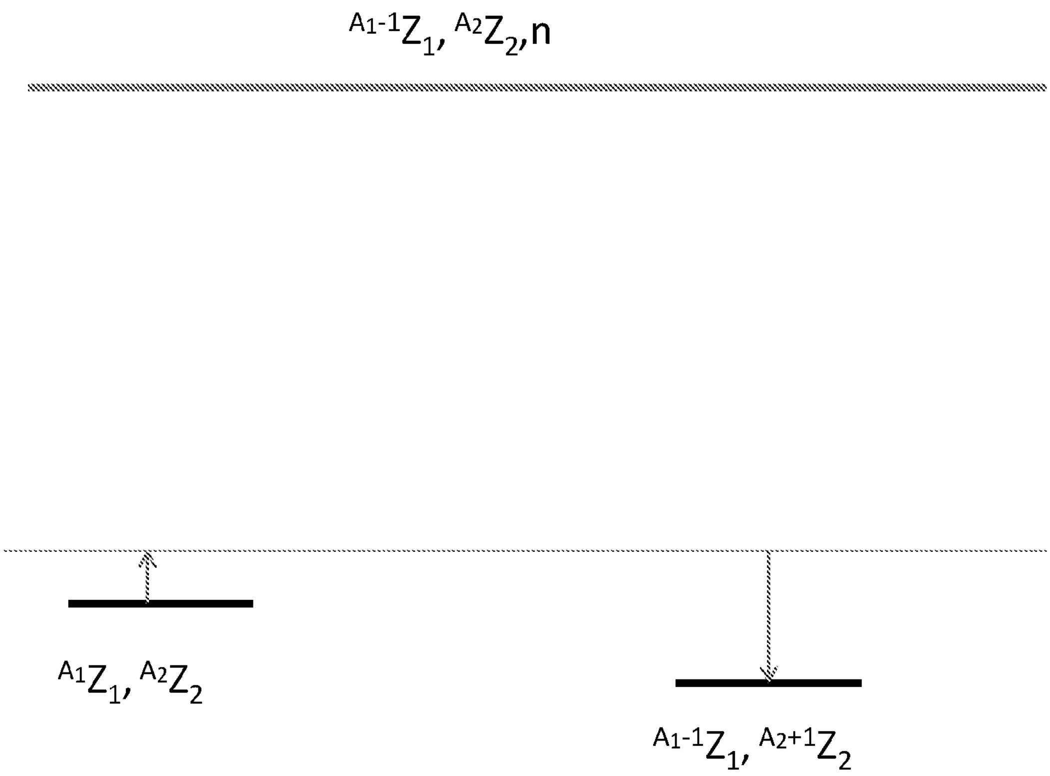
Single-neutron transfer

- 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
- 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	$T_{1/2}$	|ΔE| (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:

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

- Try 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
- Expected this version of the model will connect with experiment
- Proposal for phonon-mediated single neutron transfer reactions
- Tested 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