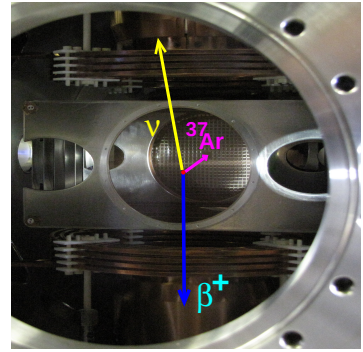
# TRIUMF *TRV* in isospin-hindered $^{45}_{19}$K, $^{47}_{19}$K $\beta^-$ decay

**Enhanced sensitivity to some sources of *TRV* for observables "*D*" and "$E_1$":**
**Barroso and Blin-Stoyle PLB 1973**

**One $E_1$ measurement:**
**$^{56}$Co Calaprice, Freedman 1977**

**Our goal: find an enhanced D measurement case for TRIumf Neutral Atom Trap (TRINAT):**

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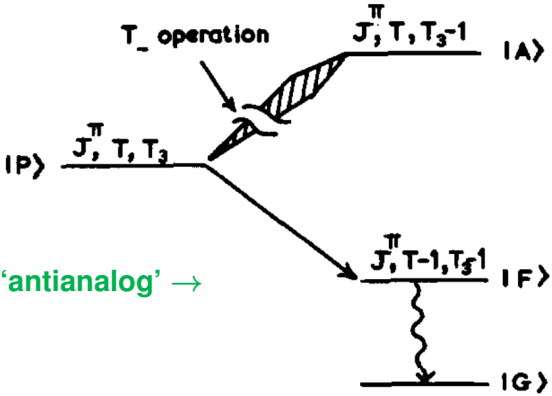
# *TRV* in isospin-hindered $\beta^-$ decay

## Barroso and Blin-Stoyle, PL 45B 178 (1973) observables:




‘antianalog’ →

$D\ \hat{\mathbf{J}} \cdot \frac{\vec{p}_\beta}{E_\beta} \times \frac{\vec{p}_\nu}{E_\beta}$

$E_1\ (\hat{\mathbf{J}} \cdot \hat{k}_\gamma)(\hat{\mathbf{J}} \cdot \hat{p}_\beta \times \hat{k}_\gamma)$

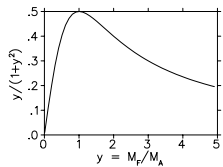
$D$, $E_1$ are both proportional to

$$K = \frac{Im(G_V G_A^* M_V M_A^*)}{|G_V|^2|M_V|^2 + |G_A|^2|M_A|^2}$$

$$= y/(1+y^2)\,\sin(\alpha_V - \alpha_A)$$

with $y = \frac{g_V|M_V|}{g_A|M_A|}$

In this system, $\tan\alpha_V = -i\,\frac{\langle F|V_{TRV}|A\rangle}{\langle F|V_{\rm Coul}|A\rangle}$




So for *TRV* physics mixing $|F\rangle$ with $|A\rangle$, then $V_{TRV}$ is only competing with $V_{\rm Coul}$, not $V_{\rm strong}$, enhancing $\alpha_V$ by $\sim 10^3$ ☺

$M_A$ can’t be too small: want $M_V \sim M_A$

JB: $M_V \approx \frac{\langle F|V_{\rm coul}|A\rangle}{\Delta E_{\rm FA}} \Rightarrow \langle F|V_{\rm TRV}|A\rangle \approx M_A\,\Delta E_{\rm FA}\sqrt{\frac{J+1}{J}}\,D$ indp of $V_{\rm coul}$

**• *P* even N-N isovector/tensor *TRV*: complementary to *TRV* neutron resonance experiments?**

**Barroso and Blin-Stoyle**

using Herczeg NP **75** 655 (1966):

$$V_{\text{t.v.}} = G_{\text{t.v.}} \tfrac{1}{2}[f(r)\hat{r}\cdot p + \text{h.c.}]$$

$$\times [1 + a\sigma^{(1)}\cdot\sigma^{(2)})(\tau_3^{(1)} + \tau_3^{(2)})$$

$$+ (b + c\sigma^{(1)}\cdot\sigma^{(2)})\tau_3^{(1)}\tau_3^{(2)}]$$

**and used SHO wf's to estimate $^{134}$Cs matrix elements**

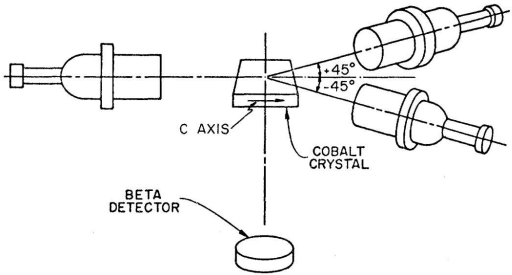
**Samart Schat Schindler Phillips PRC 2016: Isoscalar and isotensor *P* even *TRV* $\pi$-nucleon suppressed by $1/N_C$; at lowest order isovector $a_1$ contributes, not $\rho$ and $h_1$**

**Some TRV interactions in radiative $\beta$ decay (Gardner, He 2013) would also be enhanced in isospin-suppressed decays– experimentally these seem to come with discrete $\gamma$-ray backgrounds**

**• 2nd-class induced semileptonic *TRV* tensor $d_{II}$ can accidentally interfere via $\alpha_A$ (Kim+Primakoff PR 180 1502 (1969); J. Mortara Ph.D. thesis 1992)**

# $^{56}$Co *TRV* experiment

**Asymmetry of the 45$^o$ $\gamma$ detectors with nuclear alignment**




**"Test of time-reversal invariance in the beta decay of $^{56}$Co"**
**Calaprice, Freedman, (Princeton); Osgood, Thomlinson (BNL)**
**PRC 15 381 (1977)**

**$E_1$ = -0.01 $\pm$ 0.02**

**log(ft) = 8.7, yet known allowed: $E_\beta$ spectrum, no $\beta$-$\gamma$ correlation)**

**y = -0.13$\pm$0.02 PRC 26 287R (1982)**
**Markey, Boehm (RIP Felix 2021)**

**$V_{\rm Coul}$= 2.9 keV, $V_{TRV} = 54 \pm 110$eV**
**(J.L. Mortara Ph.D. thesis 1992 UCB**
**$E_1 = -0.001 \pm 0.006$**
**$\Rightarrow$ $V_{TRV}$ = 5$\pm$ 33 eV )**

# A dozen measurements of $M_V$, $\langle F|V_{\rm coul}|A\rangle$

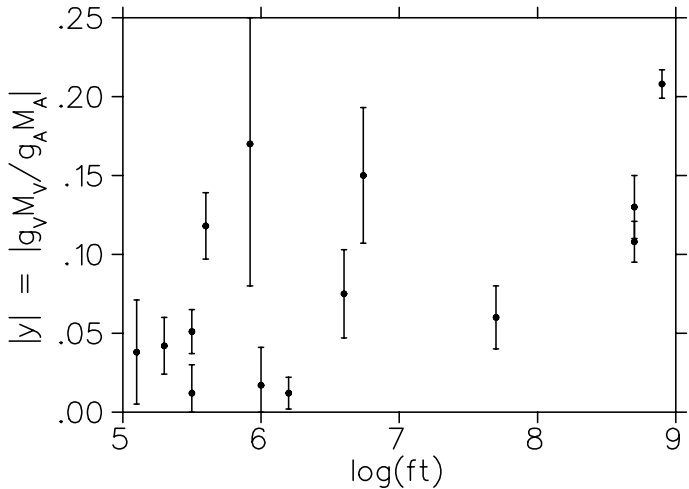
**Community pushed to find good *TRV* cases**

**Mostly $\beta$-$\gamma$ circular polarization correlation**

**Atkinson NPA114 143 (1968);**
**Mann PR 137 B1 (1965) ;**
**Behrens ZfP 201 153 (1967)**

**Some correlation for these 'antianalog' configurations: hints that $|M_V|/|M_A|$ unchanging as $|M_A|$ falls**

**I $^{57}$Fe $V_{\rm Coul}$= 54$\pm$10 keV,**
**$^{56}$Co $V_{\rm Coul}$= 2.9$\pm$0.5 keV**



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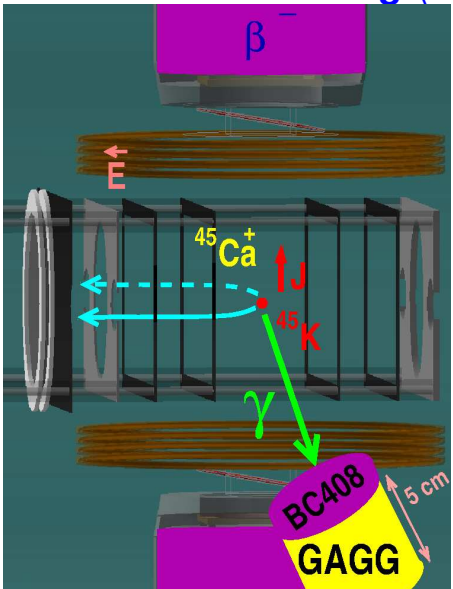
# Measuring $\langle F|V_{\rm Coul}|A\rangle$ in $^{45,47}$K




- $A_{\rm recoil} \propto A_\beta + B_\nu$

$$A_{\rm recoil} \overset{p_{\rm recoil} \gg m_\beta}{=} 5/8(A_\beta + B_\nu)$$

**(Depends on recoil energy via predicted kinematics)**

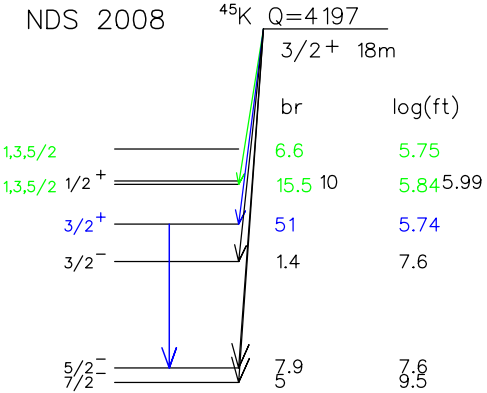
- **So $A_{\rm recoil}$ = 0 for pure Gamow-Teller**

$$A_{\rm recoil} = 2\sqrt{\frac{J}{J+1}} G_V M_V / G_A M_A$$

**linear in $M_V/M_A$**

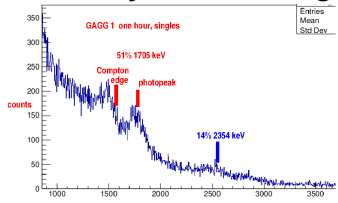
- **Recoil-$\gamma$ coincidences to select the antianalog**

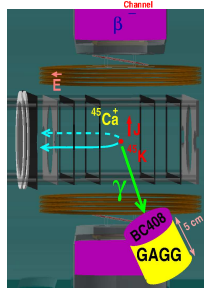
**Determination of $y$ with uncertainty $\sim$ 0.02 or better should be possible**

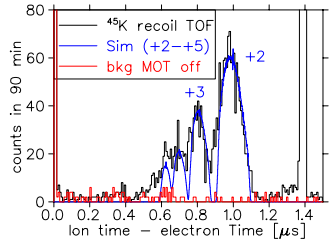



**51% branch to 3/2+ state in $^{45}$Ca. Should have the 'antianalog' configuration, $\langle F|V_{\mathrm{coul}}|A\rangle \sim$ 5 to 50 keV ?**

## $^{45}$K decay to antianalog



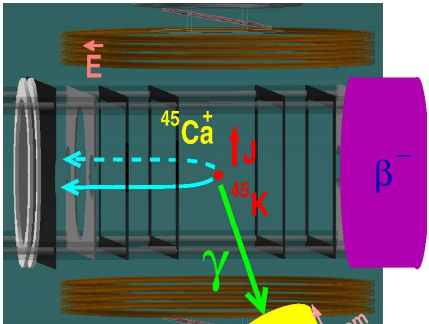




**90min data: shakeoff $e^-$& recoil clean even for $t_{1/2}$=18 min; M.Ozen HA.00073 had $\gamma$&recoil challenges**

# TRINAT and D

**Have considered D in $^{37}\vec{\mathrm{K}} \rightarrow {}^{37}\mathrm{Ar} + \beta^+ + \nu$**
**5x10$^{-4}$ statistical uncertainty per week of counting is possible.**




**Hard to compete with *n* and with $^{19}$Ne on the $G_V/G_A$ interference physics**
**(constrained by Ng-Tulin PRD 2012)**

**$\sigma_D \sim 10^{-3}$/week for $^{47}$K, an isospin-hindered case: $\beta^-$ decay always makes a charged recoil for efficient detection.**

**Uncertainty Projection:**
**Given $E_1$ = -0.01 $\pm$ 0.02 in $^{56}$Co, and winning by isospin sqrt(7/2),**
**we can get a limit on $K = y/(1+y^2)\sin\alpha$ by this effect 4x better per week of counting.**

**We project similar statistics for I=1/2 $^{47}$K**

**How that translates into sin($\alpha_V$) and $V_{TRV}$ depends on $V_{\mathrm{Coul}}$ (2.9 keV in $^{56}$Co).**

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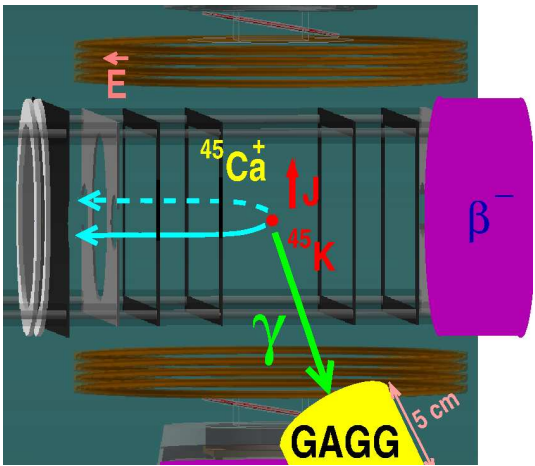
# D in atom trap: Features, Systematics




- Collect recoils going into 4 pi with electric field of 1 kV/cm
- Full reconstruction of recoil and beta momenta
- Point source: we know where it is (by sampling photoionization) and it doesn't move when we flip the polarization

- Any stray polarization along wrong axis is deadly, a lowest-order fake D: Measure with singles asymmetry for recoils and $\beta$'s

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# $^{47}$K wrt $^{45}$K

**80% branch $1/2^+ \rightarrow 1/2^+$: no need for $\gamma$ coincidence**

**Shorter $t_{1/2} \rightarrow$ less background from untrapped atoms ☺☺**

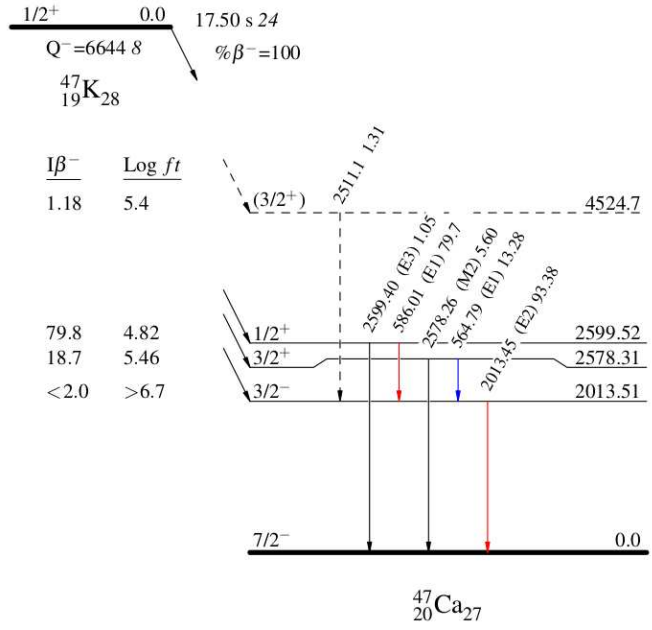
**Likely better calculation of final-state $D_{EM}$ is possible ☺**

**Faster G-T, similar to $^{36}$K ☹? ☺?**

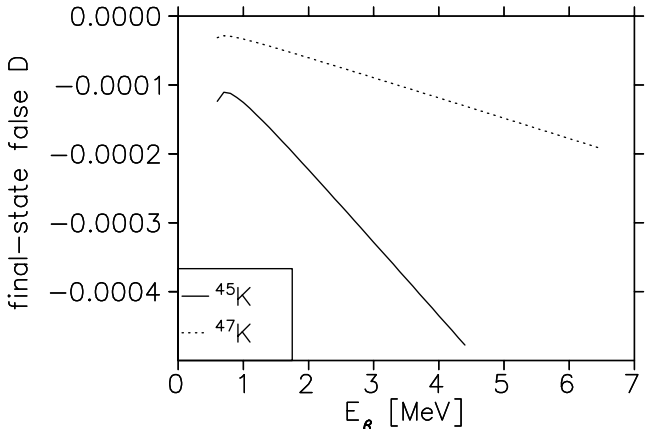
**Adequate online rates from TRIUMF/ISAC ☺?**

**Cross-shell isospin breaking: an interesting test for IMSRG?**

**(e.g. Martin Stroberg Holt Leach PRC 104 014324 (2021))**



# Final-state (false) *D*




**Holstein PRC 5 1529 (1972)**

- **Assumes weak magnetism *b* and induced tensor *d* are single-particle values, not suppressed like $M_A \Rightarrow$ Should be an upper limit**
- **Needs a full calculation, but should be OK**

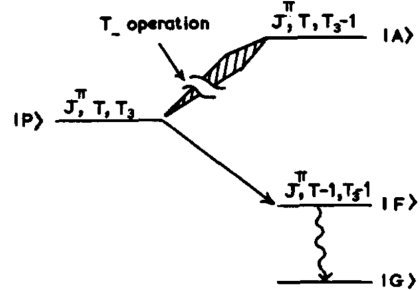
**For $^{56}$Co final-state $E_1$=0.0002 (Calaprice 1977)**

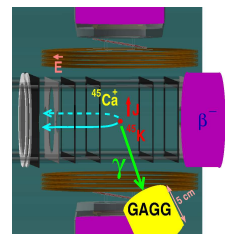
# TRIUMF *TRV* in isospin-hindered $^{45}_{19}$K, $^{47}_{19}$K decay

**Implementing Barroso and Blin-Stoyle PLB 1973 with TRINAT,**

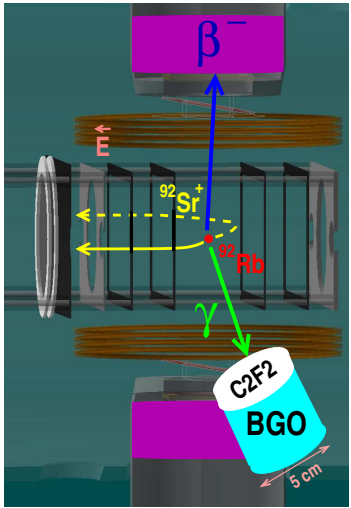
**We would measure** $D\,\hat{\mathbf{J}} \cdot \frac{\vec{p_\beta}}{E_\beta} \times \frac{\vec{p_\nu}}{E_\beta}$

- **To optimize case, and extract $V_{TRV}$ from $D$, needs a measurement of $V_{\mathrm{coul}}$ via $M_V$, using the recoil asymmetry wrt spin**
- **Project $10^{-3}$ statistics per week for $^{47}$K, which would produce 4x better precision on $K = \sqrt{\frac{J+1}{J}}D$ than $^{56}$Co Calaprice and Freedman using $E$**
- **Complementary to other *TRV*: *P* even, Isovector/tensor N-N *TRV* (evades Ng-Tulin 2012 EDM constraint on $D$)**



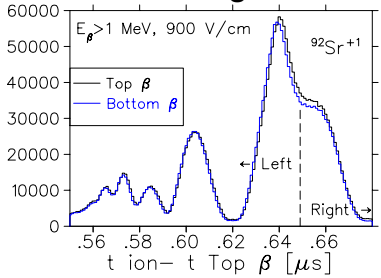



# TRIUMF *TRV* test $^{92}$Rb $0^- \rightarrow {}^{92}$Sr $0^+ + \beta^-\nu\gamma$



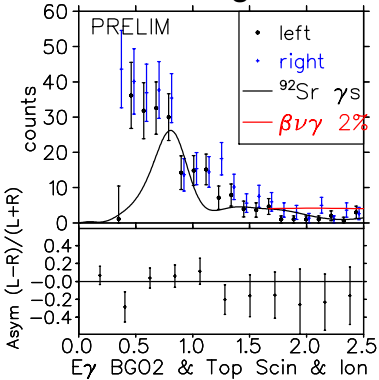

$\beta^- \cap {}^{92}Sr^+$

**'left' vs. 'right':**



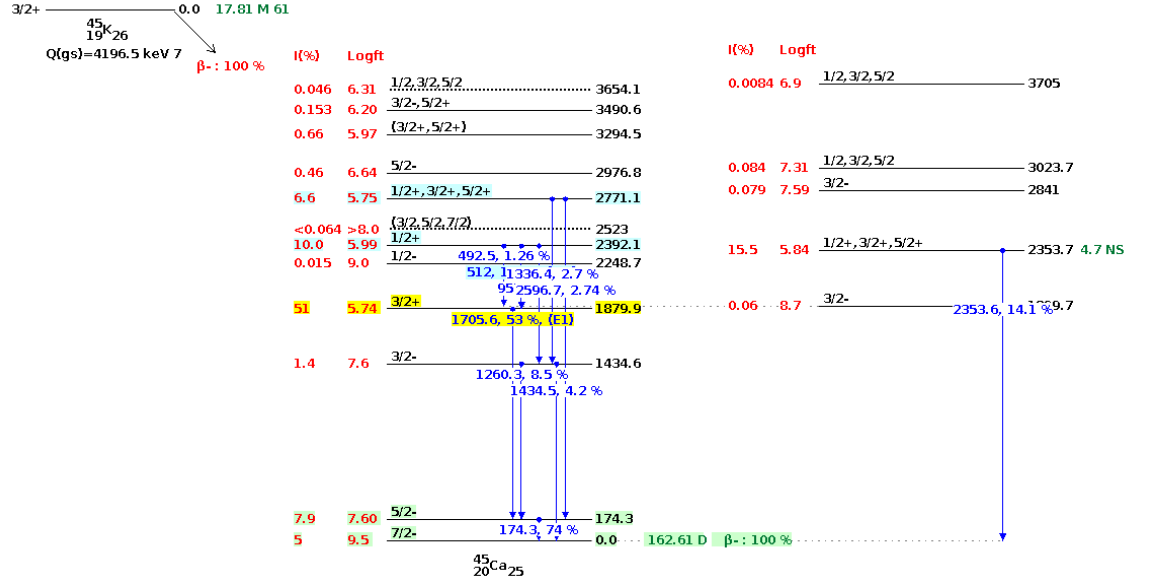

$\beta^- \cap {}^{92}Sr^+ \cap \gamma$

**'left' vs. 'right':**




**Sensitivity to**
**$\lesssim$ 2 % $\beta\nu\gamma$ branch**
**Asym of bkg is tricky**

**BGO $\rightarrow$ GAGG ($Ce:Gd_3Al_2Ga_3O_{12}$)**
**- better $E_\gamma$ resolution and timing — 6.6 g/cm$^3$**


3/2+
0.0
17.81 M 61
45 19 K 26
Q(gs)=4196.5 keV 7
β- : 100 %
I(%)
Logft
0.046 6.31 1/2,3/2,5/2 3654.1
0.153 6.20 3/2-,5/2+ 3490.6
0.66 5.97 (3/2+,5/2+) 3294.5
0.46 6.64 5/2- 2976.8
6.6 5.75 1/2+,3/2+,5/2+ 2771.1
<0.064 >8.0 (3/2,5/2,7/2) 2523
10.0 5.99 1/2+ 2392.1
0.015 9.0 1/2- 2248.7
492.5, 1.26 %
512, 1336.4, 2.7 %
95 2596.7, 2.74 %
51 5.74 3/2+ 1879.9
1705.6, 53 %, (E1)
1.4 7.6 3/2- 1434.6
1260.3, 8.5 %
1434.5, 4.2 %
7.9 7.60 5/2- 174.3
5 9.5 7/2- 174.3, 74 % 0.0
45 20 Ca 25
I(%)
Logft
0.0084 6.9 1/2,3/2,5/2 3705
0.084 7.31 1/2,3/2,5/2 3023.7
0.079 7.59 3/2- 2841
15.5 5.84 1/2+,3/2+,5/2+ 2353.7 4.7 NS
0.06 8.7 3/2- 2353.6, 14.1 %
162.61 D β- : 100 %