# Strong isospin (isotopic spin)

[Why do p + n have nearly the same mass?

[Why do mirror nuclei have similar energy levels?

The strong interaction treats p and n the same way

Heisenberg: from point of view of strong interaction,
p and n are two degenerate states of the same particle N

[Similar to spin ↑ and ↓ states of a spin $\frac{1}{2}$ particle.
In a rotationally-symmetric environment,
the energy is independent of direction of spin
$\Rightarrow$ degenerate states]

N has a property called strong isospin $\vec{I} = (I_1, I_2, I_3)$
analogous to ordinary spin $\vec{J}$.
States of isospin are denoted $|I, I_3\rangle$

N has $I = \frac{1}{2}$.

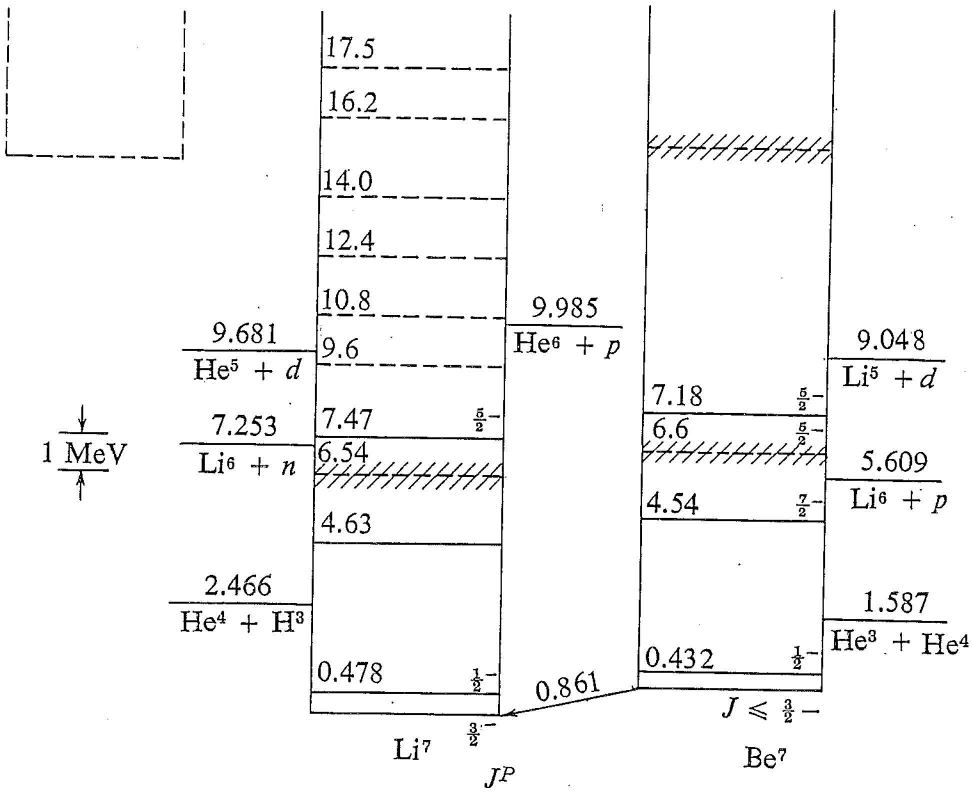
$\begin{cases} p \text{ has } I_3 = \frac{1}{2}. \\ n \text{ has } I_3 = -\frac{1}{2}. \end{cases}$

$p = |\frac{1}{2}, \frac{1}{2}\rangle$

$n = |\frac{1}{2}, -\frac{1}{2}\rangle$

The strong force is sensitive to $I$, but not to $I_3$
["isotopically isotropic"]

Electromagnetic force does depend on $I_3$
[like putting a spin in a magnetic field]


17.5
16.2
14.0
12.4
10.8
9.6
9.681
He⁵ + d
9.985
He⁶ + p
9.048
Li⁵ + d
1 MeV
7.253
Li⁶ + n
7.47 5/2−
6.54
7.18 5/2−
6.6 5/2−
5.609
Li⁶ + p
4.63
4.54 7/2−
2.466
He⁴ + H³
1.587
He³ + He⁴
0.478 1/2−
0.861
0.432 1/2−
3/2−
J ⩽ 3/2 −
Li⁷
J^P
Be⁷

Segre, p. 391

## Isospin of composite particles (e.g. nuclei)

Isospin of a system of two particles is $\vec{I} = \vec{I}_1 + \vec{I}_2$

e.g. 2 nucleons

$$(\text{isospin } \tfrac{1}{2}) \otimes (\text{isospin } \tfrac{1}{2}) = (\text{isospin } 1) \oplus (\text{isospin } 0)$$

$$\underset{\sim}{2} \otimes \underset{\sim}{2} = \underset{\sim}{3} \oplus \underset{\sim}{1}$$

Isotriplet $\underset{\sim}{3}_S$ $|I, I_3\rangle = \begin{cases} |1,1\rangle = pp \\ |1,0\rangle = \frac{1}{\sqrt{2}}(pn + np) \\ |1,-1\rangle = nn \end{cases}$ symmetric under exchange

Isosinglet $\underset{\sim}{1}_A$ $|I, I_3\rangle = |0,0\rangle = \frac{1}{\sqrt{2}}(pn - np)$ antisymmetric

Strong force conserves isospin ⇒ binding energy due to strong force does not depend on $I_3$ (direction in isospace) although it does depend on $I$

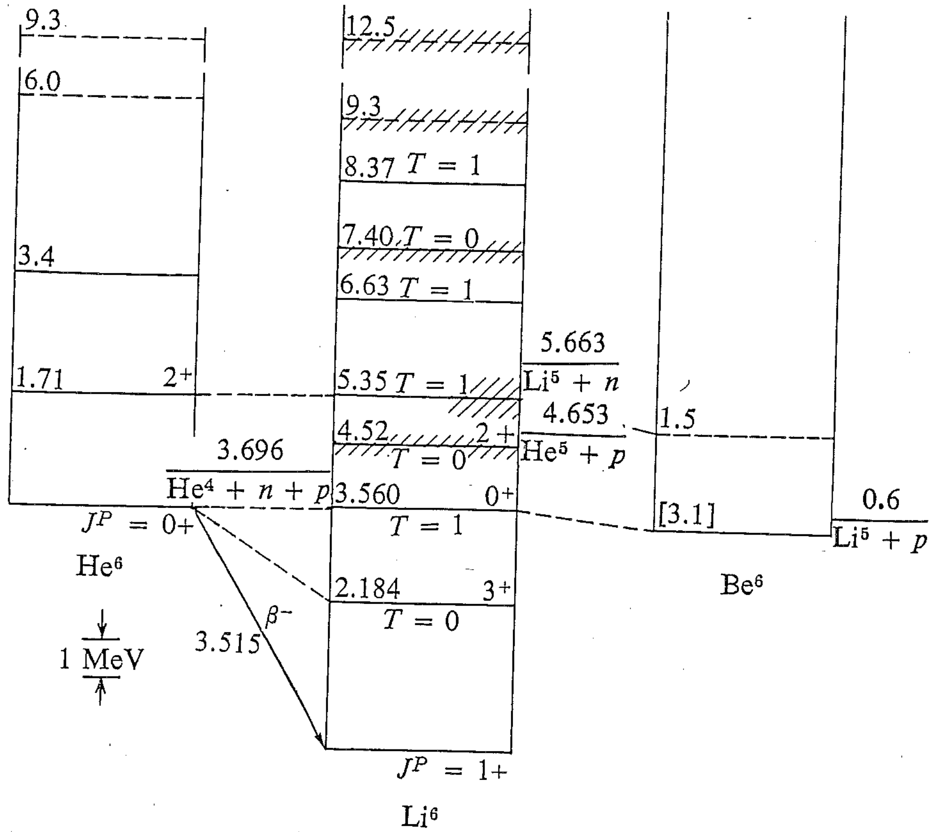
$nn$ bound state is not observed in nature [Why not?] ⇒ $I = 1$ state is not stable
Also no $pp$ bound state ($^2He$), not just due to Coulomb repulsion ($^3He$ exists)

$pn$ state is observed and is stable ($^2H$) ($B = 2.22$ MeV)
It must have $I = 0$

$$^2H = \frac{1}{\sqrt{2}}(pn - np)$$

Now consider $A=6$ isobars as $^4He$ nuclei plus 2 nucleon system ⇒ both $I=0$ and $I=1$ states

[nice picture, but does it predict anything?]


9.3
6.0
3.4
1.71
2+
$J^P = 0+$
He⁶
1 MeV
3.696
He⁴ + n + p
3.515
β⁻
12.5
9.3
8.37 T = 1
7.40 T = 0
6.63 T = 1
5.35 T = 1
4.52
2+
T = 0
3.560
0+
T = 1
2.184
3+
T = 0
$J^P = 1+$
Li⁶
5.663
Li⁵ + n
4.653
He⁵ + p
1.5
[3.1]
0.6
Li⁵ + p
Be⁶

Segre, p. 392

Nucleons have isospin $\frac{1}{2}$ and also spin $\frac{1}{2}$ so really we have

4 states: $p\uparrow,\ p\downarrow,\ n\uparrow,\ n\downarrow$

Nucleon belongs to representation $\Big(\underset{\substack{\uparrow \\ \text{isospin}}}{\underset{\sim}{2}},\ \underset{\substack{\uparrow \\ \text{spin}}}{\underset{\sim}{2}}\Big)$

NN: System of 2 nucleons $(2,2)\otimes(2,2)$ (16 states)

$$= (2\otimes 2,\ 2\otimes 2)$$

$$= (\underset{\text{unstable}}{\cancel{3}}\oplus 1,\ 3\oplus 1)$$

$$= (1,\ 3)\oplus(1,\ 1)$$

Which describes the deuteron?

NN is a system of 2 identical fermions
$\Rightarrow$ wavefunction must be overall antisymmetric under exchange

Since isosinglet is antisymmetric, the spin state must be symmetric ie $J=1$

$$(1_A, 3_S) = \frac{1}{\sqrt{2}}(pn-np)\begin{cases}\uparrow\uparrow & = \frac{1}{\sqrt{2}}(p\uparrow n\uparrow - n\uparrow p\uparrow)\\ \frac{1}{\sqrt{2}}(\uparrow\downarrow+\downarrow\uparrow) & = \frac{1}{2}(p\uparrow n\downarrow - n\uparrow p\downarrow + p\downarrow n\uparrow - n\downarrow p\uparrow)\\ \downarrow\downarrow & = \frac{1}{\sqrt{2}}(p\downarrow n\downarrow - n\downarrow p\downarrow)\end{cases}$$

Hence we predict: deuteron has spin 1! Also, $\mu = \mu_p + \mu_n$ ✓

N.B.

$$(1_A, 1_A) = \frac{1}{\sqrt{2}}(pn-np)\frac{1}{\sqrt{2}}(\uparrow\downarrow-\downarrow\uparrow) = \frac{1}{2}(\underbrace{p\uparrow n\downarrow - n\uparrow p\downarrow - p\downarrow n\uparrow + n\downarrow p\uparrow}_{\text{symmetric under exchange} \Rightarrow \text{not allowed}})$$

Do this as a problem

System of 3 nucleons NNN ← must be antisymmetric under exchange of any 2 nucleons

$(2,2) \otimes (2,2) \otimes (2,2)$

$= (2 \otimes 2 \otimes 2,\ 2 \otimes 2 \otimes 2)$

$= (\underbrace{4}_{I=\frac{3}{2}} \oplus \underbrace{2_S \oplus 2_S}_{I=\frac{1}{2}},\ \underbrace{4}_{J=\frac{3}{2}} \oplus \underbrace{2_S \oplus 2_A}_{J=\frac{1}{2}})$

isoquartet $4 = \begin{cases} ppp \\ \frac{1}{\sqrt{3}}(ppn + pnp + npp) \\ \frac{1}{\sqrt{3}}(nnp + npn + pnn) \\ nnn \end{cases}$

Not possible because isospin state is completely symmetric under exchange but cannot have completely antisymmetric spin state

↑ all nucleons in gnd state

Also trineutron state not observed

Must be an isodoublet $(I = \frac{1}{2})$

$2_S = \begin{cases} \frac{1}{\sqrt{6}}(2ppn - pnp - npp) & \leftarrow {}^3He \\ \frac{1}{\sqrt{6}}(-2nnp + npn + pnn) & \leftarrow {}^3H \text{ (tritium)} \end{cases}$

$2_A = \begin{cases} \frac{1}{\sqrt{2}}(pnp - npp) \\ \frac{1}{\sqrt{2}}(pnn - npn) \end{cases}$

What about spin? Can't be $J = \frac{3}{2}$ because 4 is completely symmetric and can't make isospin state antisymmetric

So 3 nucleon state has $I = \frac{1}{2}$ and $J = \frac{1}{2}$ ✓

⇒ $3He$, ${}^3H$ have $J = \frac{1}{2}$

To be antisymmetric under exchange of 1st 2 nucleons must choose either

$(2_S, 2_A)$ or $(2_A, 2_S)$

How to make it completely antisymmetric?

To obtain a state antisymmetric under exchange of 1st 2 nucleons choose

$$(2_S, 2_A) = \frac{1}{\sqrt{12}}(2ppn - pnp - npp)(\uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow)$$

or

$$(2_A, 2_S) = \frac{1}{\sqrt{12}}(pnp - npp)(2\uparrow\uparrow\downarrow - \uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow)$$

Can we also make it antisymmetric under exchange of 2nd 2 nucleons?

Eliminate $npp\downarrow\uparrow\uparrow$ by taking the difference of these

$$\begin{aligned}(2_S, 2_A) - (2_A, 2_S) = {} & \frac{1}{\sqrt{12}} 2ppn(\uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow) \\ & + \frac{1}{\sqrt{12}} pnp(\cancel{-\uparrow\downarrow\uparrow} + \downarrow\uparrow\uparrow - 2\uparrow\uparrow\downarrow + \cancel{\uparrow\downarrow\uparrow} + \downarrow\uparrow\uparrow) \\ & + \frac{1}{\sqrt{12}} npp(-\uparrow\downarrow\uparrow + \cancel{\downarrow\uparrow\uparrow} + 2\uparrow\uparrow\downarrow - \uparrow\downarrow\uparrow \cancel{- \downarrow\uparrow\uparrow})\end{aligned}$$

$$\begin{aligned} = {} & \frac{1}{\sqrt{3}} ppn(\uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow) \\ & + \frac{1}{\sqrt{3}} pnp(\downarrow\uparrow\uparrow - \uparrow\uparrow\downarrow) \\ & + \frac{1}{\sqrt{3}} npp(\uparrow\uparrow\downarrow - \uparrow\downarrow\uparrow\end{aligned}$$

$\vec{\mu}$

$$\begin{aligned} = \frac{1}{\sqrt{3}}[ & p\uparrow p\downarrow n\uparrow - p\downarrow p\uparrow n\uparrow + p\downarrow n\uparrow p\uparrow \\ & - p\uparrow n\uparrow p\downarrow + n\uparrow p\uparrow p\downarrow - n\uparrow p\downarrow p\uparrow]\end{aligned}$$

$=$

$2 \otimes 2 \otimes 2 \otimes 2 = 5 \oplus 3 \oplus 3 \oplus 3 \oplus 1 \oplus 1$

$= \cancel{(5, \ydiagram{4}) + 3(1}$ $S_4$ rep

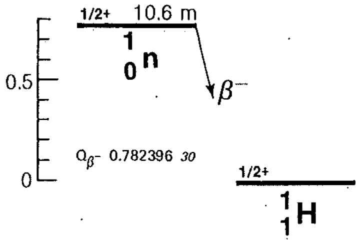
$= (5, \ydiagram{4}) + (3, \ydiagram{3,1}) + (1, \ydiagram{2,2})$

Same for 1SO

need to combine to get $\ydiagram{1,1,1,1}$ of $S_4$

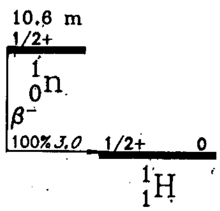
$^4He$ has $I = 0$

## A = 1 (JKT; CML)




### $^1_0$n

**Δ:** 8.071431*39* {ANDT 19 175(77)}
**I:** 1/2 *AB, nuclear scattering* {PR 96 983(54), RMP 22 64(50)}
**☢:** $\beta^-$ {PRSL 151A 479(35), PR 78 310(50)}
**$t_{1/2}$:** 10.61*16* m {RISO–226(71)}; 11.7*3* m {NP 10 395(59), ZETF 35 1059(58), ZETF 36 1012(59), Atya 12 278(62)}; 12.0*15* m {NuoS s10v4 65(56)}; 12.8*25* m {PR 83 349(51)}; **others:** {PL 26B 11(67), PR 78 310(50)}
**Class:** A; **Ident:** recoil nuclei, conservation of momentum {PRSL 136A 692(32)}; observation of (n,α) reaction {PRSL 136A 709(32), PRSL 142A 689(33), PR 44 529(33)}
**Prod:** induced fission; spontaneous fission ($^{252}$Cf); nuclear reactions using radioactive sources, e.g. $^9$Be(α,n) (alphas from $^{210}$Po, $^{225}$Ac, $^{226}$Ra, $^{238}$Pu, $^{241}$Am, etc.) and $^9$Be(γ,n) (photons from $^{88}$Y, $^{124}$Sb, electron accelerators, etc.); nuclear reactions using accelerators, e.g. $^2$H(d,$^3$He), $^3$H(d,α), $^3$H(p,t), $^7$Li(d,n), $^9$Be(d,n), $^9$Be($^3$He,n), and $^{12}$C($^3$He,n) {Cf71 Augusta}
**$\beta^-$:** 0.782*13* *mag–mag βp coinc* {PR 83 349(51)}
**others:** {PR 107 1731(57), PR 100 933(55)}




| $^1_1$H levels – References |
|---|
| **Decay:** PR 83 349(51) |

### $^1_1$H

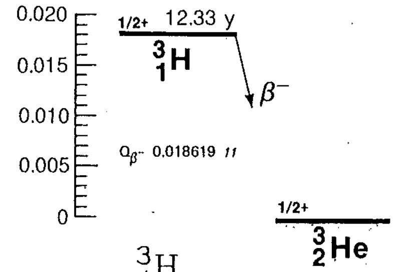
**%:** 99.985 {BNL–NCS–50605(77)}
**Δ:** 7.289034*23* {ANDT 19 175(77)}
**I:** 1/2 *O, specific heat* {RMP 22 64(50)}
**$\sigma_c$:** 0.332*2* {PC77 Holden}

## A = 2 (JKT; CML)

### $^2_1$H

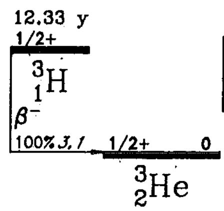
**%:** 0.0148 (Lake Michigan water); 0.0089 to 0.0230 (other sources); lower for electrolytic hydrogen {BNL–NCS–50605(77)}
**Δ:** 13.13584*4* {ANDT 19 175(77)}
**I:** 1 *N, O, ortho–para conversion* {PR 78 204(50), PR 43 837(33), PR 46 95(34), RMP 22 64(50)}
**$\sigma_c$:** 5.2*1*×10$^{-4}$ {PC77 Holden}

## A = 3 (JKT; CML)




### $^3_1$H

**Δ:** 14.94994*5* {ANDT 19 175(77)}
**I:** 1/2 *N, O* {PR 71 551(47), PR 71 373(47), PR 76 283(49)}
**$\sigma_c$:** <6×10$^{-6}$ (subcadmium) {PC77 Holden}
**☢:** $\beta^-$ {PR 56 613(39), PR 57 248(40)}
**$t_{1/2}$:** 12.346*2* y *calorim* {JINC 29 2129(67)}; 12.262*4* y *genet* {PR 100 124(55)}; 12.46*10* y *genet* {PR 80 990(50)}; 12.58*18* y *calorim* {Atya 4 296(58)}; **others:** {MLM–1160(63), PR 83 537(51), PR 73 809(48), PR 72 972(47), PR 59 1046(41), PR 58 574(40), PR 57 248(40), PR 56 613(39)}
**Class:** A; **Ident:** chem, sep isotopes, excit {PR 56 613(39), PR 57 248(40)}
**Prod:** $^6$Li(n,α) {PR 58 574(40)}
**$\beta^-$:** 0.018610*16* *mag, electrostatic* {NP B39 371(72)}
0.018648*26* *mag* {ZNat 29a 261(74)}
0.018578*40* *mag, Si(Li)* {NP A203 369(73)}
0.018570*75* *mag* {NP A138 545(69)}
0.018540*95* *Si(Li)* {NP A151 120(70)}
limit on neutrino rest mass: 55 eV (from $\beta^-$ spectrum shape) *mag, electrostatic* {NP B39 371(72)}
**others:** {NuoL s2v5 139(72), NP A138 417(69), PR 114 1286(59), PR 92 1521(53), PR 88 689(52), PR 76 853(49), PR 75 983(49)}



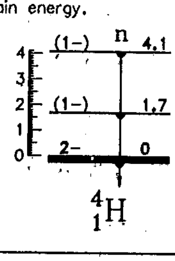

| $^3_2$He levels – References |
|---|
| **Decay:** NP B39 371(72) |

### $^3_2$He

**%:** 1.38×10$^{-4}$ (atmospheric sources); 6×10$^{-8}$ to 0.0041 (other sources) {BNL–NCS–50605(77)}
**Δ:** 14.93132*5* {ANDT 19 175(77)}
**I:** 1/2 *N, AB, O* {PR 76 1460(49), PR 90 377(53), PR 76 1529(49)}
**$\sigma_c$:** <1×10$^{-4}$ (reactor spectrum) {PC77 Holden}
**σ(n,p):** 5.33*1*×10$^3$ {PC77 Holden}

## A = 4 (JKT; CML)

**18 Reactions**
All levels are broad. There is evidence for an additional (0–) state of uncertain energy.

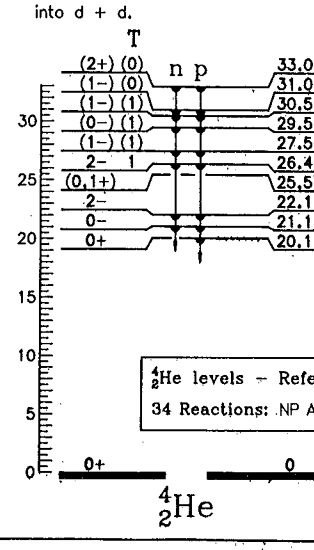



| $^4_1$H levels – References |
|---|
| **18 Reactions:** NP A206 1(73) |

### $^4_2$He

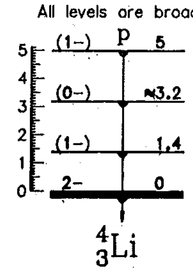
**%:** 99.99986 {BNL–NCS–50605(77)}
**Δ:** 2.42494*4* {ANDT 19 175(77)}
**I:** 0 *O* {TFar 25 634(29)}

**34 Reactions**
Levels above 20.1 MeV are broad. 31– and 33–MeV levels decay also into d + d.




| $^4_2$He levels – References |
|---|
| **34 Reactions:** NP A206 1(73) |

**14 Reactions**
All levels are broad




| $^4_3$Li levels – References |
|---|
| **14 Reactions:** NP A206 1(73) |

# A = 5 (JKT; CML)

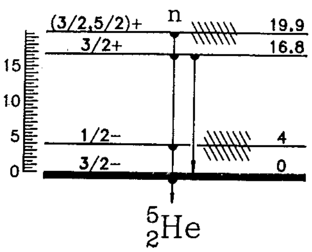
## $^{5}_{1}H$

**Δ:** 33.79 *80* {ANDT 19 175(77)}
**Class:** R; **Ident:** particle unstable {NP A227 1(74)}

## $^{5}_{2}He$

**Δ:** 11.39 *5* {ANDT 19 175(77)}
**Class:** R; **Ident:** particle unstable {NP A227 1(74)}

34 Reactions
A broad level at 24–25 MeV is not shown. 16.8– and 19.9–MeV levels decay also into d + t.

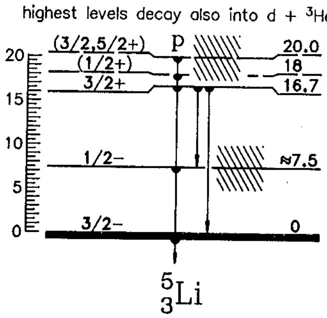



$^{5}_{2}He$ levels – References
34 Reactions: NP A227 1(74)

## $^{5}_{3}Li$

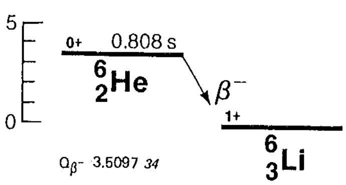
**Δ:** 11.68 *5* {ANDT 19 175(77)}
**Class:** R; **Ident:** particle unstable {NP A227 1(74)}

29 Reactions
The 18–MeV level is broad. The three highest levels decay also into d + $^{3}$He.

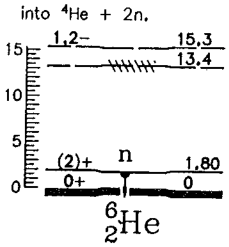



$^{5}_{3}Li$ levels – References
29 Reactions: NP A227 1(74)

# A = 6 (JKT; CML)




25 Reactions
A probable broad level at 23 MeV is not shown. 1.80–MeV level decays into $^{4}$He + 2n.

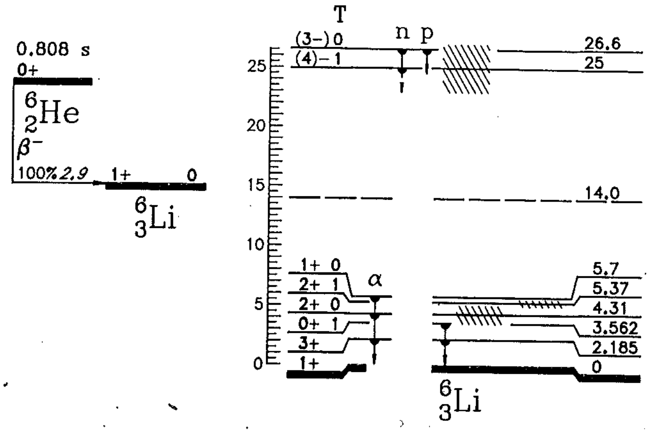



$^{6}_{2}He$ levels – References
25 Reactions: NP A227 1(74)

## $^{6}_{2}He$

**Δ:** 17.5970 *35* {ANDT 19 175(77)}
**I:** 0 *AB* {PRL 1 208(58)}
**☢:** $\beta^-$ {Nat 138 400(36)}
**$t_{1/2}$:** 0.8081 *20* s {PR C10 1993(74)}; 0.797 *3* s {NP 37 529(62), NP 40 694(63)}; 0.799 *3* s {PR 96 1620(54)}; 0.862 *17* s {NP 38 196(62)}; **others:** {MagA 4 79(62), PR 116 134(59), PRL 1 61(58), PIAS A43 319(56), PR 97 991(55), PR 89 80(53), AnP s12v7 655(52), PR 87 557(52), PR 86 416(52), PPSL 62A 293(49), PR 69 21(46), PZS 12 339(37)}
**Class:** A; **Ident:** chem {Nat 137 865(36), Nat 138 400(36)}; cross bomb, excit, chem {PR 69 21(46)}
**Prod:** $^{9}$Be(n,α) {PR 97 991(55), Nat 137 865(36), PZS 12 339(37), PR 69 21(46), PR 74 1192(48), PR 77 404(50), PR C10 1993(74)}; $^{7}$Li(γ,p) {PR 87 557(52)}
**$\beta^-$:** **3.5084** *38* *mag* {NP 41 167(63)}
**others:** {PR 132 2573(63), PR 87 1140(52)}
**γ:** no γ rays observed *ion ch* {PR 74 1192(48), PR 69 21(46)}

85 Reactions
Level at 26.6 MeV is broad. Two highest levels decay also into $^{3}$He + t and by γ emission.




$^{6}_{3}Li$ levels – References
Decay: NP 41 167(63)
85 Reactions: NP A227 1(74), ZhPi 19 531(74)

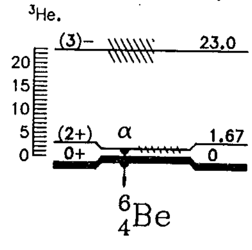
## $^{6}_{3}Li$

**%:** 7.5 (average; values range from 6.77 to 9.28); commercial sources may be depleted in $^{6}$Li {BNL–NCS–50605(77)}
**Δ:** 14.0873 *8* {ANDT 19 175(77)}
**I:** 1 *N*, *AB* {PR 81 157(51), PR 51 19(37)}
**$\sigma_c$:** 0.038 *3* (reactor spectrum) {PC77 Holden}
**σ(n,α):** 942 *2* {PC77 Holden}

## $^{6}_{4}Be$

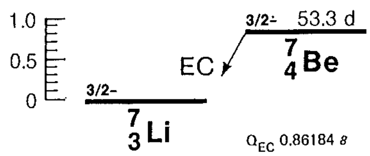
**Δ:** 18.375 *6* {ANDT 19 175(77)}
**Class:** R; **Ident:** particle unstable {NP A227 1(74)}

11 Reactions
23.0–MeV level decays into $^{3}$He + $^{3}$He.




$^{6}_{4}Be$ levels – References
11 Reactions: NP A227 1(74)

# A = 7 (JKT; CML)



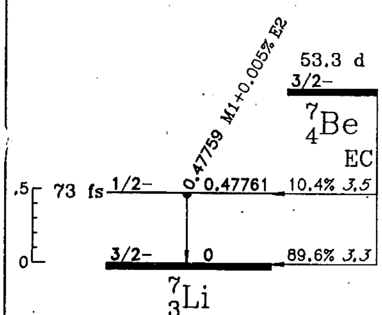

## $^{7}_{2}$He

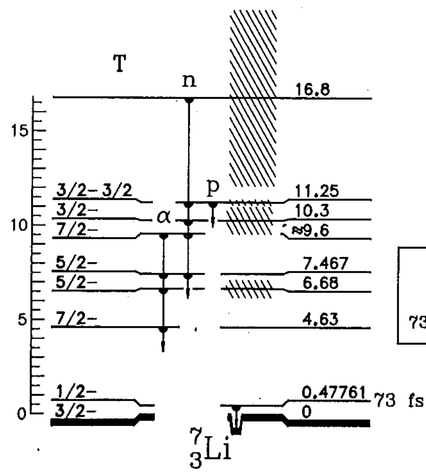
**Δ:** 26.111 30 {ANDT 19 175(77)}
**Class:** R; **Ident:** particle unstable {NP A227 1(74)}

## $^{7}_{3}$Li

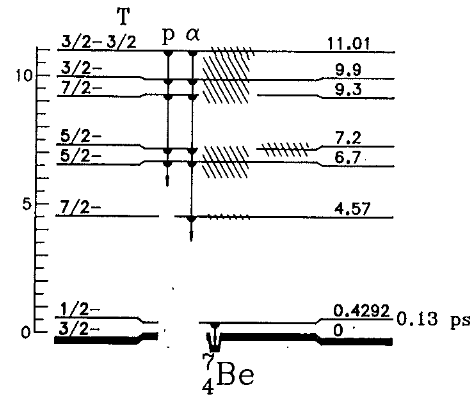
**%:** 92.5 (average; values range from 90.72 to 93.23); commercial sources may be depleted in $^{6}$Li {BNL-NCS-50605(77)}
**Δ:** 14.9082 9 {ANDT 19 175(77)}
**I:** 3/2 *AB, O* {PR 48 746(35), PR 42 44(32), PR 35 789(30)}
**$\sigma_p$:** 0.045 5 (reactor spectrum) {PC77 Holden}
**$t_{1/2}$(0.478):** 73 4 fs *$e^-$ Coulomb excit* {NP A174 173(71)}, 81 3 fs *nucl res fluor* {NIM 67 222(69)}, 87 4 fs *nucl res fluor* {PR 128 2745(62)}, 64 8 fs *nucl res fluor* {NP 57 403(64)}, 73 10 fs *Doppler* {PR 147 774(66)}, 92 11 fs *Doppler* {NP A92 222(67)}, 53 6 fs *Doppler* {PPSL 69A 165(56)}; **others:** {AmJP 40 9(72), IzUz 1971n6 54(71), PR 129 361(63), NP 19 426(60), PR 114 862(59), NP 5 595(58), PR 76 168(49)}

73 Reactions
Level at ≈9.6 MeV is broad.




32 Reactions
An additional, broad level at ≳10.0 MeV (Iπ=1/2–) is not shown.




| $^{7}_{4}$Be levels – References |
|---|
| 32 Reactions: NP A227 1(74) |

## $^{7}_{5}$B

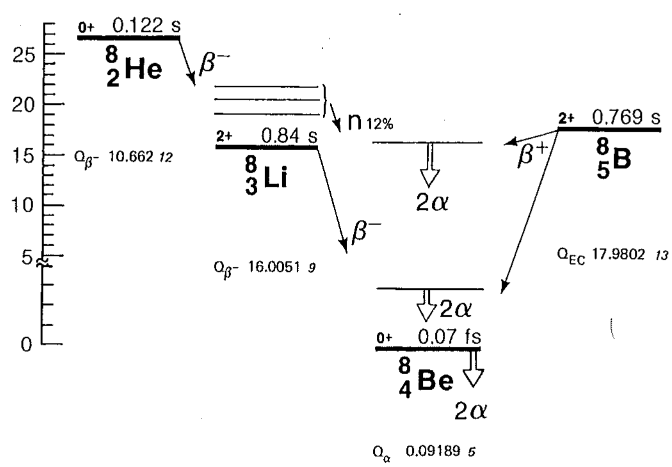
**Δ:** 27.94 10 {ANDT 19 175(77)}
**Class:** R; **Ident:** particle unstable {NP A227 1(74)}

| $^{7}_{3}$Li levels – References |
|---|
| Decay: IIso 25 373(74), Kern 7 748(64), NP A227 1(74) |
| 73 Reactions: NP A227 1(74) |

## $^{7}_{4}$Be

**Δ:** 15.7701 9 {ANDT 19 175(77)}
**σ(n,α):** 0.14 2 (subcadmium) {PC77 Holden}
**σ(n,p):** 4.9 7×10$^{4}$ (reactor spectrum) {PC77 Holden}
**☢:** EC {PR 54 657(38)}
**$t_{1/2}$:** 53.29 2 d {PC74 Merritt}; 53.17 7 d {IIso 26 131(75)}; 53.52 10 d {PR C2 1616(70)}; 53.61 17 d {PR 90 610(53)}; 53.5 2 d {NSEg 2 427(57)}; 52.93 22 d {PR 75 39(49)}; variation of $t_{1/2}$ with chemical environment ranges up to ≈0.2% {PR C2 1616(70), PR 75 39(49), PR 90 610(53), JPPa 17 363(56)}; **others:** {NSEg 55 450(74), NP 72 449(65), AnP s13v4 89(59), JPPa 17 363(56), JPPa 8 336(47), PR 57 567(40), PR 54 657(38)}
**Class:** A; **Ident:** chem, cross bomb, excit {PR 54 657(38)}
**Prod:** $^{6}$Li(d,n) {PR 54 657(38), PR 53 1016(38), PR 62 29(42)}; $^{10}$B(p,α) {PR 53 1016(38), Nwis 26 614(38)}; $^{12}$C($^{3}$He,2α) {NP 72 449(65)}
**γ:** (norm: $\gamma_{0.478}$ (γ 10.35 6%), IIso 25 373(74)) **0.477593** 12 *Ge(Li)* {ANCR-1000-2(74)}
$\gamma_{0.478}$ (e/γ 7.3 11×10$^{-7}$) *cl ch* {Kern 7 748(64)}
**others:** {IIso 24 471(73), NP A195 527(72), NIM 96 173(71), RaAc 13 171(70), NP A90 650(67), NP 74 281(65), CJP 40 926(62), PR 114 1590(59)}
**$t_{1/2}$(0.429):** 133 17 fs *Doppler* {PR 147 774(66)}
**Internal bremsstrahlung endpoint (decay to 0 level): 0.861 75** 9 *Ge(Li)* {PR C8 2089(73)}
**Internal bremsstrahlung endpoint (decay to 0.478 level): 0.388** 8 *scint-scint γγ coinc* {PR C5 1443(72)}; **0.395** 25 *scint-scint γγ coinc* {PR C3 465(71)}

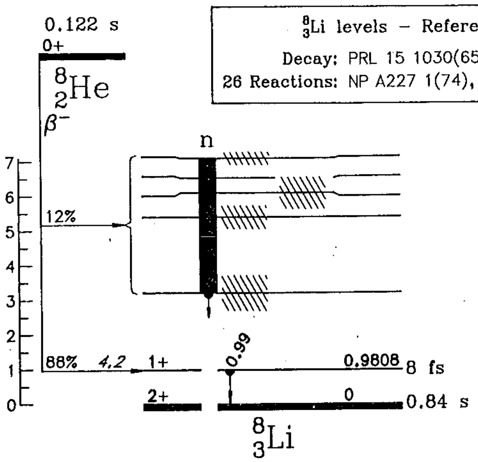
# A = 8 (JKT; CML)



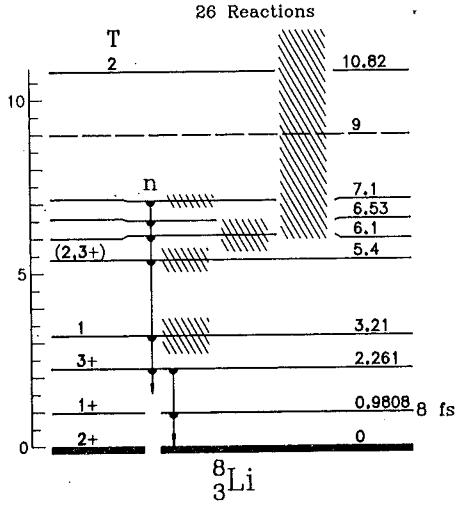
## $^{8}_{2}$He

**Δ:** 31.609 *12* {ANDT 19 175(77)}
**☢:** $\beta^-$, $\beta^-$n 12 *1*% {PRL 15 1030(65)}
**$t_{1/2}$:** 0.122 *2* s {PRL 15 1030(65)}; 0.114 *25* s {NP 88 523(66)}; **others:** {YadF 17 897(73)}
**Class:** A; **Ident:** chem, excit, cross bomb {PRL 15 1030(65)}; genet energy levels {NP 88 523(66)}
**Prod:** protons on C {PRL 15 1030(65)}; protons on O {PRL 15 1030(65)}; $^{11}$B($\gamma$,3p) {NP 88 523(66)}; fission {NuoC s10v51B 235(67)}
**$\gamma$ with $\beta^-$:** 0.99 *2* ($\gamma$ 88 *1*%) *scint* {PRL 15 1030(65)}
1.00 *3* *scint-scint $\gamma\beta$ coinc* {NP 88 523(66)}

$^{8}_{3}$Li levels – References
Decay: PRL 15 1030(65), NP A227 1(74)
26 Reactions: NP A227 1(74), PRL 34 33(75)



26 Reactions

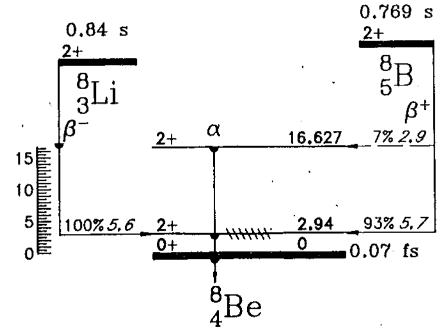


## $^{8}_{3}$Li

**Δ:** 20.9469 *9* {ANDT 19 175(77)}
**I:** 2 *OP/RD* {ZP 261 237(73)}
**☢:** $\beta^-2\alpha$ {Nat 139 24(37)}
**$t_{1/2}$:** 0.8440 *7* s {NP 81 155(66)}; 0.841 *4* s {PR 96 1620(54)}; 0.838 *6* s {PRL 26 1127(71)}; 0.854 *8* s {NP A118 689(68)}; **others:** {NP A119 233(68), PRL 10 243(63), PRL 3 429(59), PPSL 67A 946(54), CR 236 913(53), PR 90 1121(53), PR 87 557(52), PR 83 1244(51), PR 72 646(47), PR 71 378(47), PR 52 604(37)}
**Class:** A; **Ident:** excit {PR 47 971(35)}; n-capt, sep isotopes, genet {PR 72 646(47)}
**Prod:** $^{7}$Li(n,$\gamma$) {PR 114 1037(59)}; $^{7}$Li(d,p) {PR 47 971(35), PR 48 848(35), PR 51 1103(37), PR 52 604(37), Nat 139 24(37), PR 77 160(50), PR 79 893(50), PRL 26 1127(71)}
**$\alpha$:** 1.6 (broad peak) *cl ch* {PR 73 885(48)}
1.6 $\alpha$ (only $\alpha$ group observed) *mag, range emuls* {CR 251 1771(60)}
**others:** {NP 15 626(60), PR 92 1257(53)}
**$\beta^-$:** 13 *scint* {PRL 10 243(63)}
12.5 *5* *scint* {PRL 23 652(69)}
**others:** {PR 103 335(56), PR 99 8(55), PR 77 160(50)}
**$\beta\alpha(\theta)$:** {PR C12 967(75), PRL 32 314(74), ZNat 21a 908(66)}
**$\beta_{\mathrm{lon\ p}}$:** {NuoC s10v10 909(58)}
**$t_{1/2}$(0.981):** 7.0 *31* fs *Doppler* {PR C3 536(71)}, 9.7 *35* fs *Doppler* {NP A181 174(72)}

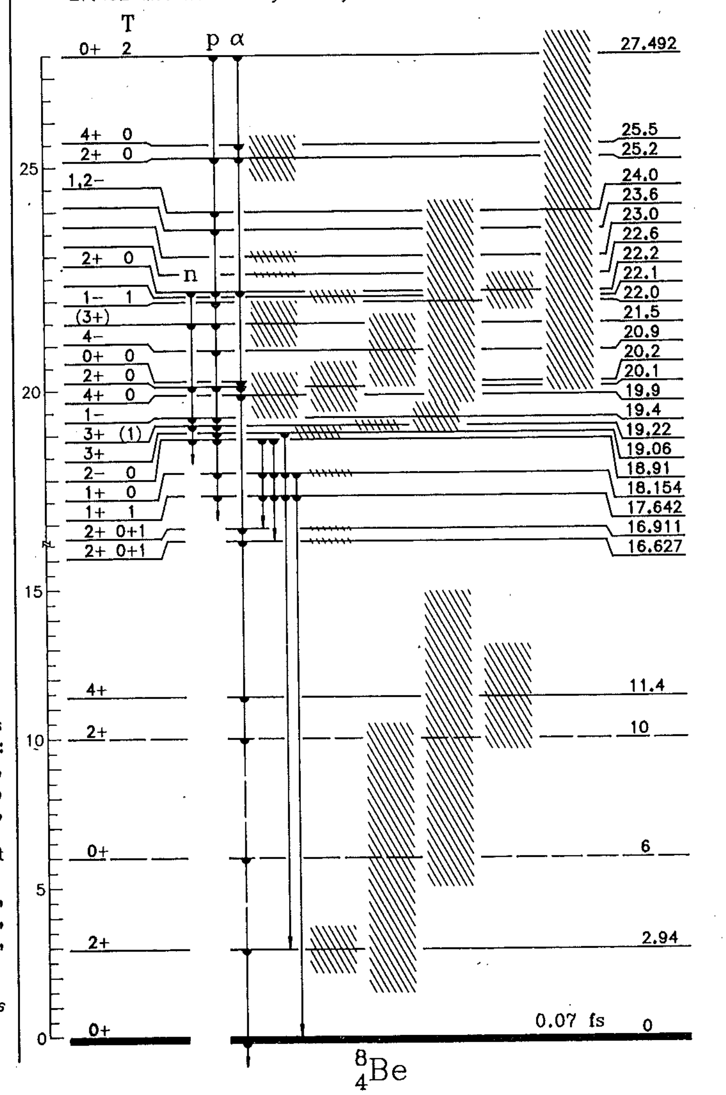
## $^{8}_{4}$Be

**Δ:** 4.94176 *10* {ANDT 19 175(77)}
**☢:** 2$\alpha$ {PR 76 428(49), PR 91 879(53)}
**$t_{1/2}$:** 0.067$^{+22}_{-13}$ fs *level width* {NP 106 296(68)}; **others:** {NP 94 301(67), PL 23 106(66), NP 38 33(62), HPAc 31 205(58), PR 104 135(56), PR 104 123(56), PPSL 68A 204(55)}
**Class:** R; **Ident:** particle unstable {PR 76 428(49), PR 91 879(53)}
**$\alpha$:** 0.04606 *3* *mag ($\alpha$–$\alpha$ scattering)* {NP A106 296(68)}
**others:** {PL 20 40(66), PR 107 508(57), PPSL 68A 204(55), PR 91 879(53), PR 76 428(49)}



62 Reactions

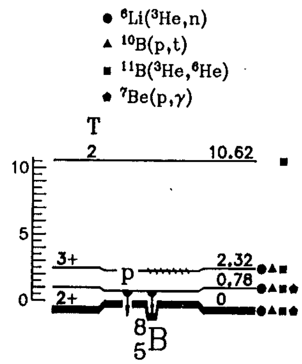
A tentative broad level at 28.6 MeV is not shown. 22.2–, 25.2–, and 27.492–MeV levels decay also by deuteron emission.



$^{8}_{4}$Be levels – References
Decay: PL 9 174(64), NP A227 1(74)
62 Reactions: NP A227 1(74), PR C13 46(76), PRL 34 33(75), JPPa 36 1055(75)

## $^{8}_{5}B$

**Δ:** 22.9219 *13* {ANDT 19 175(77)}
**☢:** $\beta^+2\alpha$ {PR 80 519(50)}
**$t_{1/2}$:** 0.772 *4* s {BAPS 18 651(73)}; 0.762 *5* s {PRL 26 1127(71)}; 0.774 *4* s {PL 9 174(64)}; **others:** {PR 110 1076(58), PR 87 557(52)}
**Class:** A; **Ident:** excit, cross bomb {PR 80 519(50)}
**Prod:** $^6$Li($^3$He,n) {PR 110 1076(58), PL 9 174(64)}
**$\beta^+$:** 13.7 *3* *abs* {PR 80 519(50)}
**$\beta\alpha(\theta)$:** {PRL 32 314(74), ZNat 21a 908(66)}
**$\beta_{\text{ion p}}$:** {PL 7 150(63)}

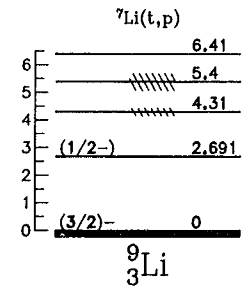



| $^{8}_{5}$B levels – References |
|---|
| $^6$Li($^3$He,n), $^{10}$B(p,t), $^{11}$B($^3$He,$^6$He), $^7$Be(p,γ): NP A227 1(74), PRL 34 33(75) |
| Other reactions: |
| $^{12}$C($^3$He,$^7$Li), $^{12}$C(α,$^8$Li): NP A227 1(74) |

## $^{8}_{6}C$

**Δ:** 35.085 *25* {ANDT 19 175(77)}
**Class:** R; **Ident:** particle unstable {NP A227 1(74)}

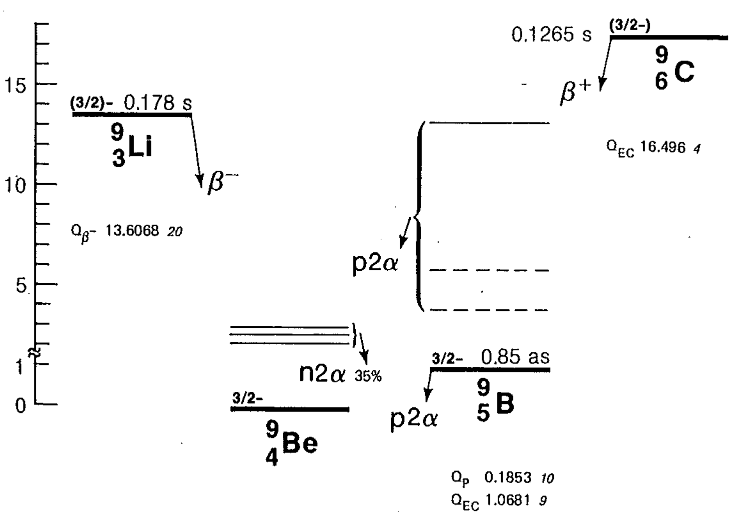
| $^{9}_{3}$Li levels – References |
|---|
| $^7$Li(t,p): NP A227 1(74), NP 84 25(66), PR C4 1597(71) |




## $^{9}_{3}Li$

**Δ:** 24.9548 *20* {ANDT 19 175(77)}
**☢:** $\beta^-$, $\beta^-$n 35.0 *35*% (breakup into n+2α) {NP A146 136(70), NP A222 621(74)}
**$t_{1/2}$:** 0.1783 *4* s {PR C13 835(76)}; 0.176 *1* s {PR 139 B1513(65)}; 0.175 *1* s {PR C10 1181(74), NP A222 621(74), NSEg 54 190(74)}; **others:** {NP A259 493(76), NP A146 136(70), NP A119 233(68), ZP 188 38(65), PR 131 1624(63), PRL 10 243(63), PR 97 744(55), PR 92 651(53), PR 87 557(52), PR 87 378(52), PR 83 1054(51)}
**Class:** A; **Ident:** excit, cross bomb {PR 83 1054(51)}; genet energy levels {PR 132 328(63)}; mass spect {PRL 23 652(69)}
**Prod:** $^9$Be(n,p) {PR 132 328(63)}; $^9$Be(d,2p) {PR 83 1054(51), ZP 188 38(65)}; $^3$H($^7$Li,p) {PR C13 835(76), NP A146 136(70)}; $^{10}$Be($^{11}$B,$^{12}$C) {NP A259 493(76)}; protons on Ir {PRL 23 652(69)}
**α:** 0.2, 0.3 (†(0.2α+0.3α) 12.4 *43*), 0.7 (†100) *semicor* {NP A146 136(70)}
**$\beta^-$:** 13.5 *3* (≈75%), 11.0 *4* (≈25%) *scint* {PR 132 328(63)}
**others:** {PRL 23 652(69), PRL 10 243(63)}
**n:** 0.3 (†93.6 *12*, broad), 0.65 (†6.4 *12*), ≈1 (†9.4 *15*, broad) *time of fl* {NP A146 136(70)}
**others:** {NP A131 250(69), ZP 188 38(65), PR 132 328(63)}

# A = 9 (JKT; CML)

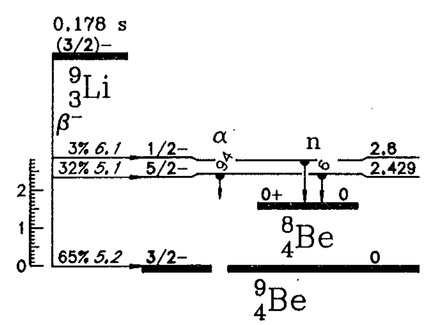



## $^{9}_{2}He$

**Class:** R; **Ident:** particle unstable {PR 154 1193(67), PL 19 335(65), NP A227 1(74)}

## $^{9}_{4}Be$

**%:** 100 {BNL–NCS–50605(77)}
**Δ:** 11.3480 *4* {ANDT 19 175(77)}
**I:** 3/2 *N* {PR 83 672(51), PR 81 886(51), JCP 24 751(56)}
**$\sigma_c$:** 0.0076 *8* {PC77 Holden}




| $^{9}_{4}$Be levels – References |
|---|
| Decay: NP A146 136(70) |
| 77 Reactions: NP A227 1(74) |