Probing Neutrino Mass Hierarchy by the IBD and ν-p ES Events of Supernova Neutrinos in Liquid Scintillation Detectors

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Outline

Motivation

- SN ν primary fluence and MSW effect
- IBD : related to Neutrino Mass Hierarchy
- ν-p ES : independent of Neutrino Mass Hierarchy
- SN evolution
  (Define Accretion Phase & Cooling Phase luminosity ratio)
- Probe neutrino mass hierarchy

Supernova neutrino fluence

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Primary fluence

$$\frac{dF}{dE} = \sum_{\alpha} \frac{128}{3} \frac{\mathcal{E}_\alpha}{4\pi d^2} \frac{E^3}{\langle E_\alpha \rangle^5} e^{-\frac{4E}{\langle E_\alpha \rangle}} \tag{1}$$

- Total energy $\mathcal{E} = \sum_\alpha \mathcal{E}_\alpha \approx 3 \times 10^{53}$ erg
- 10 s duration
- 10 kpc
- Energy unit fix to MeV

Supernova neutrino fluence

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MSW[1] : Normal Hierarchy

$$F_e = F_x^0 \tag{2}$$

$$\boxed{F_{\bar{e}} = (1 - \bar{P}_{2e})F_{\bar{e}}^0 + \bar{P}_{2e}F_x^0} \tag{3}$$

$$4F_x = F_e^0 + \bar{P}_{2e}F_{\bar{e}}^0 + (3 - \bar{P}_{2e})F_x^0 \tag{4}$$

MSW : Inverted Hierarchy

$$F_e = P_{2e}F_e^0 + (1 - P_{2e})F_x^0 \tag{5}$$

$$\boxed{F_{\bar{e}} = F_x^0} \tag{6}$$

$$4F_x = (1 - P_{2e})F_e^0 + F_{\bar{e}}^0 + (2 + P_{2e})F_x^0 \tag{7}$$

F_e, F_x = e and μ τ neutrino flux. $\bar{P}_{2e} \approx 0.3$

[1] Kwang-Chang Lai et al., JCAP 1607 (2016) no.07, 039

Supernova neutrino fluence

MSW : Normal Hierarchy

$$F_{\bar{e}} = (1 - \bar{P}_{2e})F_{\bar{e}}^{0} + \bar{P}_{2e}F_{x}^{0} \tag{8}$$

MSW : Inverted Hierarchy

$$F_{\bar{e}} = F_{x}^{0} \tag{9}$$

	Situation 1	**Situation 2**
Avg. $\mathcal{L}_\alpha$ Frac.	$\mathcal{L}_x/\mathcal{L}_{\bar{e}} < 1$	$\mathcal{L}_x/\mathcal{L}_{\bar{e}} > 1$
Result $F_{\bar{e}}$	F_{NH}	$F'_{\mathrm{NH}} < F_{\mathrm{NH}}$
	F_{IH}	$F'_{\mathrm{IH}} > F_{\mathrm{IH}}$

- Total energy is conserved
- Related to SN evolution

Neutrino proton elastic scattering

Event number of ν-p ES

- N_p in LS
- SN neutrino fluence $\frac{dF}{dE_\nu}$
- Differential cross section[2] $\frac{d\sigma_{\nu\text{-}p}}{dT_e}$
- Quenching function

The quenching function

$$T_d(T_e) = \int_0^T \frac{dT}{1 + k_B \left\langle \frac{dT}{dx} \right\rangle + C \left\langle \frac{dT}{dx} \right\rangle^2}$$

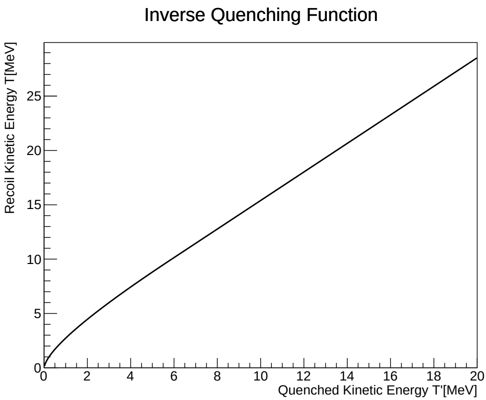
k_B : Birks constant

C : 2nd order Birks constant

Detector	Mass [kton]	Density [g/cm^3]	Chemical comp.	N_p [10^{31}]	k_B [cm/MeV]	C [cm/MeV]^2
Borexino	0.278	0.876	C_9H_{12}	1.7	0.01	–
KamLAND	0.697	0.77	$C_{12}H_{26}$(80%)C_9H_{12}(20%)	5.9	0.01	2.73×10^{-5}
SNO+	0.8	0.86	$C_6H_5C_{12}H_{25}$	5.9	0.0073	–
LENA	44	0.863	$C_{18}H_{30}$	330	0.01	–
JUNO	20	0.856	$C_6H_5C_{11}H_{23}$	145	0.00759	2.05×10^{-6}

[2] B. Dasgupta & F. Beacom, Phys. Rev. D83 (2011) 113006

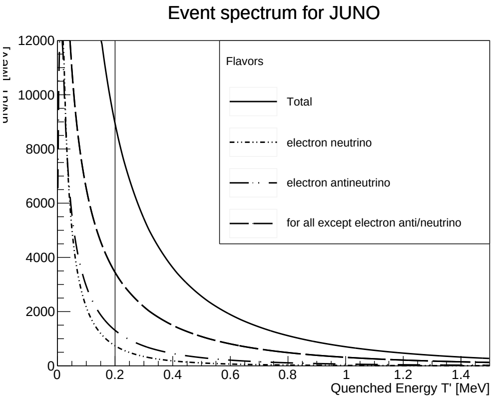
Qunching function



- JUNO detector[3]
- Chemical comp. dependent
- PSTAR table at physics.nist.gov

[3] JUNO Collaboration, J. Phys. G43 (2016) no.3, 030401

ν-p Event spectrum



- Energy equipartition
- $\{\langle E_e \rangle, \langle E_{\bar{e}} \rangle, \langle E_x \rangle\} = \{12, 15, 18\}$
- No Oscillation $N_{\nu\text{-}p} \approx 2548$
- Independent of neutrino mass hierarchy

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Motivation

SN ν fluence

Event spectrum

SN evolution

Probe NMH

Conclusion

Inverse Beta Decay

Event number of IBD

- N_p in LS
- SN electron anti-neutrino fluence $\frac{dF_{\bar{e}}}{dE_\nu}$
- Differential cross section[4] $\frac{d\sigma_{\mathrm{IBD}}}{dT_d}$

Detector	**Mass** [kton]	**Density** [g/cm^3]	**Chemical comp.**	N_p [10^{31}]	k_B [cm/MeV]	C [cm/MeV]^2
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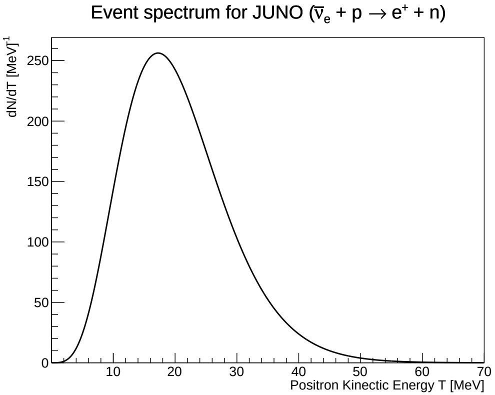
[4] A. Strumia & F. Vissani, Phys. Lett. B564 (2003) 42-54

IBD Event spectrum



Event number of IBD

- Energy equipartition
- $\langle E_e \rangle = 12$, $\langle E_{\bar{e}} \rangle = 15$, $\langle E_x \rangle = 18$
- No Oscillation $N_{\text{IBD}} \approx 5128$
- Sensitive to neutrino mass hierarchy

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Definition of AP and CP

	Condition
AP	$\mathcal{L}_{\nu_e} \approx \mathcal{L}_{\bar{\nu}_e} > \mathcal{L}_{\nu_x}$
EE	$\mathcal{L}_{\nu_e} = \mathcal{L}_{\bar{\nu}_e} = \mathcal{L}_{\nu_x}$
CP	$\mathcal{L}_{\nu_e} \approx \mathcal{L}_{\bar{\nu}_e} < \mathcal{L}_{\nu_x}$

	$\mathcal{L}_{\bar{\nu}_e}/\mathcal{L}_{\nu_e}$	$\mathcal{L}_{\nu_x}/\mathcal{L}_{\nu_e}$
AP	1.00	0.80
EE	1.00	1.00
CP	1.00	1.14

- SN evolve from AP $\rightarrow$ CP
- $\mathcal{E}_{\text{AP}} \neq \mathcal{E}_{\text{CP}}$

Event Ratio[5] R

The event ratio R is defined as

$$R \equiv \frac{N_{\text{IBD}}}{N_{\nu\text{-}p}} : \frac{(\text{no. of } \nu_{\bar{e}})}{(\text{no. of } \nu)} \Rightarrow (\text{fraction of } \nu_{\bar{e}}) \qquad (10)$$

- sensitive to neutrino mass hierarchy
- independent of total energy emission
- absolute value is not important
- AP$\rightarrow$CP $\Rightarrow$ R$\searrow$ in NH
- AP$\rightarrow$CP $\Rightarrow$ R$\nearrow$ in IH

[5] Kwang-Chang Lai et al., JCAP 1607 (2016) no.07, 039

Probe neutrino mass hierarchy

- JUNO detector
- Threshold = 0.2 MeV
- R $\searrow$ in NH
- R $\nearrow$ in IH

Hierarchy	Phases	$N_{\nu\text{-}p}$	N_{IBD}	R
NH 12 14 16	AP	1759	5376	3.056
	EE	1820	4995	2.745
	CP	1853	4789	2.584
IH 12 14 16	AP	1759	5039	2.865
	EE	1820	5459	2.999
	CP	1853	5687	3.069

Hierarchy	Phases	$N_{\nu\text{-}p}$	N_{IBD}	R
NH 12 15 18	AP	2447	5829	2.382
	EE	2548	5427	2.130
	CP	2604	5210	2.001
IH 12 15 18	AP	2447	5631	2.301
	EE	2548	6101	2.394
	CP	2604	6355	2.440

Hierarchy	Phases	$N_{\nu\text{-}p}$	N_{IBD}	R
NH 10 15 24	AP	4424	6328	1.430
	EE	4709	5968	1.267
	CP	4863	5773	1.187
IH 10 15 24	AP	4424	7252	1.639
	EE	4709	7857	1.669
	CP	4863	8184	1.683

Conclusion

- For the normal hierarchy, event ratio R becomes smaller as neutrino emissions evolve from accretion phase to cooling phase, but it becomes larger for the inverted hierarchy.

- Neutrino mass hierarchy can therefore be probed by detecting IBD and ν-p ES events.