



(51) International Patent Classification:
G21B 1/00 (2006.01)

(21) International Application Number:
PCT/US2020/021271

(22) International Filing Date:
05 March 2020 (05.03.2020)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/822,831 23 March 2019 (23.03.2019) US

(71) Applicant: INDUSTRIAL HEAT, LLC [US/US]; 310 S.
West Street, Suite 100, Raleigh, North Carolina 27603 (US).

(72) Inventor: HAGELSTEIN, Peter L.; 33 Heald Road,
Carlisle, Massachusetts 01741 (US).

(74) Agent: MACDONALD, Brian D.; NK Patent Law, 4917
Waters Edge Drive, Suite 275, Raleigh, North Carolina
27601 (US).

(81) Designated States (unless otherwise indicated, for every
kind of national protection available): AE, AG, AL, AM,
AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ,
CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO,
DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN,
HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP,
KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME,
MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ,
OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA,
SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR,
TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every
kind of regional protection available): ARIPO (BW, GH,
GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ,
UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ,
TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK,
EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV,
MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM,
TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW,
KM, ML, MR, NE, SN, TD, TG).

(54) Title: PHONON-MEDIATED OFF-RESONANT NEUTRON TRANSFER

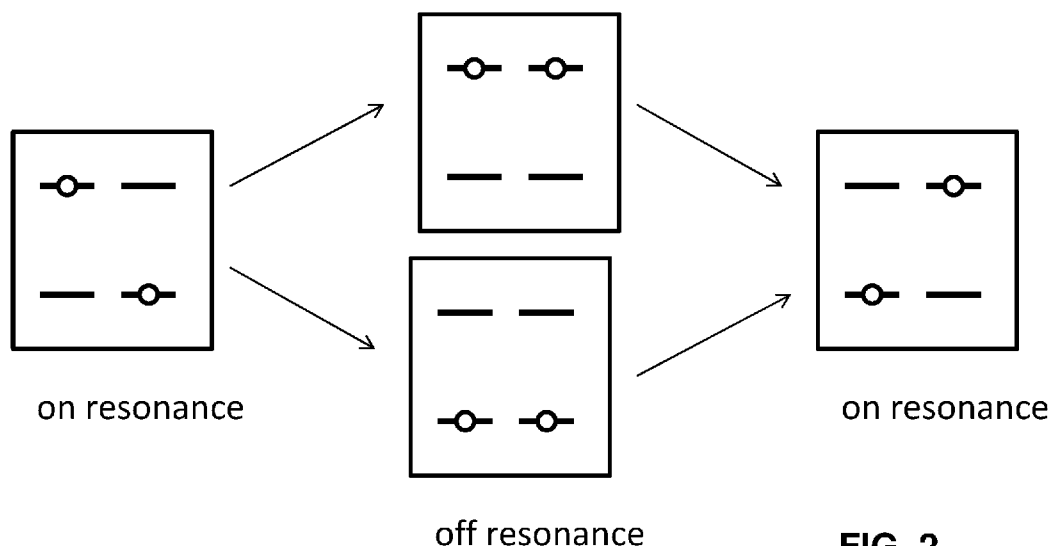


FIG. 2

(57) Abstract: A method of neutron enriching a portion of a sample includes applying phonons to a first side of a sample, thereby transferring neutrons from first nuclei within the sample to second nuclei within the sample, whereby the second nuclei are enriched with the transferred neutrons. An apparatus for neutron enriching a portion of a sample includes a phonon source in contact with or mechanically coupled to a first side of a sample, the phonon source configured to apply phonons to the first side of the sample, thereby transferring neutrons from first nuclei within the sample to second nuclei within the sample, whereby the second nuclei are enriched with the transferred neutrons.

Published:

— *with international search report (Art. 21(3))*

PHONON-MEDIATED OFF-RESONANT NEUTRON TRANSFER

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of priority of U.S. provisional patent application no. 62/822,831, titled “PHONON-MEDIATED OFF-RESONANT NEUTRON TRANSFER,” filed on March 23, 2019, which is incorporated herein in its entirety by this reference.

TECHNICAL FIELD

[0002] The present invention relates generally to off-resonant neutron transfer, and more specifically to phonon-mediated, off-resonant neutron transfer.

BACKGROUND

[0003] 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.

[0004] The present disclosure relates to improved systems and methods of off-resonant neutron transfer.

SUMMARY

[0005] 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.

[0006] According to at least one embodiment, a method of neutron enriching a portion of a sample includes applying phonons to a first side of a sample, thereby transferring neutrons from first nuclei within the sample to second nuclei within the sample, whereby the second nuclei are enriched with the transferred neutrons.

[0007] According to at least one embodiment, an apparatus for neutron enriching a portion of a sample includes a phonon source in contact with or mechanically coupled to a first side of a sample, the phonon source configured to apply phonons to the first side of the sample, thereby transferring neutrons from first nuclei within the sample to second nuclei within the sample, whereby the second nuclei are enriched with the transferred neutrons.

[0008] The phonons may be applied to the first side of the sample by a phonon source in contact with or mechanically coupled to the first side of the sample.

[0009] The phonons may have a frequency of at least one terahertz.

[0010] Transferring neutrons may include moving the neutrons away from the first side of the sample and toward a second side of the sample opposite the first side.

[0011] The second nuclei may be enriched with the transferred neutrons along or proximal the second side of the sample relative to the first nuclei along or proximal the first side of the sample.

[0012] The first nuclei may include Fe-57.

[0013] The second nuclei may include Fe-56.

[0014] Applying phonons to a first side of a sample may include triggering phonon-mediated, off-resonant neutron transfer.

[0015] According to at least one embodiment, 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.

[0016] The different isotope may be an isotope of the first element.

[0017] The different isotope may be an isotope of a second element, wherein the first element and second element are not the same element.

[0018] The method of transferring a neutron from one isotope of a first element to a different isotope may further include detecting neutron transfer using nuclear magnetic resonance (NMR) spectroscopy.

[0019] The method of transferring a neutron from one isotope of a first element to a different isotope may further include detecting neutron transfer using neutron activation analysis (NAA).

[0020] In at least one embodiment, a method of neutron transfer includes: transferring a neutron to a stable isotope, thereby producing a daughter that is unstable with one more neutrons; and, verifying the transferring step by looking for an emitted beta, characteristic x-ray, gamma, or alpha.

[0021] The above summary is to be understood as cumulative and inclusive. The above described embodiments and features are combined in various combinations in whole or in part in one or more other embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

[0022] 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.

[0023] 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.

[0024] FIG. 1A shows an apparatus, according to at least one embodiment, for implementing a method of moving neutrons from a first nucleus to another nucleus;

[0025] FIG. 1B is an enlarged view of a portion of the apparatus of FIG. 1A as shown in dashed line;

[0026] FIG. 2 is diagrammatic representation of excitation transfer, according to at least one embodiment;

[0027] FIG. 3 diagrammatically illustrates low-level energetic α , n emission, according to at least one embodiment, in which transferred energy disintegrates a Pd nucleus;

[0028] FIG. 4 illustrates incoherent excitation transfer in which proton energy including recoil is 0.889 MeV;

[001] FIG. 5 illustrates incoherent excitation transfer in which an alpha energy including recoil is 9.13 MeV;

[0029] FIG. 6A illustrates an apparatus, according to at least one embodiment, in which a radioactive source and a vibratory excitation element are attached to opposite sides of a steel plate;

[0030] FIG. 6B is a plot of 14.4 keV counts versus time;

[0031] FIG. 7 is a decay scheme for the decay of Co-57 to Fe-57;

[0032] FIG. 8 diagrammatically represents cancellation without off-res shift;

[0033] FIG. 9 diagrammatically represents less cancellation with shift;

[0034] FIG. 10 is a plot of deuteron binding energy shift;

[0035] FIG. 11 is a plot showing dineutron scattering length for several different hard core radius parameter values;

[0036] FIG. 12 is a plot showing dineutron binding energy for several different hard core radius parameter values;

[0037] FIG. 13 is an illustration of the implementation of a prior art transmutation experiment (Iwamura, 2003);

[0038] FIG. 14 is a plot of prior art data resulting from the Iwamura experiment of FIG. 13;

[0039] FIG. 15 is a decay scheme showing several decay processes;

[0040] FIG. 16 is a diagram of resonant neutron transfer; and

[0041] FIG. 17 is a diagram of off-resonant neutron transfer.

DETAILED DESCRIPTION

[0042] 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.

[0043] 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.

[0044] 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.

[0045] Following long-standing 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.

[0046] 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.

[0047] 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 $\pm 20\%$, in some embodiments $\pm 10\%$, in some embodiments $\pm 5\%$, in some embodiments $\pm 1\%$, in some embodiments $\pm 0.5\%$, and in some embodiments $\pm 0.1\%$, from the specified amount, as such variations are appropriate in the presently disclosed subject matter.

[0048] **Introduction**

[0049] 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.

[0050] 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.

[0051] 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.

[0052] In one or more embodiments, a (phonon-mediated) resonant neutron transfer mechanism is provided, 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.

[0053] Phonon-Mediated Off-Resonant Transfer

[0054] 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.

[0055] 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.

[0056] Isotope Separation

[0057] 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 implementation it may be observed.

[0058] According to one or more embodiments, an isotope separation kind of application is possible in which a phonon source on one side of a thin sample sends THz phonons into the sample 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 a side of the sample opposite the phonon source.

[0059] Accordingly, an apparatus 10 for implementing a method of neutron enriching a portion of a sample by moving neutrons from a first nucleus to a neighboring or other nucleus, for example to implement isotope separation or concentration, is shown in FIG. 1A, according to at least one embodiment. As shown, a source 12 of phonons 14 is in contact with or mechanically coupled to the first side 16 of a thin sample 20. In at least one embodiment, the phonons 14 have a frequency of at least one terahertz (1 THz). The phonons 14 represent a vibrational signal transmitted into the sample 20 from source 12.

[0060] FIG. 1B is an enlarged view of a portion 1B, as marked in FIG. 1A, of the apparatus 10. Transferred neutrons 22 are preferentially moved or migrated away from the phonon source 12 and first side 16, and toward a second side 18 of the sample 20, opposite the first side 16. By applying phonons 14 into the sample 20 at the first side 16, the neutrons 22 are transferred and moved from first nuclei 24 to neighboring or other second nuclei 26. This effect, over time, may enrich, with neutrons 22, the second nuclei 26 along or proximal the second side 18 relative to the first nuclei 24 along or proximal the first side 16. Accordingly, in the example of the sample

20 having a random mix of Fe-56 and about 2% of Fe-57, Fe-57 enrichment may occur proximal or along the second side 18 of the sample 20.

[0061] Transfer from One Nucleus to Produce an Inequivalent Isotope

[0062] 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.

[0063] Producing an Unstable Isotope

[0064] 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.

[0065] Minimization of the Mass Difference

[0066] 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:

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

[0067] 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.

[0068] 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 Table 1 below.

[0069] Table 1:

Stable	Stable	Stable	Unstable	$T_{1/2}$	$ \Delta E (\text{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

[0070] 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.

[0071] Incoherent Dissipation of a Mass Excess

[0072] 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.

[0073] **Mass Difference**

[0074] 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).

[0075] 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 emissions 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.

[0076] This approach triggers the Fukai effect of D₂ / H₂ 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 previously unknown.

[0077] 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 Cu₃Au structure (Pd₃VacH₄) 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.

[0078] Applications and Implementations

[0079] Applications of interest include implementations 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.

[0080] 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 and industrial applications.

[0081] 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 $^{83}\text{Kr}/^{82}\text{Kr}$ (210 eV), $^{99}\text{Ru}/^{98}\text{Ru}$ (240 eV) and $^{174}\text{Yb}/^{173}\text{Yb}$.

[0082] Excitation transfer: New Results, Applications

[0083] Implementations of excitation transfer are driven by interests in understanding new physics involved in excess heat production in F&P experiment, which is interpreted as involving a nuclear origin, but without energetic nuclear radiation. Thus conventional and known nuclear diagnostics to study the underlying mechanism is insufficient. Implementations herein therefore focus on mechanisms in isolation, with phonon-nuclear coupling proposed as important interactions as experimental evidence supports consistent with our approach to excess heat models with implication of a much larger family of effects than just excess heat.

[0084] Overview of Models

[0085] Regarding now phonon-nuclear coupling, with no energetic lattice phonons, excitation transfer is a lowest-order physical process. Excitation transfer may be responsible for some low-energy nuclear emissions from F&P experiments. Many excitation transfer reactions lead to up-conversion, and down-conversion. Up-conversion is proposed for collimated x-ray emission implementations. Subdivision (one deexcitation to multiple lower energy excitations) and down-conversion may explain excess heat, providing a toolbox to address many anomalies.

[0086] Phonon-nuclear interaction

[0087] The possibility of boosting a correction of nuclear interaction was noted by Breit (1937). Nuclear interaction is modified, in approaches described herein, in a moving frame compared to a rest frame so oscillations or accelerations can couple to internal nuclear transitions. The effect was not previously known for coupling with phonons.

[0088] The relativistic problem can be expressed below with Equations 2-4:

$$\text{Relativistic Hamiltonian: } H = \sum_j \alpha_j \cdot c \mathbf{p}_j + \sum_j \beta_j m c^2 + \sum_{j < k} V_{jk}(\mathbf{r}_k - \mathbf{r}_j) \quad (\text{Equation 2})$$

$$\text{Incomplete F-W rotation: } H' = e^{iS} \left(H - i\hbar \frac{\partial}{\partial t} \right) e^{-iS}, \quad S = -i \frac{1}{2Mc^2} \sum_j \beta_j \alpha_j \cdot c \mathbf{P} \quad (\text{Equation 3})$$

$$H' \rightarrow \frac{|\mathbf{P}|^2}{2M} + \sum_j \alpha_j \cdot c \boldsymbol{\pi}_j + \sum_j \beta_j m c^2 + \sum_{j < k} V_{jk}(\xi_k - \xi_j) + \sum_j \mathbf{a}_j \cdot c \mathbf{P} \quad (\text{Equation 4})$$

nucleus as a particle
internal nuclear model
coupling

[0089] Equation 5 includes terms for the nucleus as a particle, internal nuclear structure, and coupling between center of mass motion and internal nuclear degrees of freedom.

$$\begin{aligned} \hat{H}' = & \frac{|\hat{\mathbf{P}}|^2}{2M} + \sum_j \beta_j m c^2 + \sum_j \alpha_j \cdot c \hat{\boldsymbol{\pi}}_j + \sum_{j < k} \hat{V}_{jk} \\ & + \left\{ \sum_j \beta_j \frac{\hat{\boldsymbol{\pi}}_j}{M} + \frac{1}{2Mc} \sum_{j < k} \left[(\beta_j \alpha_j + \beta_k \alpha_k), \hat{V}_{jk} \right] \right\} \cdot \hat{\mathbf{P}} \end{aligned} \quad (\text{Equation 5})$$

[0090] Excitation transfer was proposed around 1930 in connection with energy exchange in biomolecules and is used in biophysics these days. Excitation transfers from one quantum system to another. The transfer of electronic excitation is known and observed. Embodiments herein implement phonon-mediated nuclear excitation transfer.

[0091] FIG. 1 is diagrammatic representation of excitation transfer, according to at least one embodiment, involving on-resonance and off-resonance states.

[0092] A simple model with weak coupling is expressed in Equations Ec₁ – Ec₆:

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

$$Ec_2 = (n - 1 + \frac{1}{2})\hbar\omega_0c_2 + V_{21}c_1 + V_{26}c_6$$

$$Ec_3 = (n + 1 + \frac{1}{2})\hbar\omega_0c_3 + V_{31}c_1 + V_{36}c_6$$

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

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

$$Ec_6 = (\Delta E + (n + \frac{1}{2})\hbar\omega_0)c_6 + V_{62}c_2 + V_{63}c_3 + V_{64}c_4 + V_{65}c_5 \quad (\text{Equations } Ec_1 - Ec_6)$$

$$E \begin{pmatrix} c_1 \\ c_6 \end{pmatrix} = \begin{pmatrix} H_{11} & V_{16} \\ V_{61} & H_{66} \end{pmatrix} \begin{pmatrix} c_1 \\ c_6 \end{pmatrix} \quad (\text{Equation 6})$$

$$V_{16} = V_{61}^* = \frac{V_{12}V_{26} - V_{15}V_{56}}{\Delta E + \hbar\omega_0} + \frac{V_{13}V_{36} - V_{14}V_{46}}{\Delta E - \hbar\omega_0} \quad (\text{Equation 7})$$

$$\begin{aligned} V_{16} &= \frac{V_0^2(n - (n+1))}{\Delta E + \hbar\omega_0} + \frac{V_0^2((n+1) - n)}{\Delta E - \hbar\omega_0} \\ &= -\frac{V_0^2}{\Delta E + \hbar\omega_0} + \frac{V_0^2}{\Delta E - \hbar\omega_0} \\ &\approx -\frac{V_0^2}{\Delta E} \left(1 - \frac{\hbar\omega_0}{\Delta E}\right) + \frac{V_0^2}{\Delta E} \left(1 + \frac{\hbar\omega_0}{\Delta E}\right) = \frac{2V_0^2\hbar\omega_0}{\Delta E^2} \end{aligned} \quad (\text{Equation 8})$$

$$V_{16} = V_{61} \approx \frac{2V_0^2\hbar\omega_0}{\Delta E^2} \quad (\text{Equation 9})$$

[0093] Reasonings: quantum mechanical effect; intermediate states off of resonance; at least 2 phonon exchange interactions may be needed 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.

[0094] FIG. 3 illustrates low-level energetic α , n emission, in which energy is transferred to a Pd nucleus. The transfer of $D_2/^4He$ (24 MeV) energy disintegrates a Pd nucleus (FIG. 3). This would produce low-level energetic alphas (observations reported by Chambers et al, Lipson et al, others). This would produce low-level energetic neutrons (observations reported by Roussetki et al, by Mosier-Boss et al).

[0095] Lipinski and Lipinski claimed observations of very large enhancement of $p(^7Li, \alpha)\alpha$ fusion reaction cross section at low (sub keV) energy. This is interpreted as due to a gravitational resonance effect. Data shows a very strong proton signal at 0.79 MeV. Results from 25 different experimental series were considered. The below focuses on a “series 13” experiment and results thereof.

[0096] FIG. 4 illustrates incoherent excitation transfer in which proton energy including recoil is 0.889 MeV.

[0097] Lipinski and Lipinski interpret an observed 8537.59 keV alpha signal peak as due to (anomalous) $p(^7Li, \alpha)\alpha + 17.34$ MeV due to sub-keV proton beam. The 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 $O(100)$. We also considered the ejected alpha as perhaps due to incoherent excitation transfer reaction as in FIG. 5, in which an alpha energy including recoil is 9.13 MeV.

[0098] Reasoning: Fusion is not expected with protons below 1 keV. Inventors attribute effect to gravity resonance effect between p and ^7Li . The 0.79 MeV proton signal is attributed to “backscatter.” The 0.79 MeV proton signal might be a result of incoherent excitation transfer reaction from $\text{HD}/^3\text{He}$, and the 8.54 MeV α signal might be a result of incoherent excitation transfer reaction from $\text{D}_2/^4\text{He}$.

[0099] FIG. 6A illustrates an apparatus 100, according to at least one embodiment, in which a Co-57 source 102 and a transducer 104 are attached to opposite sides of a steel plate 106 secured between wood blocks 108 at opposite ends thereof. An aluminum mesh 110 is placed between the source and an X-ray detector 112. Data taken is represented in FIG. 6B.

[00100] The apparatus 100 of FIG. 6A was set up to look for excitation transfer due to MHz phonon exchange. A plot of 14.4 keV counts versus time is shown in FIG. 6B. Although no obvious response to MHz vibrations was observed, a response connected to creep was seen. This is interpreted as delocalization of excitation of the 14.4 keV (FIG. 7) state due to phonon-mediated non-resonant excitation transfer. There was also evidence for angular anisotropy of 122 keV and 136 keV gammas, interpreted as phase correlation of the 136 keV state due to phonon-mediated resonant excitation transfer.

[00101] Basic model predictions for E1, M1 transitions – Modeling

[00102] A developed formalism for coupling phonons and nuclei:

$$H = \sum_k \hbar \omega_k a_k^\dagger a_k + \sum_j \mathbf{M}_j c^2 + \sum_j \mathbf{a}_j \cdot c \mathbf{P}_j \quad (\text{Equation 10})$$

with

$$\mathbf{P}_j = \sum_k \frac{\partial \mathbf{P}_j}{\partial a_k} a_k + \sum_k \frac{\partial \mathbf{P}_j}{\partial a_k^\dagger} a_k^\dagger \quad (\text{Equation 11})$$

[00103] The model includes phonon-nuclear coupling to nuclear electric dipole and related nuclear transitions. E1 (electric dipole) nuclear transitions are simplest, and M1 (magnetic dipole) and E2 (electric quadrupole) transitions are more complicated. In the E1 transitions, resonant case:

$$\begin{aligned}
 \left(\hat{V}(E - \hat{H}_0)^{-1} \hat{V} \right)_{\text{resonant}} &\rightarrow \frac{Mc^2}{(\Delta E)^2} \sum_{j < j'} \sum_{m_0} \sum_{m_1} \sum_{m'_0} \sum_{m'_1} \left(|J_0 m_0\rangle \langle J_1 m_1| \right)_j \left(|J_1 m'_1\rangle \langle J_0 m'_0| \right)_{j'} \\
 &\langle J_0 m_0 | \mathbf{a}_j | J_1 m_1 \rangle \cdot \left[\frac{1}{N} \sum_{\mathbf{k}, \sigma} (\hbar \omega_{\mathbf{k}, \sigma})^2 \mathbf{u}_{\mathbf{k}, \sigma} \mathbf{u}_{\mathbf{k}, \sigma} \cos \left(\mathbf{k} \cdot (\mathbf{R}_{j'}^{(0)} - \mathbf{R}_j^{(0)}) \right) \right] \cdot \langle J_1 m'_1 | \mathbf{a}_{j'} | J_0 m'_0 \rangle \\
 &+ \frac{Mc^2}{(\Delta E)^2} \sum_{j < j'} \sum_{m_0} \sum_{m_1} \sum_{m'_0} \sum_{m'_1} \left(|J_1 m_1\rangle \langle J_0 m_0| \right)_j \left(|J_0 m'_0\rangle \langle J_1 m'_1| \right)_{j'} \\
 &\langle J_1 m_1 | \mathbf{a}_j | J_0 m_0 \rangle \cdot \left[\frac{1}{N} \sum_{\mathbf{k}, \sigma} (\hbar \omega_{\mathbf{k}, \sigma})^2 \mathbf{u}_{\mathbf{k}, \sigma} \mathbf{u}_{\mathbf{k}, \sigma} \cos \left(\mathbf{k} \cdot (\mathbf{R}_{j'}^{(0)} - \mathbf{R}_j^{(0)}) \right) \right] \cdot \langle J_0 m'_0 | \mathbf{a}_{j'} | J_1 m'_1 \rangle \}.
 \end{aligned}$$

(Equation 12)

[00104] In the 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}} \rightarrow \\
& \frac{(Mc^2)^2}{4N} \sum_{J_2} \sum_{J'_2} \left(\frac{(E_1 - E_0)^2 - 3(E_1 - E_0)[(E_2 - E_0) + (E'_2 - E_0)]}{(E_2 - E_0)(E'_2 - E_0)(E_1 - E_2)(E_1 - E'_2)(E_2 + E'_2 - E_0 - E_1)} \right) \\
& \sum_j \sum_{j'} \sum_{m_0} \sum_{m_1} \sum_{m_2} \sum_{m'_0} \sum_{m'_1} \sum_{m'_2} \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'} \\
& \sum_{\alpha} \sum_{\beta} \sum_{\gamma} \sum_{\delta} (\langle J_0 m_0 | \mathbf{a}_j | J_2 m_2 \rangle)_{\alpha} (\langle J_2 m_2 | \mathbf{a}_j | J_1 m_1 \rangle)_{\beta} (\langle J_1 m'_1 | \mathbf{a}_{j'} | J'_2 m'_2 \rangle)_{\gamma} (\langle J'_2 m'_2 | \mathbf{a}_{j'} | J_0 m'_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_0 m_0\rangle \langle J_1 m_1| \right)_j \left(|J_1 m'_1\rangle \langle J_0 m'_0| \right)_{j'} \\
& \sum_{\alpha} \sum_{\beta} \sum_{\gamma} \sum_{\delta} (\langle J_0 m_0 | \mathbf{a}_j | J_2 m_2 \rangle)_{\alpha} (\langle J_2 m_2 | \mathbf{a}_j | J_1 m_1 \rangle)_{\beta} (\langle J_1 m'_1 | \mathbf{a}_{j'} | J'_2 m'_2 \rangle)_{\gamma} (\langle J'_2 m'_2 | \mathbf{a}_{j'} | J_0 m'_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 \left(2\mathbf{k}(\mathbf{R}_{j'}^{(0)} - \mathbf{R}_j^{(0)}) \right) \right].
\end{aligned}$$

(Equation 13)

[00105] Augmenting spin-boson models with asymmetric loss can dramatically increase rates for up-conversion, and down-conversion. Modification of excitation transfer rates with loss is also expected.

[00106] In the E1 transitions, loss, resonant case:

$$\begin{aligned}
& \left(\hat{V}(E - \hat{H}_0)^{-1} \hat{V} \right)_{\text{resonant}} \rightarrow \\
& -i \frac{\hbar}{2} (\gamma_{00} + \gamma_{11} - \gamma_{01} - \gamma_{10}) \frac{Mc^2}{2(\Delta E)^2} \sum_{j < j'} \sum_{m_0} \sum_{m_1} \sum_{m'_0} \sum_{m'_1} \left(|J_0 m_0\rangle \langle J_1 m_1| \right)_j \left(|J_1 m'_1\rangle \langle J_0 m'_0| \right)_{j'} \\
& \langle J_0 m_0 | a_j | J_1 m_1 \rangle \cdot \left[\frac{1}{N} \sum_{\mathbf{k}, \sigma} (\hbar \omega_{\mathbf{k}, \sigma})^2 u_{\mathbf{k}, \sigma} u_{\mathbf{k}, \sigma} (2\hat{n}_{\mathbf{k}, \sigma} + 1) \cos \left(\mathbf{k} \cdot (\mathbf{R}_{j'}^{(0)} - \mathbf{R}_j^{(0)}) \right) \right] \cdot \langle J_1 m'_1 | a_{j'} | J_0 m'_0 \rangle \\
& -i \frac{\hbar}{2} (\gamma_{00} + \gamma_{11} - \gamma_{01} - \gamma_{10}) \frac{Mc^2}{2(\Delta E)^2} \sum_{j < j'} \sum_{m_0} \sum_{m_1} \sum_{m'_0} \sum_{m'_1} \left(|J_1 m_1\rangle \langle J_0 m_0| \right)_j \left(|J_0 m'_0\rangle \langle J_1 m'_1| \right)_{j'} \\
& \langle J_1 m_1 | a_j | J_0 m_0 \rangle \cdot \left[\frac{1}{N} \sum_{\mathbf{k}, \sigma} (\hbar \omega_{\mathbf{k}, \sigma})^2 u_{\mathbf{k}, \sigma} u_{\mathbf{k}, \sigma} (2\hat{n}_{\mathbf{k}, \sigma} + 1) \cos \left(\mathbf{k} \cdot (\mathbf{R}_{j'}^{(0)} - \mathbf{R}_j^{(0)}) \right) \right] \cdot \langle J_0 m'_0 | a_{j'} | J_1 m'_1 \rangle \Big\}.
\end{aligned}$$

(Equation 14)

[00107] Reasonings: The 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 smaller than effect observed.

[00108] Basis state shifts off of resonance

[00109] As shown in the diagrams of FIG. 8 and 9, more cancellation occurs without off-res shift (FIG. 8), and less cancellation with shift (FIG. 9).

[00110] Basis state energy shift off of resonance

[00111] This might provide a possible resolution to the problem in 2018. Papers in the literature discuss modification of nuclear interaction off of resonance, but with no prior systematic quantification of the amount of shift expected. Thus, there was a need to develop excitation transfer formulae that take these effects into account, and a need to quantify energy shifts off of resonance.

[00112] In the E1 transitions, shifts, resonant case (below is Equation 15):

$$\begin{aligned}
& \left(\hat{V}(E - \hat{H}_0)^{-1} \hat{V} \right)_{\text{resonant}} \\
& \rightarrow \sum_j \sum_{j'} \sum_{m_0} \sum_{m_1} \sum_{m'_0} \sum_{m'_1} \sum_{\mathbf{k}, \sigma} \frac{Mc^2 \hbar \omega_{\mathbf{k}, \sigma}}{2N} \\
& \left\{ |J_0 m_0\rangle \langle J_0 m_0| \mathbf{u}_{\mathbf{k}, \sigma} \cdot \mathbf{a}_j |J_1 m_1\rangle \langle J_1 m_1| |J_1 m'_1\rangle \langle J_1 m'_1| \mathbf{u}_{\mathbf{k}, \sigma} \cdot \mathbf{a}_{j'} |J_0 m'_0\rangle \langle J_0 m'_0| \right. \\
& \frac{E_{00} + E_{11} - 2E_{10}}{(E_{10} - E_{00})(E_{11} - E_{10})} (2\hat{n}_{\mathbf{k}, \sigma} + 1) \cos[\mathbf{k} \cdot (\mathbf{R}_{j'}^{(0)} - \mathbf{R}_j^{(0)})] \\
& + |J_1 m_1\rangle \langle J_1 m_1| \mathbf{u}_{\mathbf{k}, \sigma} \cdot \mathbf{a}_j |J_0 m_0\rangle \langle J_0 m_0| |J_0 m'_0\rangle \langle J_0 m'_0| \mathbf{u}_{\mathbf{k}, \sigma} \cdot \mathbf{a}_{j'} |J_1 m'_1\rangle \langle J_1 m'_1| \\
& \left. \frac{E_{00} + E_{11} - 2E_{10}}{(E_{10} - E_{00})(E_{11} - E_{10})} (2\hat{n}_{\mathbf{k}, \sigma} + 1) \cos[\mathbf{k} \cdot (\mathbf{R}_{j'}^{(0)} - \mathbf{R}_j^{(0)})] \right\},
\end{aligned}$$

[00113] In M1 transitions, 1-mode, resonant case (below is Equation 16):

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

[00114] Below is Equation 17:

$$\begin{aligned}
T_{c0} = & \frac{(Mc^2)^2}{4N} \sum_{J_2} \sum_{J'_2} \left(\frac{2}{(E_{10} - E_{00})(E_{10} - E_{20})(E_{10} - E_{2'0})} + \frac{2}{(E_{10} - E_{11})(E_{10} - E_{21})(E_{10} - E_{2'1})} \right. \\
& \left. + \frac{1}{(E_{10} - E_{20})(E_{10} - E_{2'0})(E_{10} - E_{2'2})} + \frac{1}{(E_{10} - E_{21})(E_{10} - E_{2'1})(E_{10} - E_{2'2})} \right) \\
& \sum_j \sum_{j'} \sum_{m_0} \sum_{m_1} \sum_{m_2} \sum_{m'_0} \sum_{m'_1} \sum_{m'_2} \left(|J_0 m_0\rangle \langle J_1 m_1| \right)_j \left(|J_1 m'_1\rangle \langle J_0 m'_0| \right)_{j'} \\
& \sum_{\alpha} \sum_{\beta} \sum_{\gamma} \sum_{\delta} (\langle J_0 m_0 | \mathbf{a}_j | J_2 m_2 \rangle)_{\alpha} (\langle J_2 m_2 | \mathbf{a}_j | J_1 m_1 \rangle)_{\beta} (\langle J_1 m'_1 | \mathbf{a}_{j'} | J'_2 m'_2 \rangle)_{\gamma} (\langle J'_2 m'_2 | \mathbf{a}_{j'} | J_0 m'_0 \rangle)_{\delta} \\
& \left[\frac{1}{N} \sum_{\mathbf{k}, \sigma} (\hbar \omega_{\mathbf{k}, \sigma})^2 (\mathbf{u}_{\mathbf{k}, \sigma})_{\alpha} (\mathbf{u}_{\mathbf{k}, \sigma})_{\beta} (\mathbf{u}_{\mathbf{k}, \sigma})_{\gamma} (\mathbf{u}_{\mathbf{k}, \sigma})_{\delta} \cos \left(2\mathbf{k} \cdot (\mathbf{R}_{j'}^{(0)} - \mathbf{R}_j^{(0)}) \right) \right]
\end{aligned}$$

[00115] Even larger increases in indirect coupling rate, if the energy shifts off of resonance are greater than the loss rates. So, there was a need to develop estimates for the shifts. This

version of the model connects with experiment. Note that if so, would not need loss for up-conversion and down-conversion models.

[00116] Deuteron off of resonance

[00117] Many models for the deuteron are available. Calculation of the nuclear force off of resonance from scratch in the chiral effective field theory model is lots of work. Thus, it is preferable to start with a simpler calculation, for which it is not so difficult to calculate extension of single-pion exchange contribution off of resonance. This would get the long-range contribution, which should be the dominant contribution to the shift for the deuteron. The increment can be added to an existing model for the deuteron.

[00118] One-pion exchange

[00119] Relativistic one-pion exchange interaction off of resonance (Equation 18):

$$\begin{aligned}
 V_{12} &= -\frac{f^2}{\mu_\pi^2}(\boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_1)(\beta\gamma^{(5)})_2(\beta\gamma^{(5)})_1 \frac{1}{2} \int \frac{e^{i\mathbf{k} \cdot (\mathbf{r}_2 - \mathbf{r}_1)}}{\hbar\omega_{\mathbf{k}}(E_{off} - \hbar\omega_{\mathbf{k}})} \frac{d^3\mathbf{k}}{(2\pi)^3} + (1 \leftrightarrow 2) \\
 &= -\frac{f^2}{\mu_\pi^2}(\boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_1)(\beta\gamma^{(5)})_2(\beta\gamma^{(5)})_1 \frac{1}{2\pi^2|\mathbf{r}_2 - \mathbf{r}_1|} \int_0^\infty \frac{k \sin(k|\mathbf{r}_2 - \mathbf{r}_1|)}{\hbar\omega_{\mathbf{k}}(E_{off} - \hbar\omega_{\mathbf{k}})} dk
 \end{aligned}$$

[00120] Pseudo-scalar and pseudo-vector interactions result in the same contribution for the one-pion exchange contribution (below is Equation 19):

$$\begin{aligned}
\int_0^\infty \frac{k \sin(k|r_2 - r_1|)}{\hbar\omega_k(E_{off} - \hbar\omega_k)} dk &= \int_0^\infty \frac{k \sin(k|r_2 - r_1|)}{\sqrt{(\mu c^2)^2 + \hbar^2 c^2 k^2} (E_{off} - \sqrt{(\mu c^2)^2 + \hbar^2 c^2 k^2})} dk \\
&= -\sum_i C_i \int_0^\infty \frac{k \sin(k|r_2 - r_1|)}{(\mu_i c^2)^2 + \hbar^2 c^2 k^2} dk \quad (\text{fitting})
\end{aligned}$$

[00121] Deuteron model

Modification of the Hamada-Johnston model

$$\hat{H} = \frac{|\hat{\mathbf{p}}|^2}{M} + V_C + V_T \hat{S}_{12} + V_{LS} \hat{\mathbf{L}} \cdot \hat{\mathbf{S}} + V_{LL} \mathbf{L}_{12} + \Delta V_C + \Delta V_T \hat{S}_{12} \quad (\text{Equation 20})$$

[00122] In Equation 20, the first term represents kinetic energy, where the reduced mass is $M/2$. The last two terms represent an off-resonant correction. The four intermediate terms represent a Hamada-Johnston potential.

[00123] Deuteron binding energy shift

[00124] A big shift of the deuteron binding energy off of resonance is shown in FIG. 10. The 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. Shifts are needed for other nuclei.

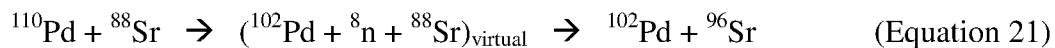
[00125] Dineutron off of resonance

[00126] The deuteron problem important since it is simplest. But deuterons are not expected off of resonance. The story is different for dineutrons. Experimental results (Iwamura) show mass increases. Multiple-neutron transfer is a possible explanation. But a dineutron is not bound (same for multi-neutron clusters). A dineutron would be bound off of resonance. It is possible to use same approach to evaluate dineutron binding off of resonance.

[00127] FIGS. 11 and 12 are plots showing, respectively, dineutron scattering length (FIG. 11) and dineutron binding energy (FIG. 12) for several different hard core radius parameter values. The plots in FIGS. 11 and 12 are labeled for four hard core radius values: 0.343, 0.342, 0.341, and 0.340.

[00128] A dineutron can be bound off of resonance, as long as the off-resonant energy is large enough. Multi-neutron clusters are expected to be bound also far off of resonance, meaning multi-neutron exchange might be expected to be possible off of resonance. This poses perhaps an explanation for the Iwamura transmutation experiment (2003), an illustration of the implementation of which is shown in FIG. 13, and a plot of data resulting therefrom is shown in FIG. 14.

[00129] An example of off-resonant neutron cluster transfer is shown in Equation 21.



[00130] FIG. 15 is a decay scheme showing several decay processes, including beta decay of ^{96}Sr populated in Equation 21. The 8-neutron cluster on resonance is not bound. The nuclear potential much stronger off of resonance. A dineutron is bound at about +25 MeV off-resonance. An 8 neutron cluster would be expected to be bound with +20-35 MeV off of resonance. This is possibly in connection with single or multiple $\text{D}_2/{}^4\text{He}$ excitation transfer coherent processes. If true, then a similar implementation with restricted Pd isotopes would transfer a smaller neutron cluster, and beta decay products may be seen, or this could rule out a proposed mechanism if decay products are not present

[00131] **Phonon-mediated neutron transfer**

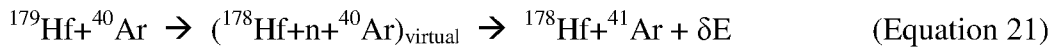
[00132] Single-neutron transfer was proposed in the 1990s by Hagelstein. Analysis of the time did not support the possibility. This is revisited herein in light of a phonon-nuclear

interactions and a phonon-induced neutron transfer mechanism. Resonant transfer may be expected, but may not be a good mode of detection. Off-resonant neutron transfer could make new nuclei, and if radioactive nuclei are made, they are much easier to detect. This opens the possibility for eliminating some radioactive nuclei as an application.

[00133] FIGS. 16 and 17 are diagrams showing resonant neutron transfer and off-resonant neutron transfer, respectively.

[00134] To implement phonon-mediated neutron transfer as a mechanism, candidates preferably minimize energy mismatch between initial and final states. The mass table was thus analyzed, and computer code sorted through all possible neutron transfer reactions to look for nuclei pairs where a new unstable nucleus is made. The results are shown in Table 1 in the preceding.

[00135] Candidates are available with relatively small overall mass defects ($|\Delta E|$). The lowest one is (Table 1):



[00136] In one embodiment, an Ar ion beam is incident on a Hf sample, to produce radioactive ^{41}Ar . Others embodiments could be implemented with either alloys, co-deposited material, and/or evaporations along with stress (similar to excitation transfer experiments).

[00137] Herein, excitation transfer models are analyzed. Straightforward prior predictions may be too low to connect with experiments. Loss helps, but not enough to fix things. Off-resonance energy shifts are proposed to address the problem. Computations of deuteron binding energy off of resonance calculate a big shift, and strong nonlinearity. This version of the model may connect with experiments. Phonon-mediated single neutron transfer reactions are proposed, and tested by making and detecting short-lived unstable nuclei. Dineutron stabilization off of

resonance is expected. Multi-neutron cluster exchange off of resonance where clusters can be bound is proposed.

[00138] 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.

[00139] 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.

[00140] 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 neutron enriching a portion of a sample, the method comprising:
applying phonons to a first side of a sample, thereby transferring neutrons from first nuclei within the sample to second nuclei within the sample, whereby the second nuclei are enriched with the transferred neutrons.
2. The method of claim 1, wherein the phonons are applied to the first side of the sample by a phonon source in contact with or mechanically coupled to the first side of the sample.
3. The method of claim 1, wherein the phonons have a frequency of at least one terahertz.
4. The method of claim 1, wherein transferring neutrons comprises moving the neutrons away from the first side of the sample and toward a second side of the sample opposite the first side.
5. The method of claim 4, wherein the second nuclei are enriched with the transferred neutrons along or proximal the second side of the sample relative to the first nuclei along or proximal the first side of the sample.
6. The method of claim 1, wherein the first nuclei comprises Fe-57.

7. The method of claim 1, wherein the second nuclei comprise Fe-56.
8. The method of claim 1, wherein applying phonons to a first side of a sample, thereby transferring neutrons from first nuclei within the sample to second nuclei within the sample, comprises triggering phonon-mediated, off-resonant neutron transfer.
9. 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.
10. The method of claim 9, wherein the different isotope is an isotope of the first element.
11. The method of claim 9, wherein the different isotope is an isotope of a second element, wherein the first element and second element are not the same element.
12. The method of claim 9, further comprising detecting neutron transfer using nuclear magnetic resonance (NMR) spectroscopy.
13. The method of claim 9, further comprising detecting neutron transfer using neutron activation analysis (NAA).
14. A method of neutron transfer, comprising:
transferring a neutron to a stable isotope, thereby producing a daughter that is unstable
with one more neutrons; and

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

15. An apparatus for neutron enriching a portion of a sample, the apparatus comprising:
a phonon source in contact with or mechanically coupled to a first side of a sample, the phonon source configured to apply phonons to the first side of the sample, thereby transferring neutrons from first nuclei within the sample to second nuclei within the sample, whereby the second nuclei are enriched with the transferred neutrons.
16. The apparatus of claim 15, wherein the phonons are applied to the first side of the sample by a phonon source in contact with or mechanically coupled to the first side of the sample.
17. The apparatus of claim 15, wherein the phonons have a frequency of at least one terahertz.
18. The apparatus of claim 15, wherein transferring neutrons comprises moving the neutrons away from the first side of the sample and toward a second side of the sample opposite the first side.
19. The apparatus of claim 18, wherein the second nuclei are enriched with the transferred neutrons along or proximal the second side of the sample relative to the first nuclei along or proximal the first side of the sample.

20. The apparatus of claim 15, wherein applying phonons to a first side of a sample, thereby transferring neutrons from first nuclei within the sample to second nuclei within the sample, comprises triggering phonon-mediated, off-resonant neutron transfer.

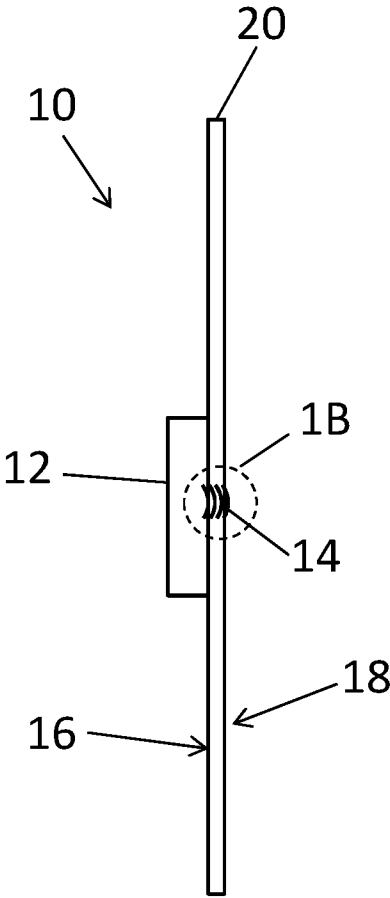


FIG. 1A

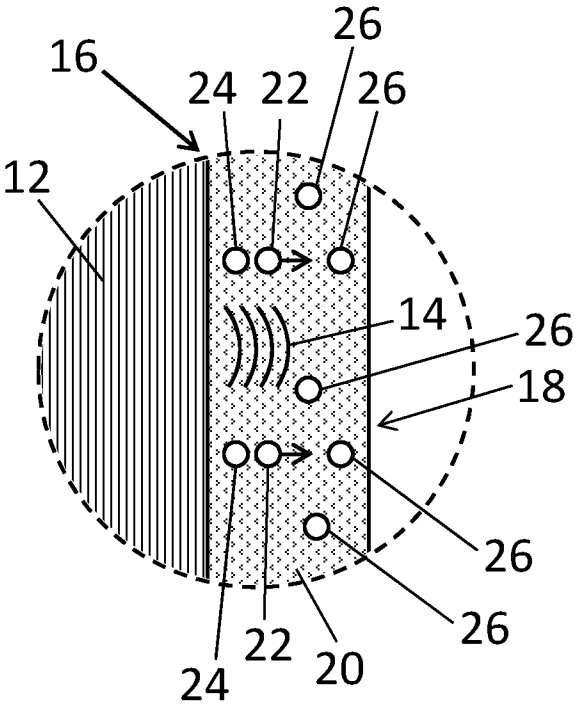


FIG. 1B

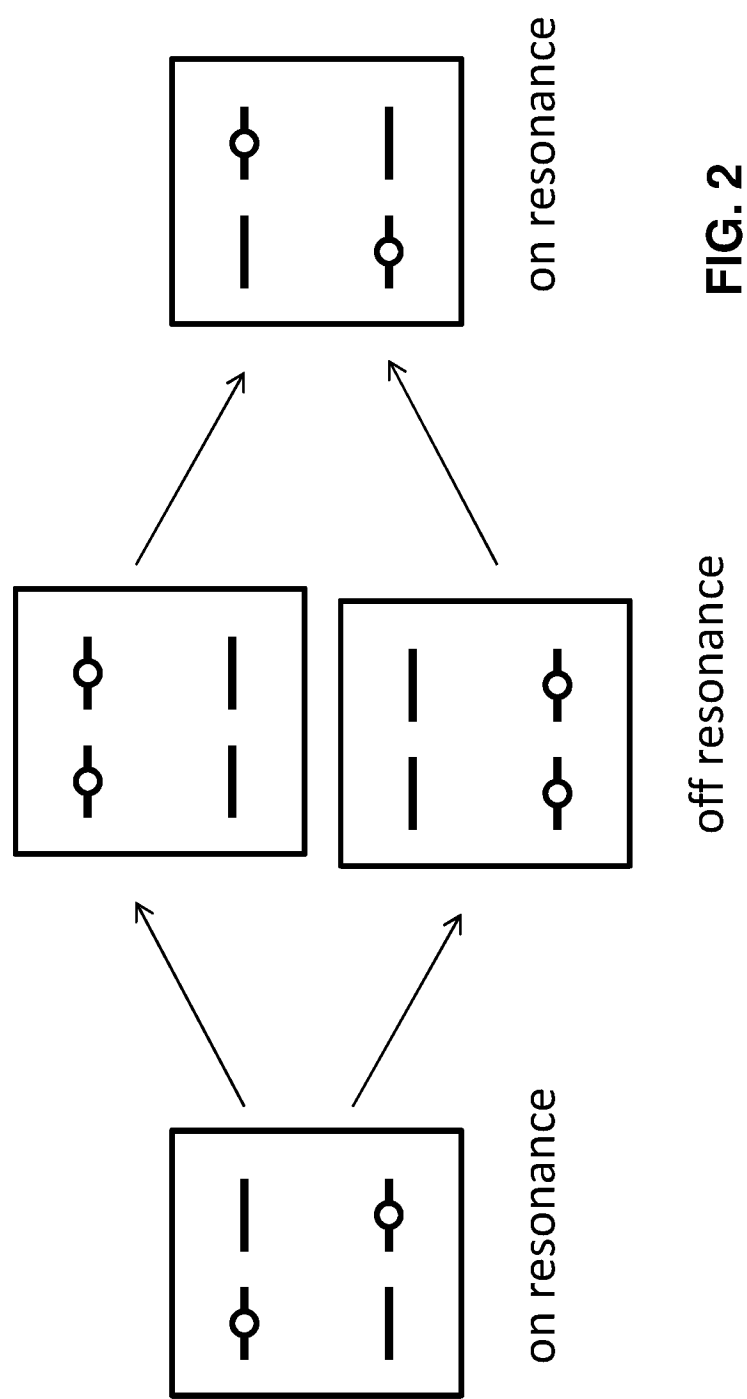


FIG. 2

3/17

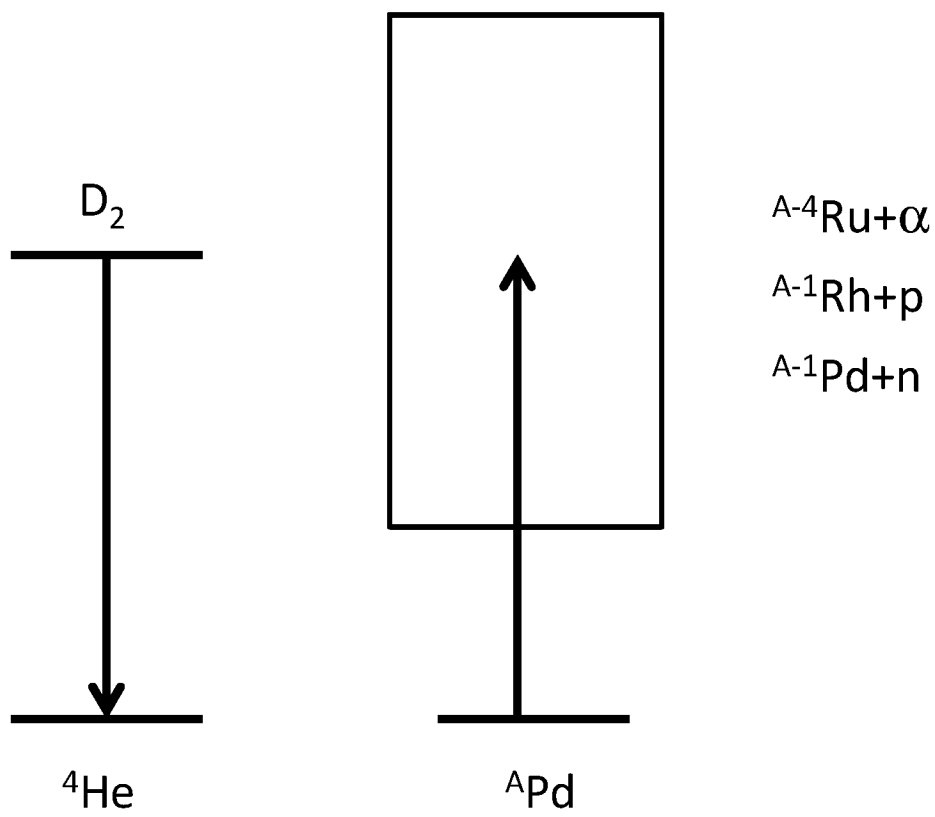
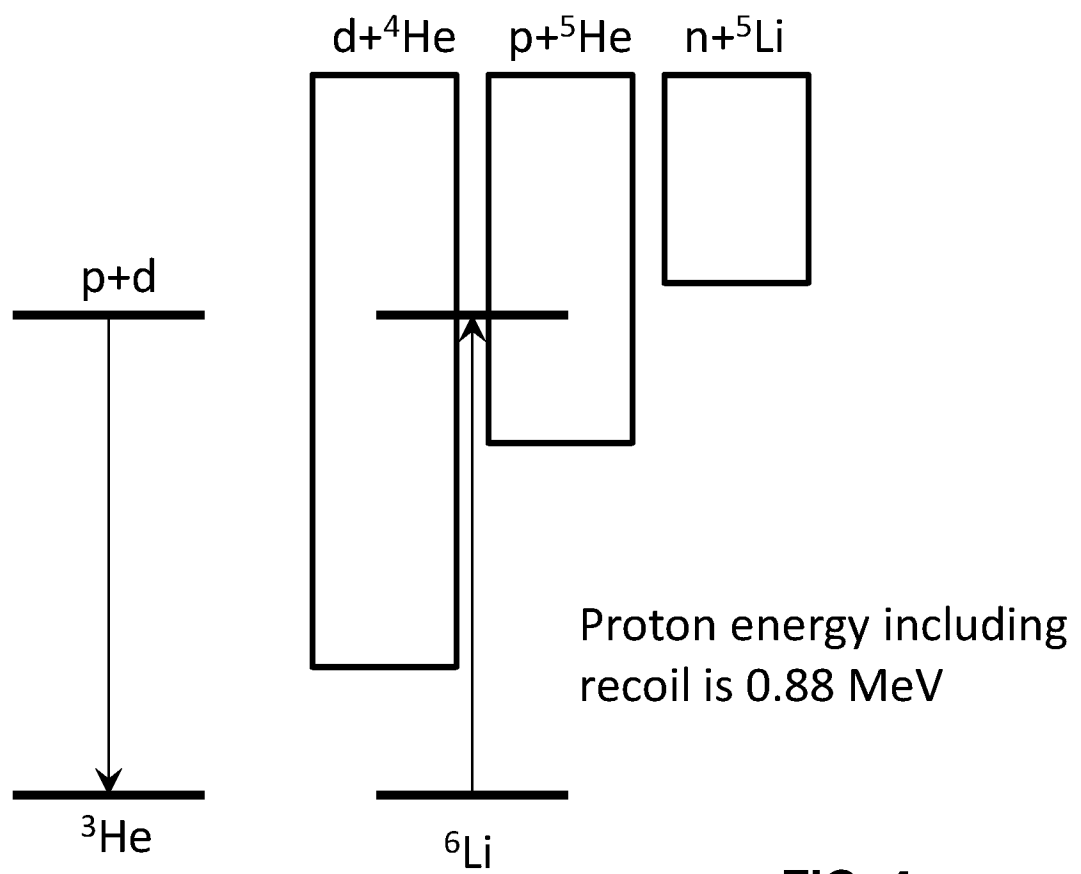


FIG. 3

4/17

**FIG. 4**

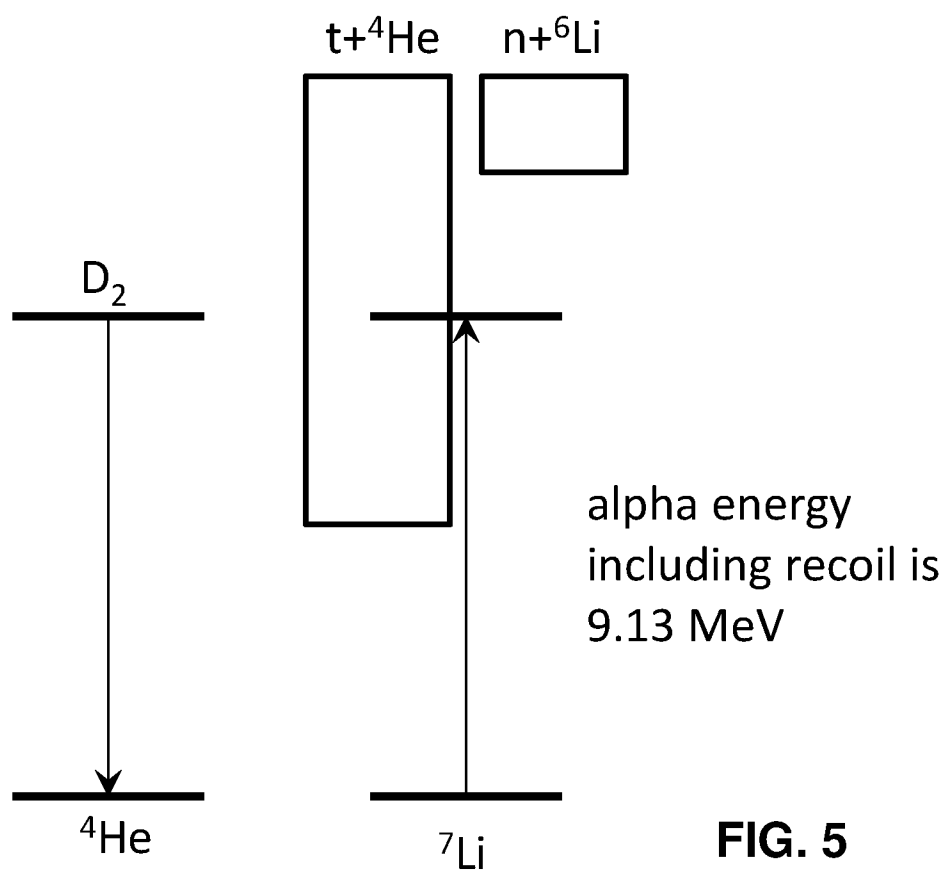


FIG. 5

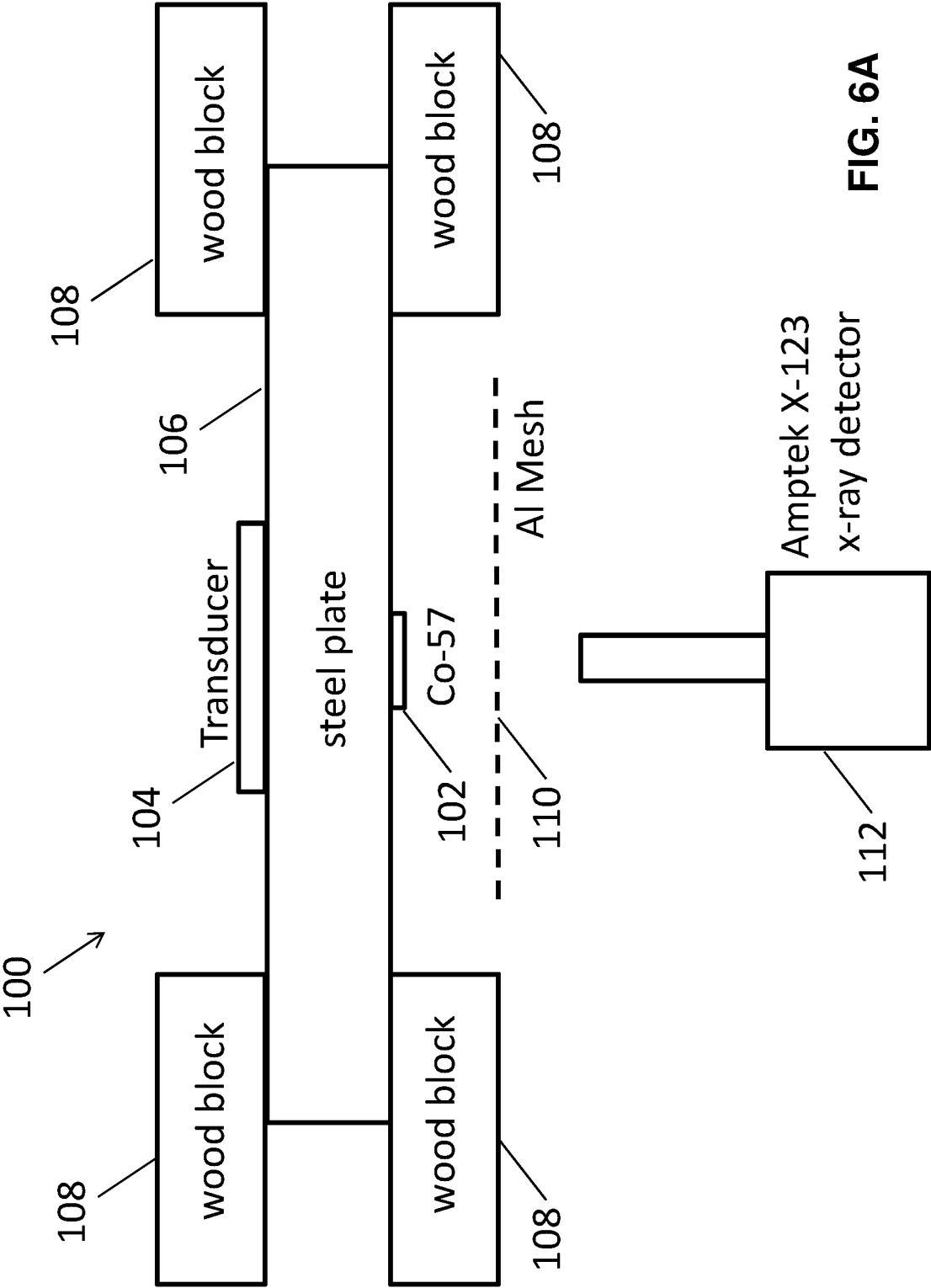


FIG. 6A

7/17

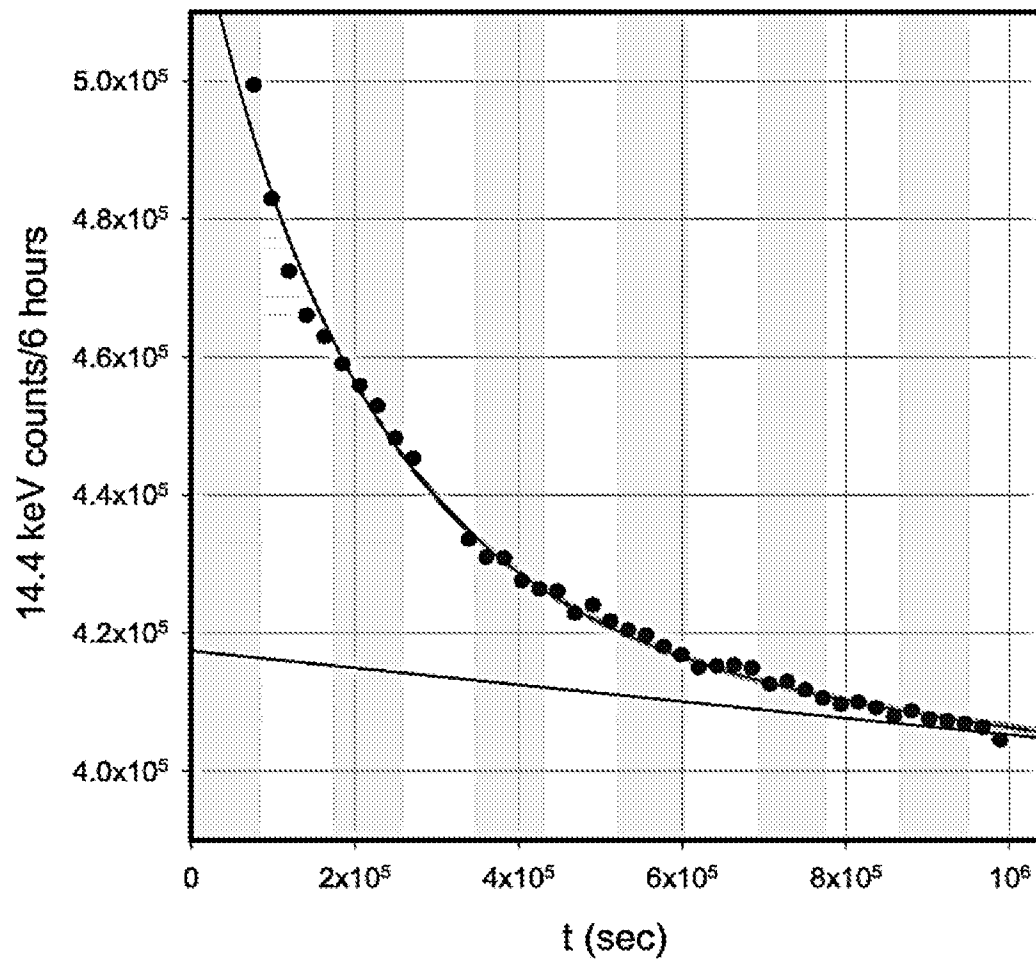
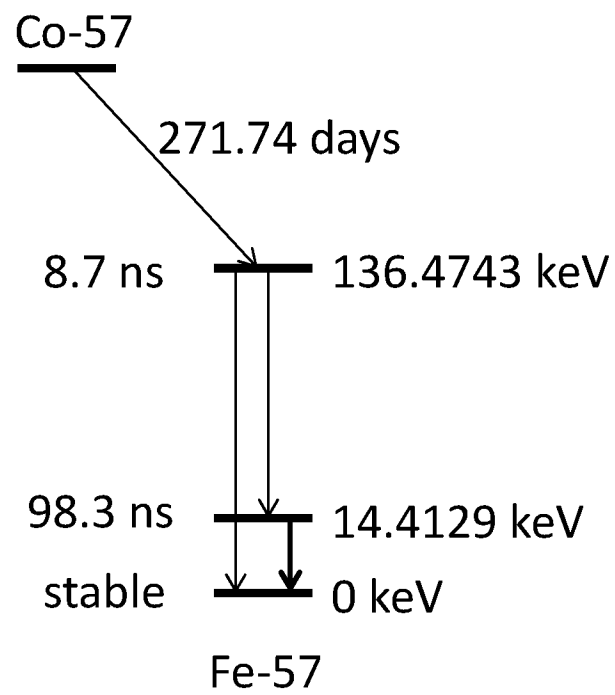


FIG. 6B

8/17

**FIG. 7**

9/17

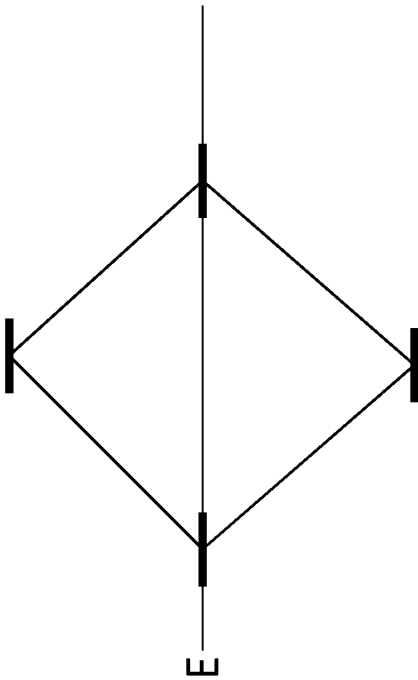


FIG. 9

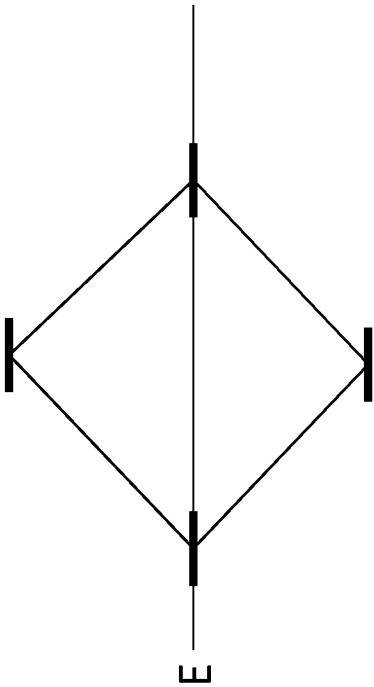


FIG. 8

10/17

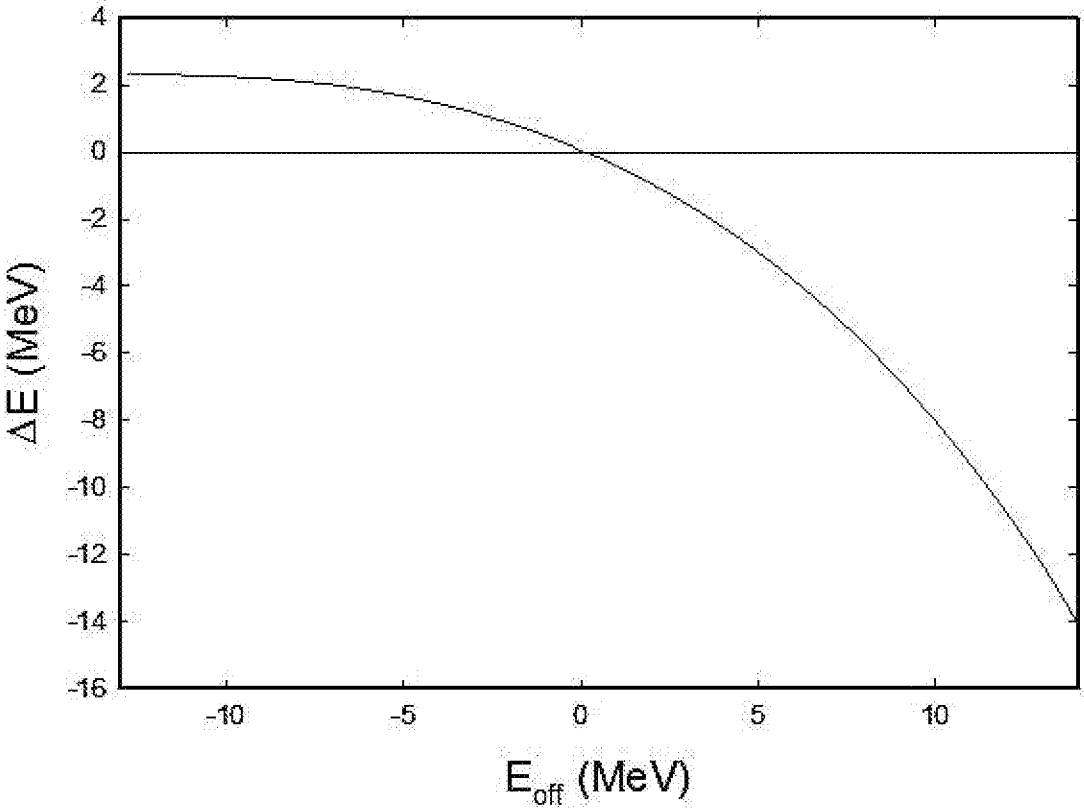


FIG. 10

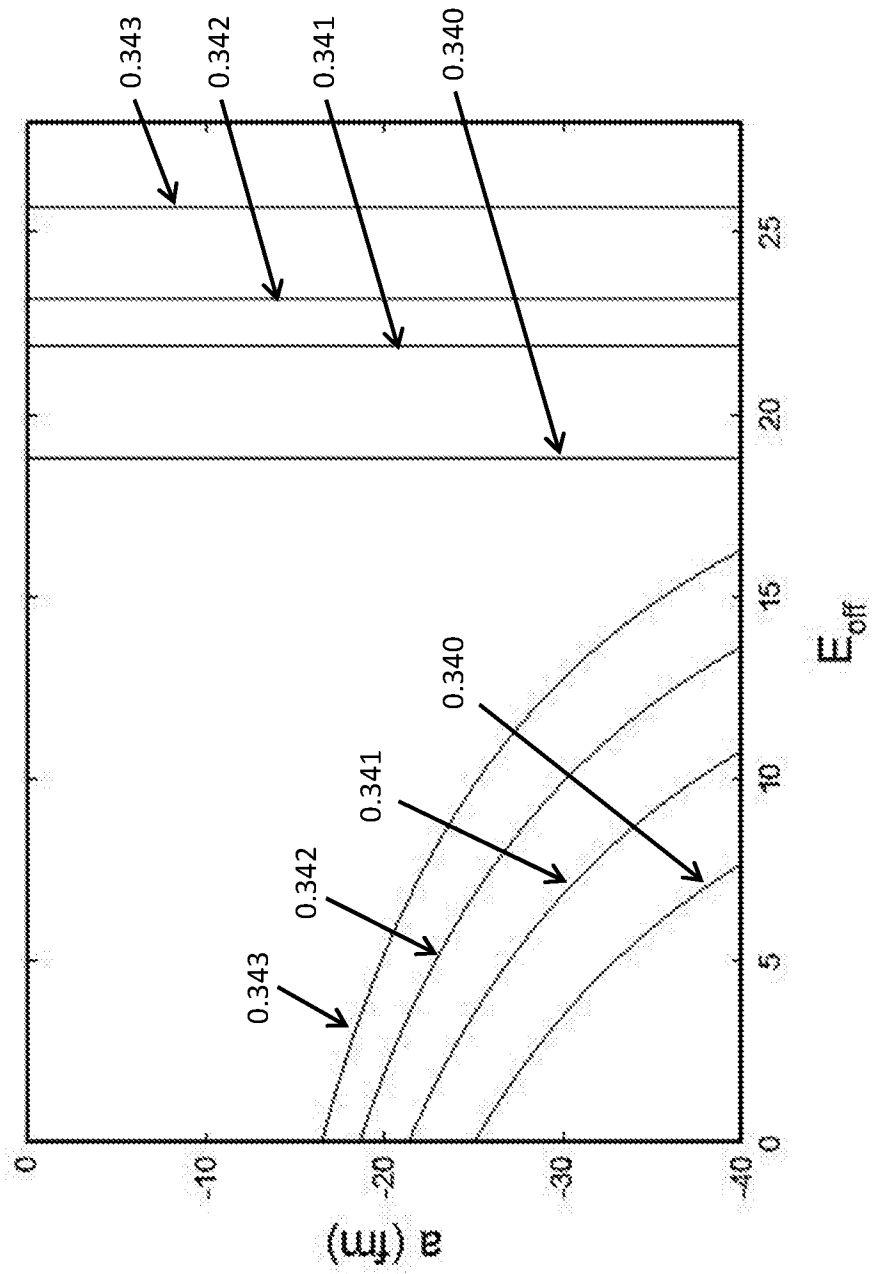


FIG. 11

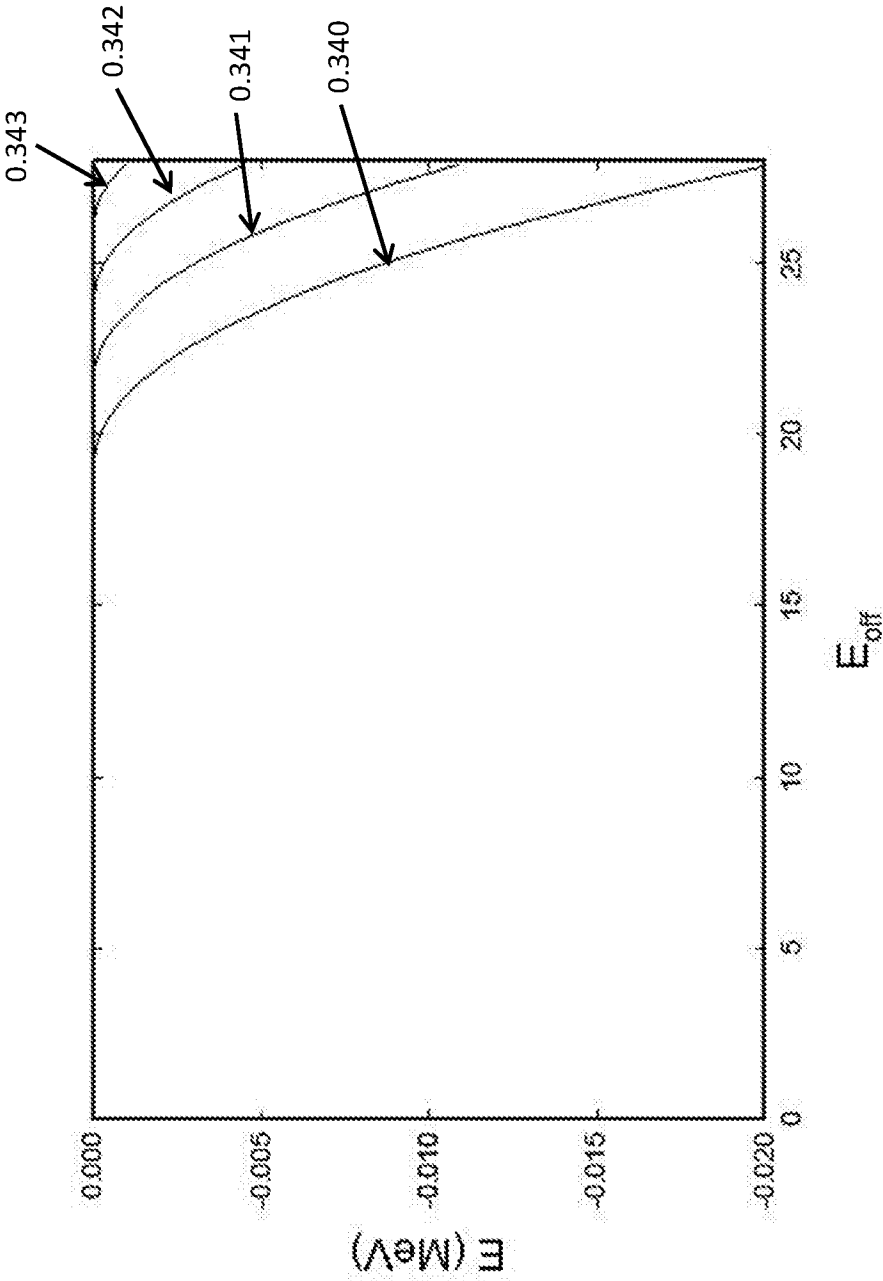


FIG. 12

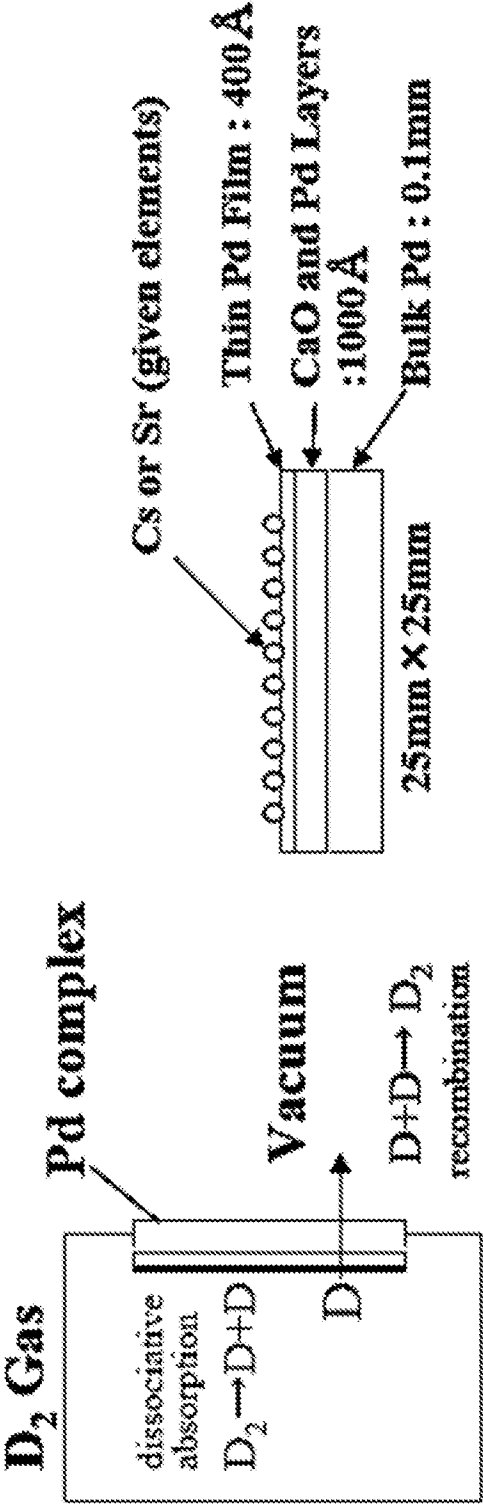


FIG. 13 Prior Art

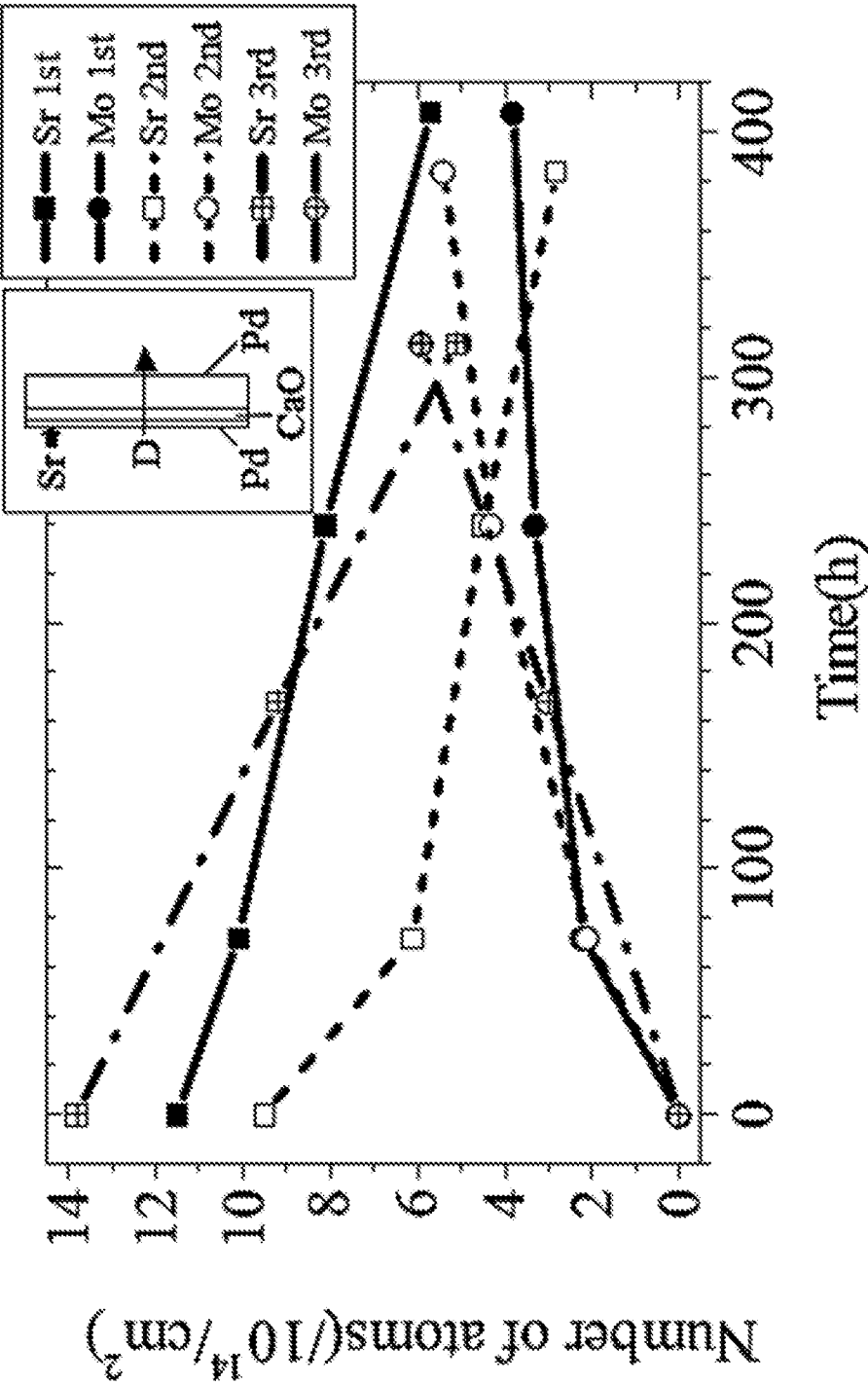


FIG. 14

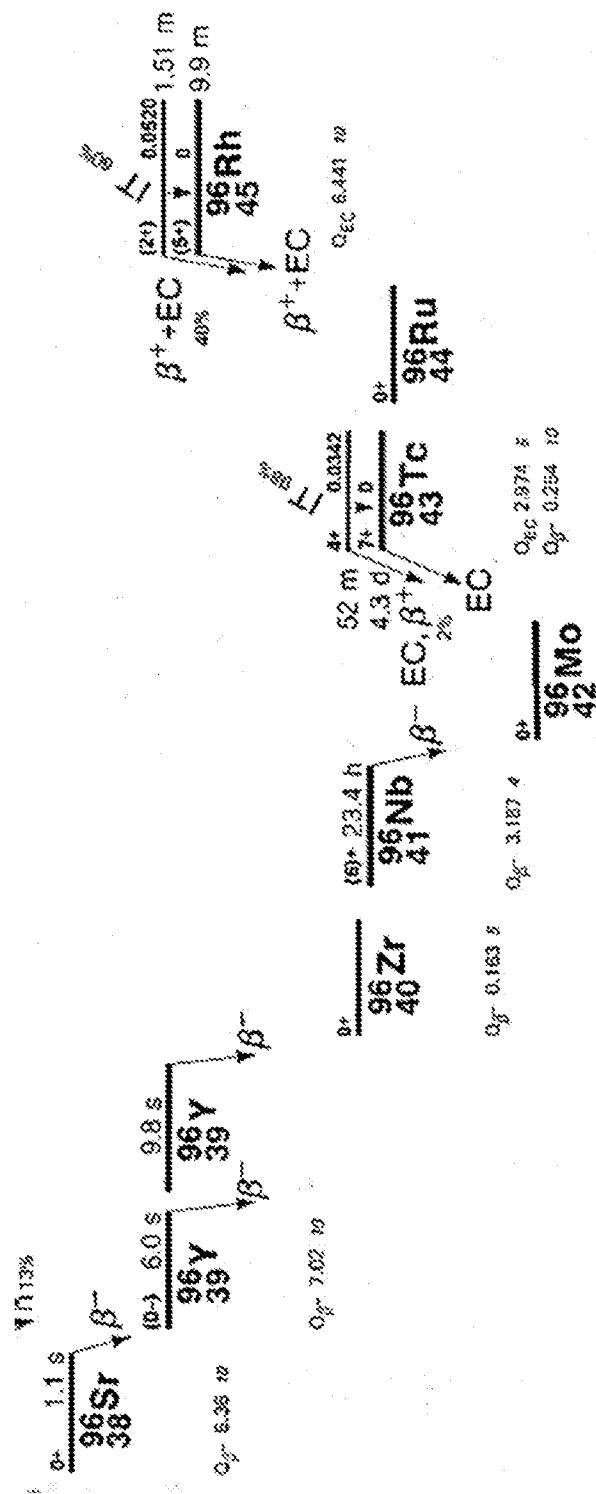


FIG. 15

16/17

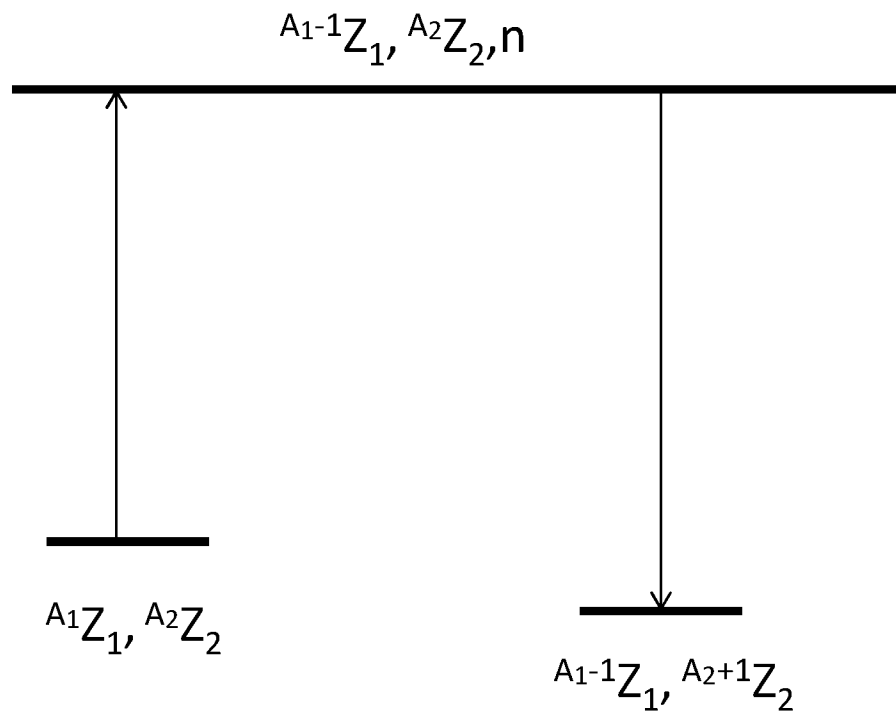


FIG. 16

17/17

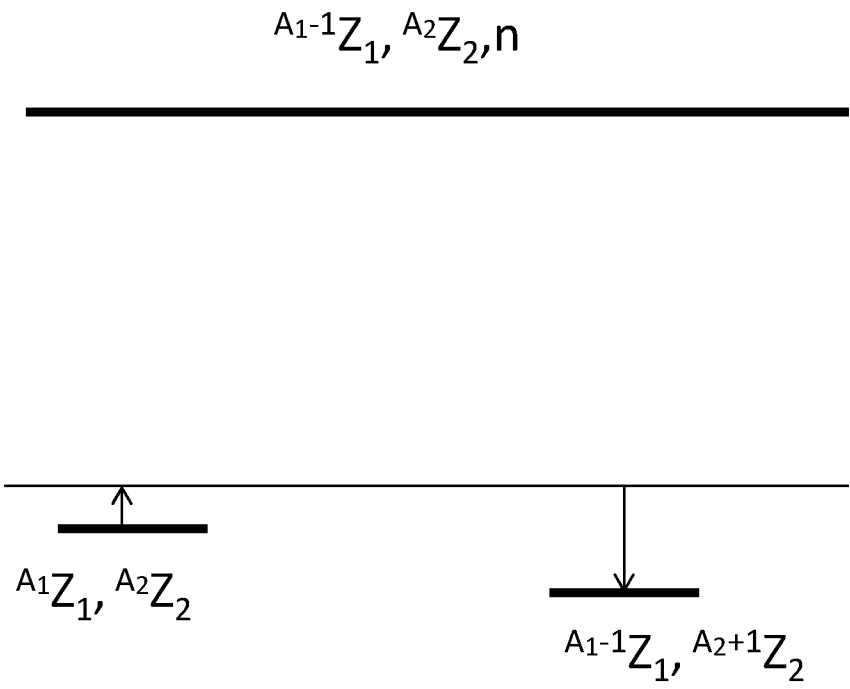


FIG. 17

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2020/021271**A. CLASSIFICATION OF SUBJECT MATTER****G21B 1/00(2006.01)i**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G21B 1/00; G01N 23/222; G01T 3/00; G01T 3/02; G21C 17/00; G21G 1/00; G21G 1/06; G21G 1/10; G21G 4/08; H01L 33/16

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & keywords: phonon, neutron, transfer, isotope, nuclei

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 2018-226597 A1 (FLORIAN METZLER) 13 December 2018 See page 20, line 20 - page 30, line 26, and claims 1-3.	1-20
Y	JP 2007-298497 A (WESTINGHOUSE ELECTRIC CO., LLC) 15 November 2007 See paragraphs 21-26, and figure 1.	1-20
Y	US 2017-0023500 A1 (XRSCIENCES LLC) 26 January 2017 See paragraphs 71, 81, and claims 1-3.	12-13
A	WO 2015-175116 A1 (ISO EVOLUTIONS, LLC) 19 November 2015 See the whole document.	1-20
A	US 10186337 B2 (JAMES J. HAMILL et al.) 22 January 2019 See the whole document.	1-20



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"D" document cited by the applicant in the international application

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

26 June 2020 (26.06.2020)

Date of mailing of the international search report

26 June 2020 (26.06.2020)

Name and mailing address of the ISA/KR

International Application Division

Korean Intellectual Property Office

189 Cheongsa-ro, Seo-gu, Daejeon, 35208, Republic of Korea



Facsimile No. +82-42-481-8578

Authorized officer

PARK, Hye Lyun

Telephone No. +82-42-481-3463



INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2020/021271

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2018-226597 A1	13/12/2018	CA 3067633 A1 EP 3635794 A1 US 2019-0170896 A1 WO 2018-226698 A1 WO 2019-099546 A2 WO 2019-236455 A1	13/12/2018 15/04/2020 06/06/2019 13/12/2018 23/05/2019 12/12/2019
JP 2007-298497 A	15/11/2007	JP 5030600 B2	19/09/2012
US 2017-0023500 A1	26/01/2017	AU 2015-202235 A1 CN 105158215 A CN 105158215 B US 2015-0338356 A1 US 9500604 B2 US 9719948 B2	19/11/2015 16/12/2015 28/09/2018 26/11/2015 22/11/2016 01/08/2017
WO 2015-175116 A1	19/11/2015	US 2015-0332799 A1	19/11/2015
US 10186337 B2	22/01/2019	US 2012-0069946 A1 US 2020-0027619 A1 US 2020-0027620 A1	22/03/2012 23/01/2020 23/01/2020