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''The nuclear response of terrestrial detectors to low-energy neutrino spectra''

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Motivation

Low-energy Neutrino searches (ν-production, ν-detection, ν-interactions with matter, etc.) are interesting research topics in:

A. Neutrino-Astrophysics

– Astrophysical neutrino energy-spectra (solar, supernova, etc)
– Modeling of stellar evolution [Janka et al, PR 442(07)38]

B. Neutrino-detection (terrestrial experiments)

– For solar neutrino-detection experiments (E_ν < 20 MeV)
– Supernova neutrino-detection experiments (E_ν < 60 -70 MeV)
– Rare event processes (0νββ-decay, etc.)

(i) MOON-Experiment **(^{100}Mo)** [H.Ejiri, Phys.Rep. 338 (00)265]

(ii) Cobra-Experiment: **(Cd, Te, Zn)** [K.Zuber, Phys. Lett. B 571(03)148]

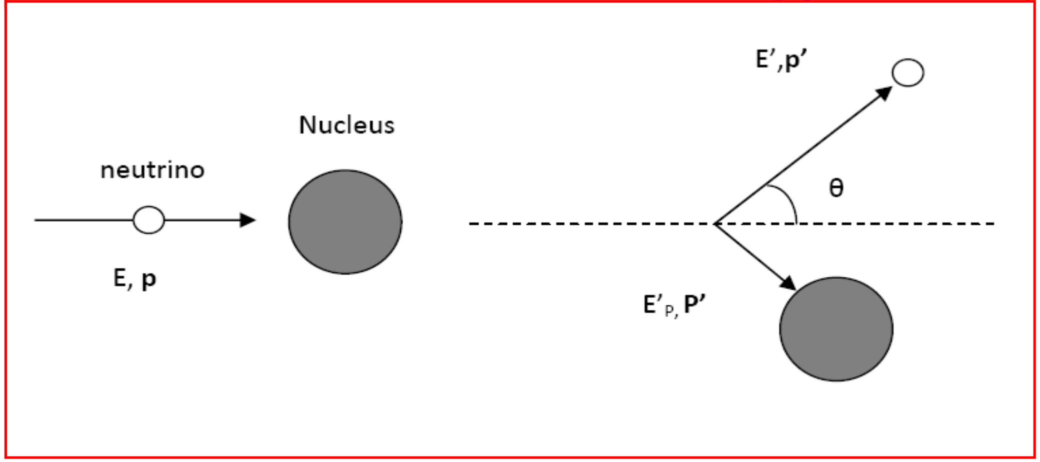
C. Neutrino-nucleus interactions (nuclear-structure calculations)

– neutral-current interactions --charged-current interactions

Recently, it became feasible to detect low-rate neutrinos by measuring the recoiling nucleus with very-low threshold-energy gaseous-detectors. **Such studies are in conjunction with the direct-detection of CDM events.**

Nuclear recoil: Neutral-Current ν–Nucleus interactions

$$\nu + {}_Z A_N \longrightarrow {}_Z A^*_N + \nu'$$



- Most important transition: |gs> ➔ |gs>, |gs>=|J$^\pi$ > = |0$^+$>
- The |gs> ➔ |gs> differential cross section reads

$$\frac{d\sigma}{d(\cos\Phi)} = G^2 \frac{\sin^2\theta_w}{2\pi} A^2 E_\nu^2 (1+\cos\Phi)$$

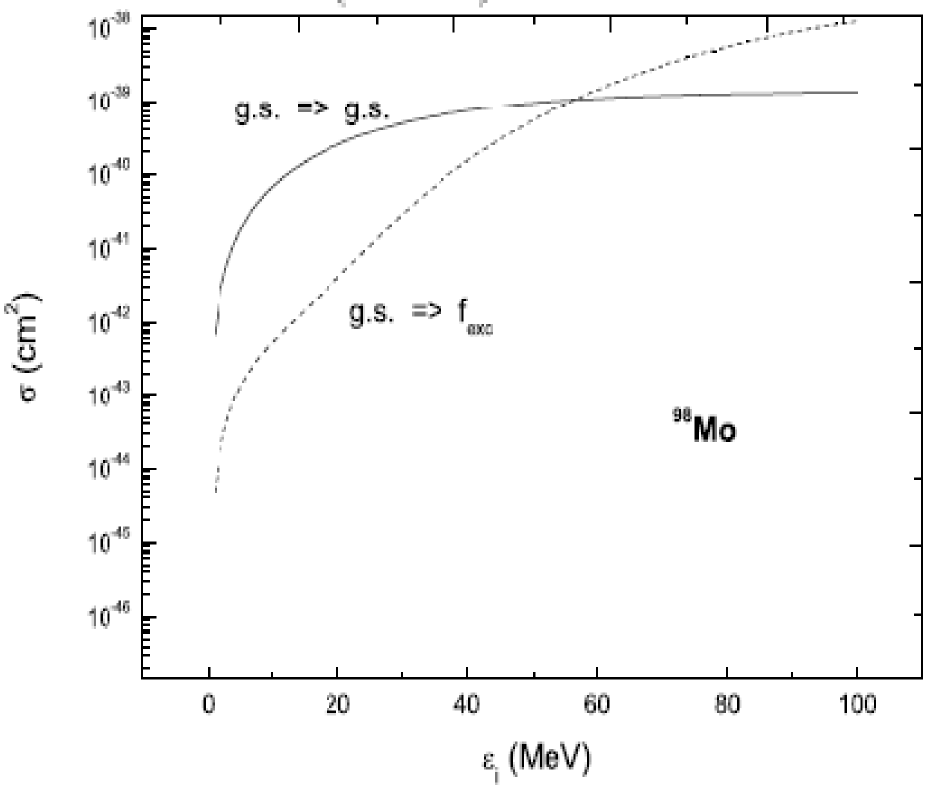
Φ = scattering angle, θ_W =Weinberg angle, Eν = incoming-neutrino energy

- Nucleons contribute coherently (coherent process dominates)

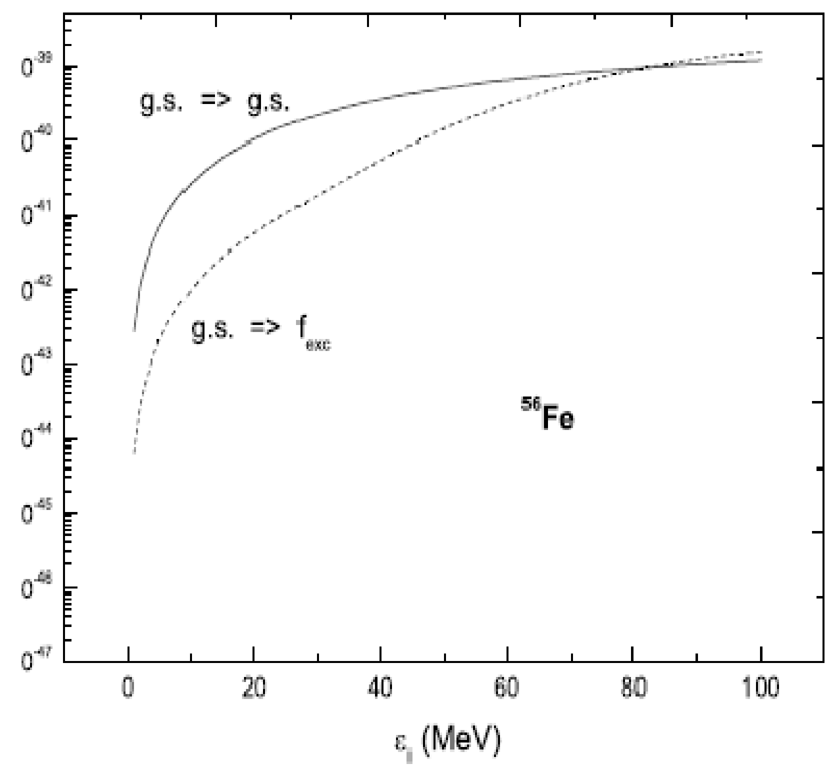
Coherent vs Incoherent Cross section in NC reactions

In the low-energy region (solar neutrinos) the coherent channel dominates the total cross section (tsk, et al., NPA, submitted).

$^{98}Mo(\bar{\nu},\bar{\nu}')^{98}Mo^*$



$^{56}Fe(\nu,\nu')^{56}Fe^*$



Nuclear recoil

In experimental studies of NC neutrino-nucleus scattering, the only observable is the average recoil energy

$$\langle E_N \rangle = \frac{2}{3A}\left(\frac{E_\nu}{1MeV}\right)^2 keV$$

(i) Proportional to E_ν^2 , inversely proportional to A (mass number)

(ii) Including other experimental criteria, ^{28}Si, ^{32}S best choices

The physical observable $d\sigma/dT_A$ reads

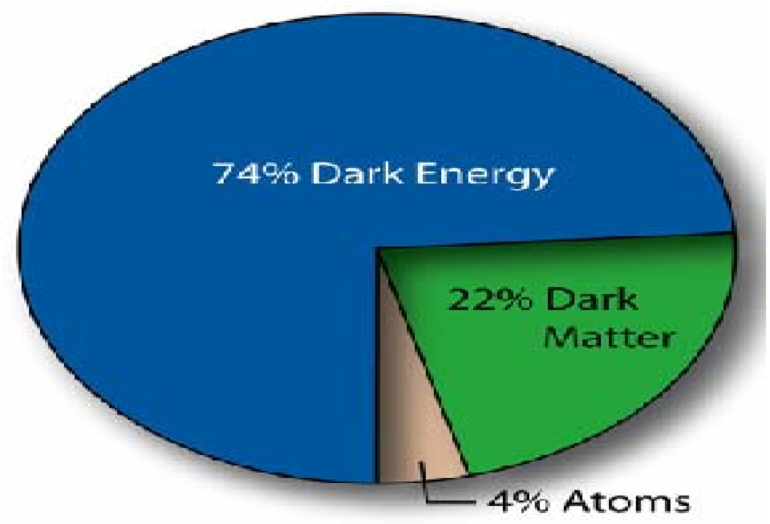
$$\left(\frac{d\sigma}{dT_A}\right)_{weak} = \frac{G_F^2 A m_N}{2\pi}(N^2/4)F_{coh}(T_A, E_\nu)$$

$$F_{coh}(T_A, E_\nu) = F^2(q^2)(1 + (1 - \frac{T_A}{E_\nu})^2 - \frac{A m_N T_A}{E_\nu^2}$$

$q^2 = T_A^2 + 2Am_N T_A$

This study is in conjunction with dark matter detection

Scattering of CDM particles off nuclei (Direct detection)



The Content of the universe:
Dark Energy ≈ 73%, Atoms ≈ 4%
Cold Dark Matter ≈ 23%

LSP-nucleus scattering ➡ $\chi + (A, Z) \Longrightarrow \chi' + (A,Z)^*$

A) Coherent process is possible : Vector & Axial-Vector Currents

B) Dominance of Axial-Vector contributions
(Odd-A nuclear targets : ^{73}Ge, ^{127}I, ^{115}In, ^{129,131}Xe)

Exotic 1-body Semi-leptonic Nuclear Processes

Lepton Flavor violating process: $\mu^-_b \rightarrow e^-$ conversion in nuclei

$$\mu^-_b + (A, Z) \Longrightarrow e^- + (A,Z)^*$$

a) Coherent (g.s => g.s.) transitions dominates
c) Only the Coherent channel, 'is measured' by experiments :

Best upper limits:

(i) PSI	$\Longrightarrow$ ^{197}Au	$R_{\mu e} < 10^{-13}$	
(ii) MECO (Brookhaven)	$\Longrightarrow$ ^{27}Al	$R_{\mu e} < 2x\ 10^{-17}$	(Cancelled)
(iii) PRIME (at PRISM)	$\Longrightarrow$ ^{48}Ti	$R_{\mu e} < 10^{-18}$	

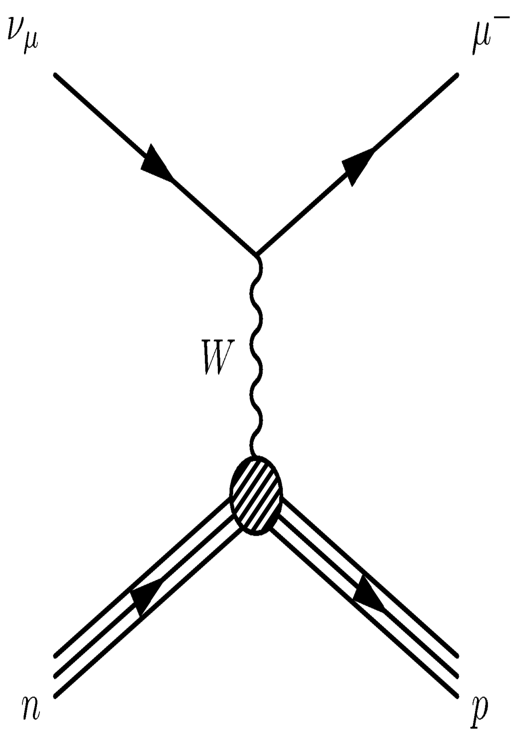
Shaaf , J.Phys.G (2003); Kuno, AIP Conf.Proc. (2000); Molzon, Spr. Trac. Mod. Phys., (2000)
Scwienger,Kosmas,Faessler,PLB (1998);Kosmas,NPA (2001);Deppisch,Kosmas,Valle,NPB (2006)

Neutrino-nucleus interactions

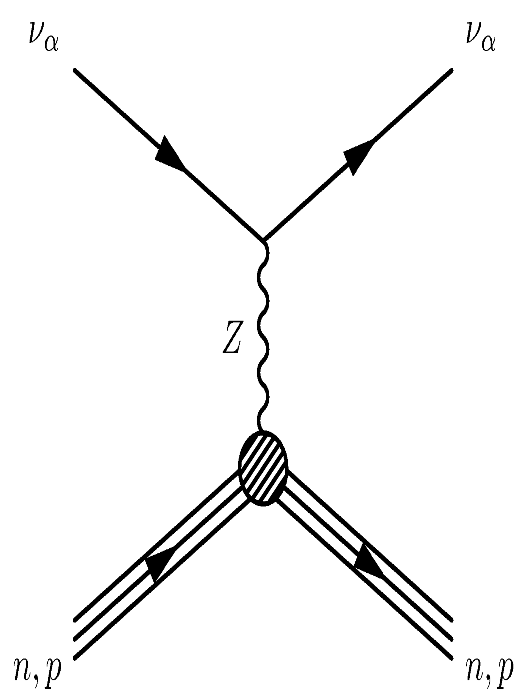
Neutral current (NC) processes (mediated by Z-bozon)

Charged-currents processes (mediated by charged W-bozons)

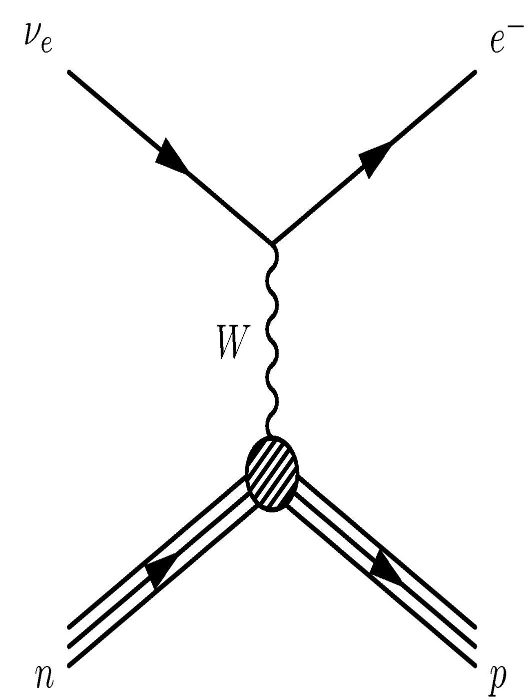
ν_μ CC Event



NC Event



ν_e CC Event



ν–Nucleus Interaction (Cross section)

In Walecka-Donnely-Haxton method [PRC 6 (1972)719, NPA 201(1973)81]

$$\frac{d^2\sigma_{i\to f}}{d\Omega d\omega} = \frac{G^2}{\pi}\frac{\varepsilon_f^2}{(2J_i+1)}\left(\sum_{J=0}^{\infty}\sigma_{CL}^J + \sum_{J=1}^{\infty}\sigma_T^J\right)$$

where

$$\omega = \varepsilon_i - \varepsilon_f \qquad q = |\mathbf{q}| = \left[\omega^2 + 2\varepsilon_i\varepsilon_f(1-\cos\Phi)\right]^{\frac{1}{2}}$$

The Coulomb-Longitudinal (1st sum), and Transverse (2nd sum) are:

$$\begin{aligned}\sigma_{CL}^J &= (1+\cos\Phi)\left|\langle J_f||\widehat{\mathcal{M}}_J(q)||J_i\rangle\right|^2 + (1+\cos\Phi - 2b\sin^2\Phi)\left|\langle J_f||\widehat{\mathcal{L}}_J(q)||J_i\rangle\right|^2 \\ &+ \left[\frac{\omega}{q}(1+\cos\Phi)\right]2\Re e\langle J_f||\widehat{\mathcal{L}}_J(q)||J_i\rangle\langle J_f||\widehat{\mathcal{M}}_J(q)||J_i\rangle^* \,, \qquad (5.21)\end{aligned}$$

$$\begin{aligned}\sigma_T^J &= (1-\cos\Phi + b\sin^2\Phi)\left[\left|\langle J_f||\widehat{\mathcal{T}}_J^{mag}(q)||J_i\rangle\right|^2 + \left|\langle J_f||\widehat{\mathcal{T}}_J^{el}(q)||J_i\rangle\right|^2\right] \\ &\mp \left[\frac{(\varepsilon_i+\varepsilon_f)}{q}(1-\cos\Phi)\right]2\Re e\langle J_f||\widehat{\mathcal{T}}_J^{mag}(q)||J_i\rangle\langle J_f||\widehat{\mathcal{T}}_J^{el}(q)||J_i\rangle^*\end{aligned}$$

Compact expressions for the 7-basic reduced ME

For H.O. bases w-fs, all basic reduced ME take the compact forms

$$\langle j_1 || T^J || j_2 \rangle = e^{-y} y^{\beta/2} \prod(y) = e^{-y} y^{\beta/2} \sum_{\mu=0}^{n_{max}} \mathcal{P}_\mu^J \, y^\mu ;$$

The Polynomials of even terms in q have constant coefficients as

$$\prod(y) = \sum_{\mu=0}^{n_{max}} \mathcal{P}_\mu^J \, y^\mu , \quad y = \frac{q^2 b^2}{4}$$

$$n_{max} = (N_1 + N_2 - \beta)/2 \,.$$

V.Chasioti, TSK, Czech. J. Phys. 52 (2002)467; Nucl. Phys. A, submitted

Advantages of the above formalism (FORTRAN Code) :

(i) The coefficients P^J are calculated once (reduction of computer time)

(ii) They can be used for phenomenological description of ME

(iii) They are useful for other bases sets (expansion in HO wave-functions)

Nuclear Matrix Elements - The Nuclear Model

The initial and final states, $|J_i>$, $|J_f>$, in the ME $<J_f||T(qr)||J_i>^2$ are determined by using **QRPA**

$$\langle J_f||T(q\mathbf{r})||J_i\rangle = \sum_{j_1,j_2} \langle j_1||T(q\mathbf{r})||j_2\rangle \, D(j_1,j_2;J)$$

j_1, j_2 ⇨ run over all active single-particle levels (coupled to J)

$D(j_1, j_2; J)$ ⇨ one-body transition densities determined by the model

1). Interactions:

- Woods-Saxon + Coulomb corrections (as Field)
- Bonn-C Potential (as two-body interaction)

2). Parameters:

- In the BCS level: the pairing parameters g^n_{pair} , g^p_{pair}
- In the QRPA level: the strength parameters g_{pp} , g_{ph}

3). Testing the reliability of the Method:

- Low-lying nuclear excitations (up to about 5 MeV)
- magnetic moments (separate spin, orbital contributions)

Questions to be answered

A). On the basis of the original calculations we could study:

i) State-by-state calculations of $d\sigma/d\Omega$

ii) Angular dependence of the differential cross-section

iii) Dominance of Axial-Vector contributions in σ

B). Nuclear response of terrestrial ν-detectors to various neutrino sources:

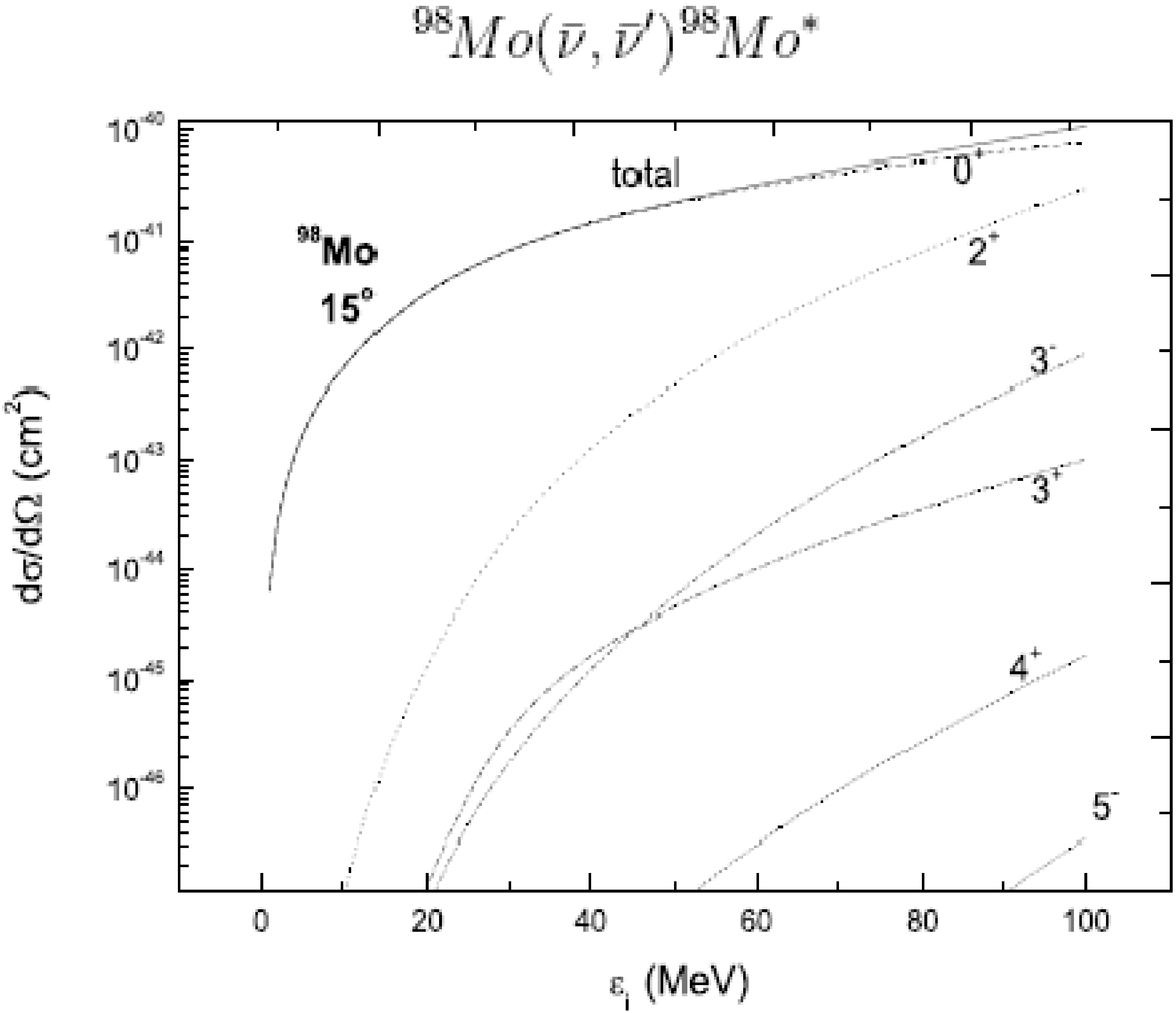
i) solar neutrino spectra

ii) SN neutrino spectra

iii) reactor neutrino spectra

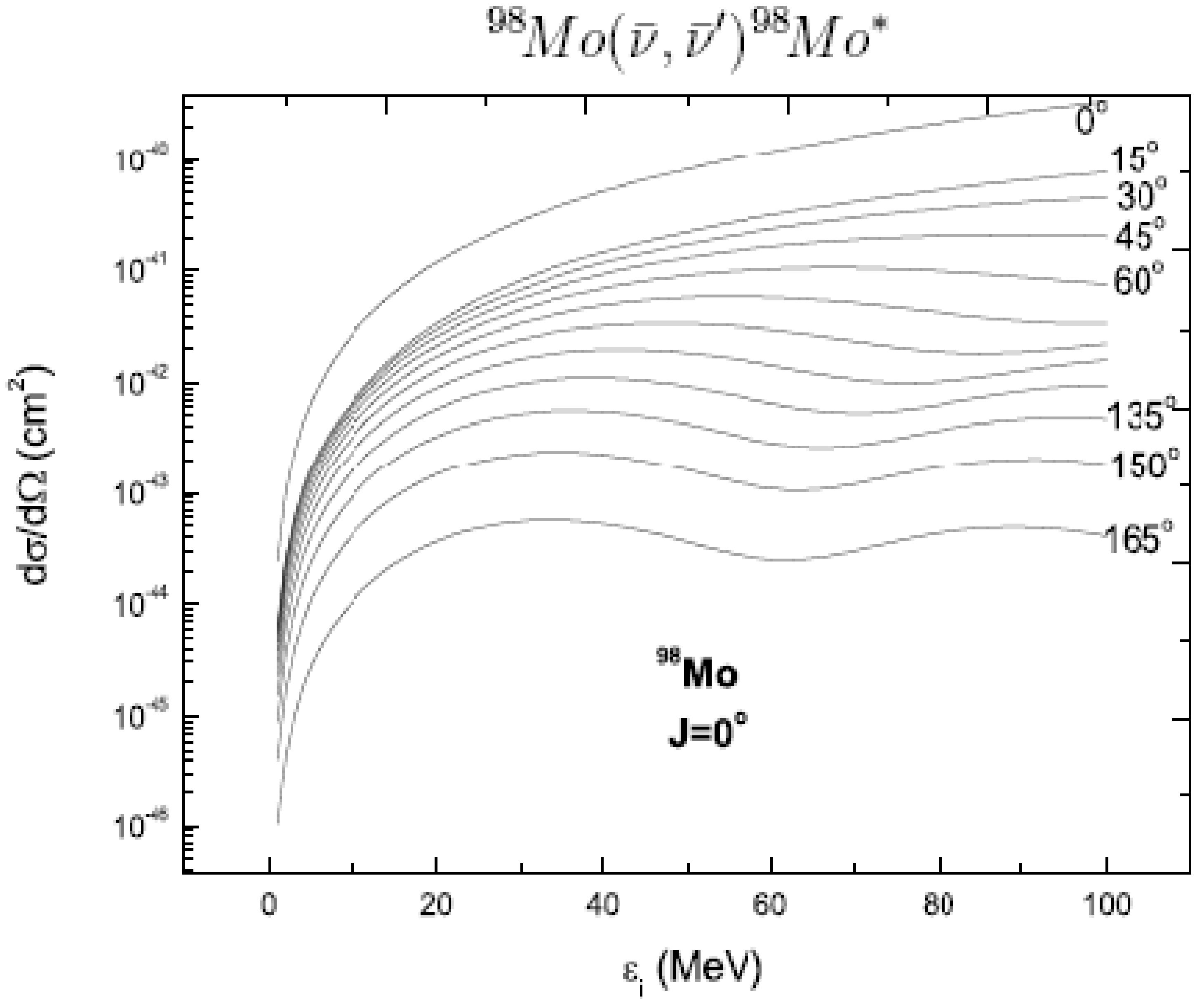
State-by-state calculations of dσ/dΩ

^{98}Mo



Angular dependence of the differential cross-section

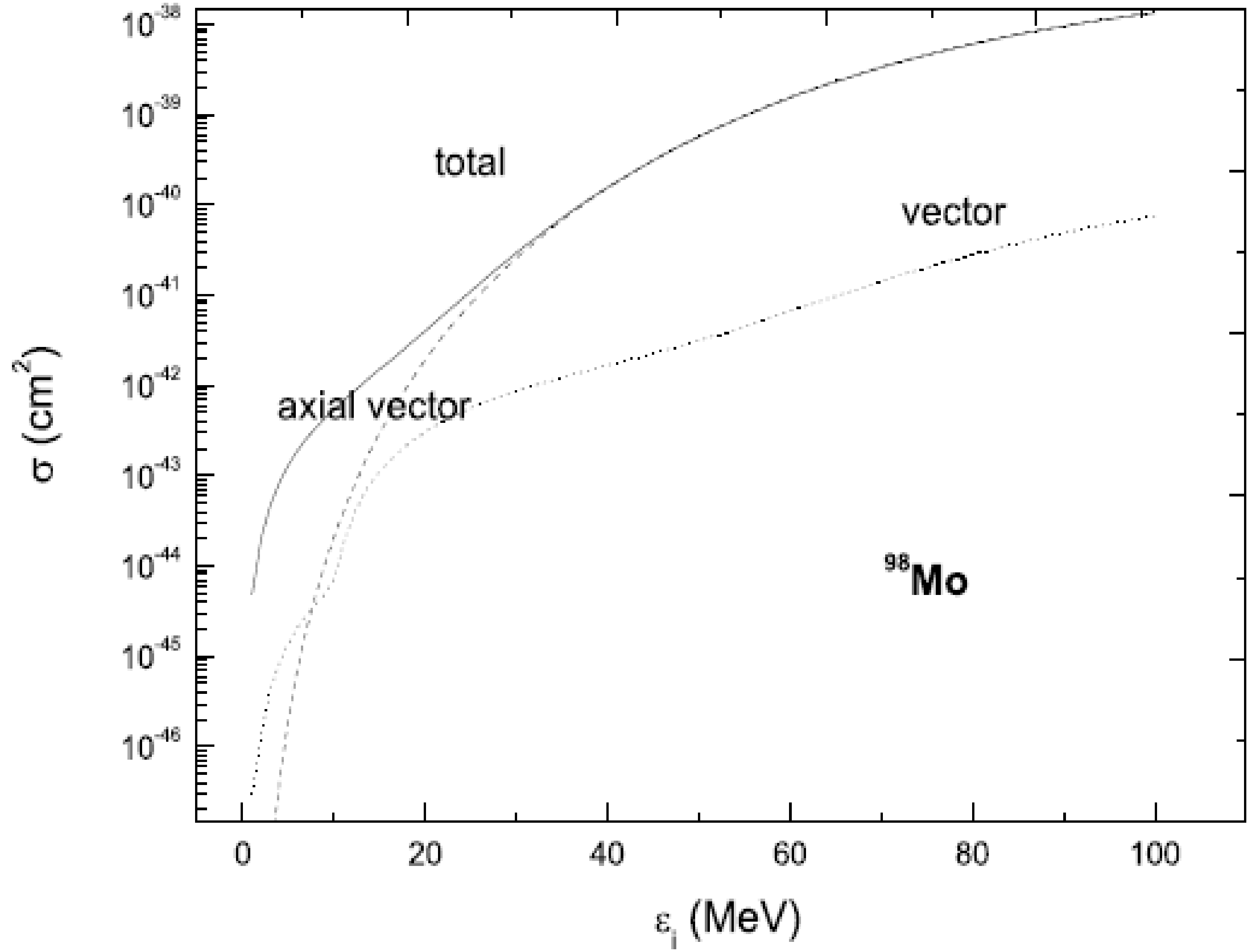
^{98}Mo



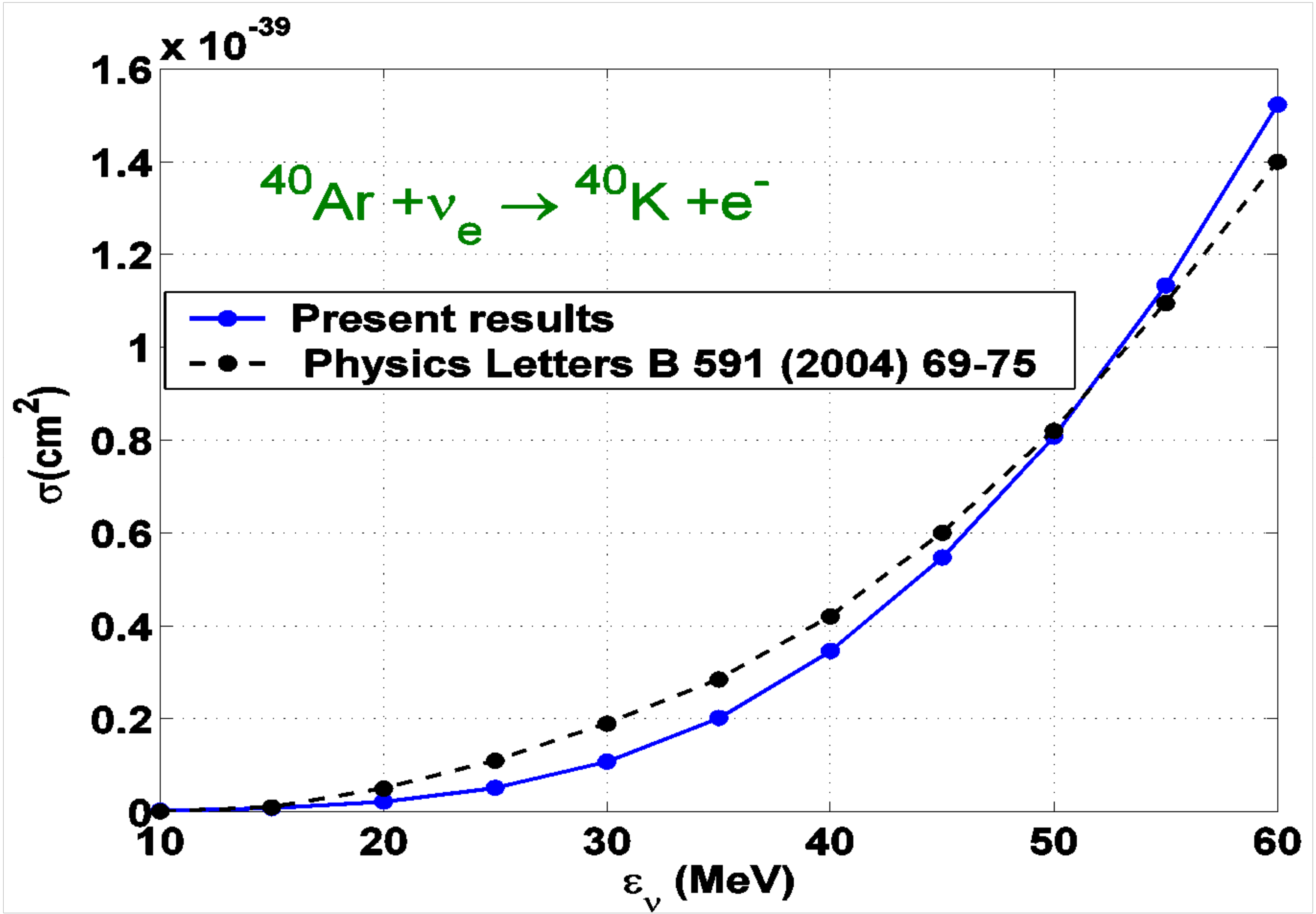
Dominance of Axial-Vector contributions in σ

$$^{98}Mo(\bar{\nu}, \bar{\nu}')^{98}Mo^*$$

^{98}Mo



Results for C-C ν-nucleus reactions



Nuclear response to SN-ν

The SN-ν energies are between

2-3 MeV < E_ν < 40-60 MeV)

This is the region of nuclear excitations where G-T and F Giant Resonances, and isospin and spin-isospin Dipole Resonances play crucial role.

For NC processes, important GR associated with nuclear responses are :
Isospin and isospin-spin resonances with $J^\pi = 1^+ , 1^-$, etc.

Aim of our studies: To investigate the Response as low-energy neutrino detectors of :

i) Te, Cd, Zn –isotopes (COBRA ββ-decay experiment)
ii) Mo-isotopes (MOON ββ-decay experiment)

i) K.Zuber, Phys. Lett. B 571(03)148, talk at MEDEX-09, June 15-19, 2009, Prague.
ii) H. Ejiri, Phys. Rep. 338 (2000)265; H. Ejiri et a., Phys.Lett. B 530 (02)265;

Nuclear response to SN-ν for various targets

Assuming Fermi-Dirac distribution for the SN-ν spectra

$$f(E_\nu) = \frac{1}{F_2(\alpha)T^3}\frac{E_\nu^2}{exp[(E_\nu/T) - \alpha] + 1}$$

f(E_ν) is normalized to unity as

$$\int f(E_\nu)dE_\nu = 1$$

Using our results, we calculated for various ν–nucleus reaction channels the flux-averaged cross sections

$$\langle\sigma_f\rangle = \int \sigma(E_\nu)f(E_\nu)dE_\nu$$

$F_2(\alpha)$ = Normalization factor

α = degeneracy parameter

T = Neutrino Temperature

E_ν = neutrino energy

Supernova Neutrino physics

The energy-spectra of neutrinos emitted in a core collapse SN can be approximated by Fermi-Dirac type distribution

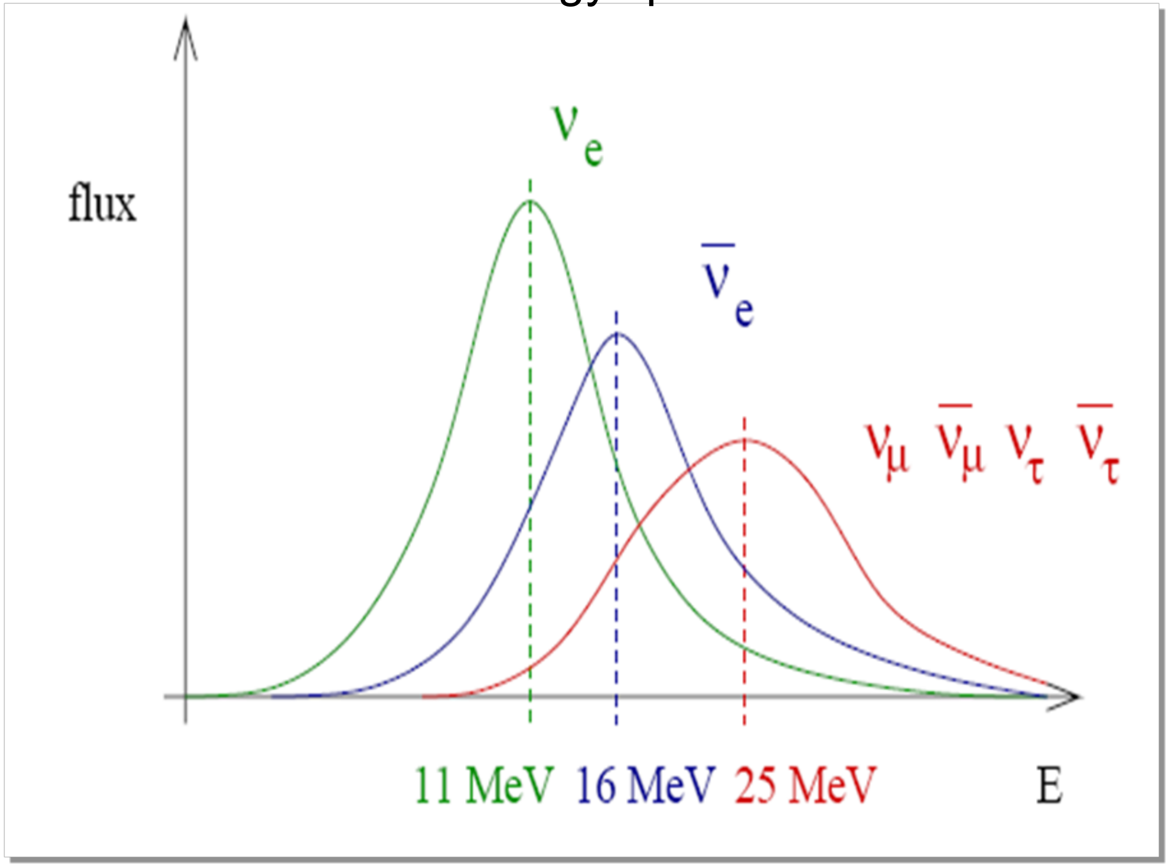
Mean Energy SN spectra

$$\langle E_{\nu_e} \rangle \approx 11\, MeV$$

$$\langle E_{\bar{\nu}_e} \rangle \approx 16\, MeV$$

$$\langle E_{\nu_{\mu\tau}} \rangle \approx 25\, MeV$$

SN Energy spectra



Parameterization of SN-ν energy-spectra

The SN ν energy-spectra can be accurately parameterized with a **power- law** (PL-distibution)

$$PL\left(\langle\varepsilon_\nu\rangle,\varepsilon_\nu,\alpha\right)=\left(\frac{\varepsilon_\nu}{\langle\varepsilon_\nu\rangle}\right)^{\alpha} e^{-(a+1)\frac{\varepsilon_\nu}{\langle\varepsilon_\nu\rangle}}$$

$\langle\varepsilon_\nu\rangle$ = the average neutrino energy

α = spectral pinching parameter

These parameters allow to adjust the width w

$$w=\sqrt{\langle\varepsilon_\nu^2\rangle-\langle\varepsilon_\nu\rangle^2}$$

Energy-spectra of SN-ν

The low–energy **beta-beam neutrinos** can be exploited to interpret a SN–ν signal

Linear combinations of normalized beta-beam spectra are used

$$n_{N_\gamma}(\varepsilon_\nu) = \sum_{i=1}^{N} \alpha_i n_{\gamma_i}(\varepsilon_\nu)$$

The fitting of coefficients α_i and boost factors γ_i of this energy distribution to SN-neutrino spectrum is achieved by minimization

$$\int_{\varepsilon_\nu} d\varepsilon_\nu \left| n_{N_\gamma}(\varepsilon_\nu) - n_{SN}(\varepsilon_\nu) \right|$$

Low-energy neutrino sources in SN physics

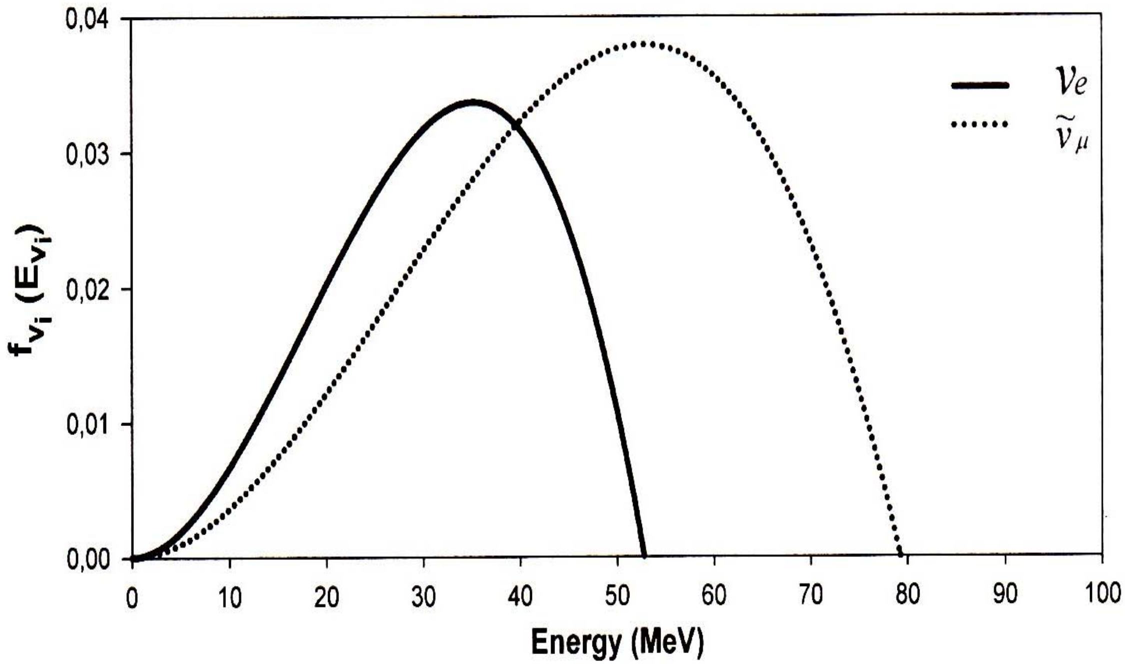
Experimental neutrino beams, stemming from slow pion decay and μ-decay (reactor neutrinos) are used to study low-energy neutrino interactions:

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \to \mu^- + \bar{\nu}_\mu$$

$$\mu^- \to e^- + \nu_e + \nu_\mu$$



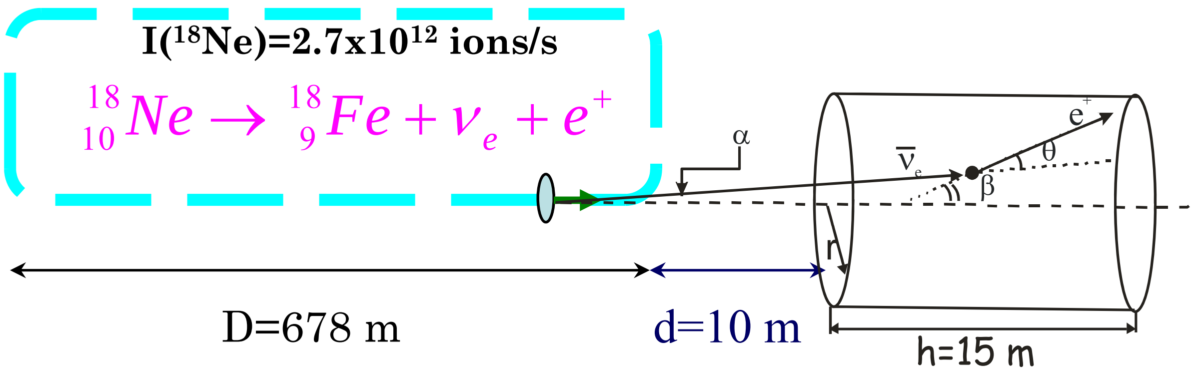
Michel spectrum

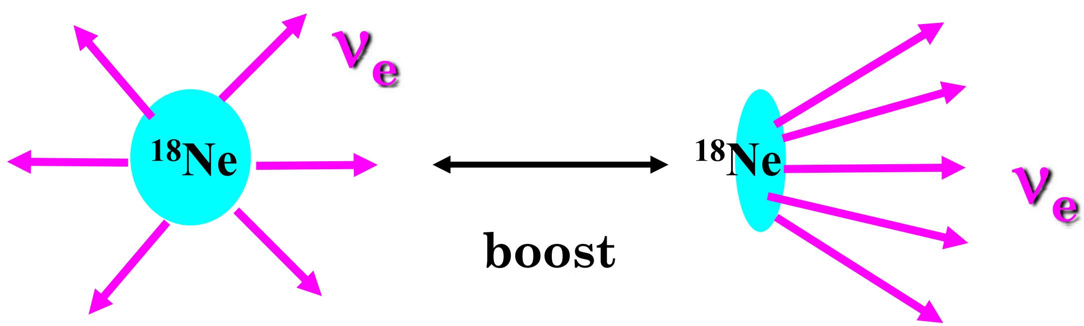
$$n_{\nu_e}(\varepsilon_{\nu_e}) = \frac{96\varepsilon_{\nu_e}^2}{m_\mu^4}(m_\mu - 2\varepsilon_{\nu_e})$$

$$n_{\bar{\nu}_\mu}(\varepsilon_{\bar{\nu}_\mu}) = \frac{32\varepsilon_{\bar{\nu}_\mu}^2}{m_\mu^4}(\frac{3}{2}m_\mu - 2\varepsilon_{\bar{\nu}_\mu})$$

Boosted beta-beam neutrinos for SN-ν studies

Small Storage ring-detector





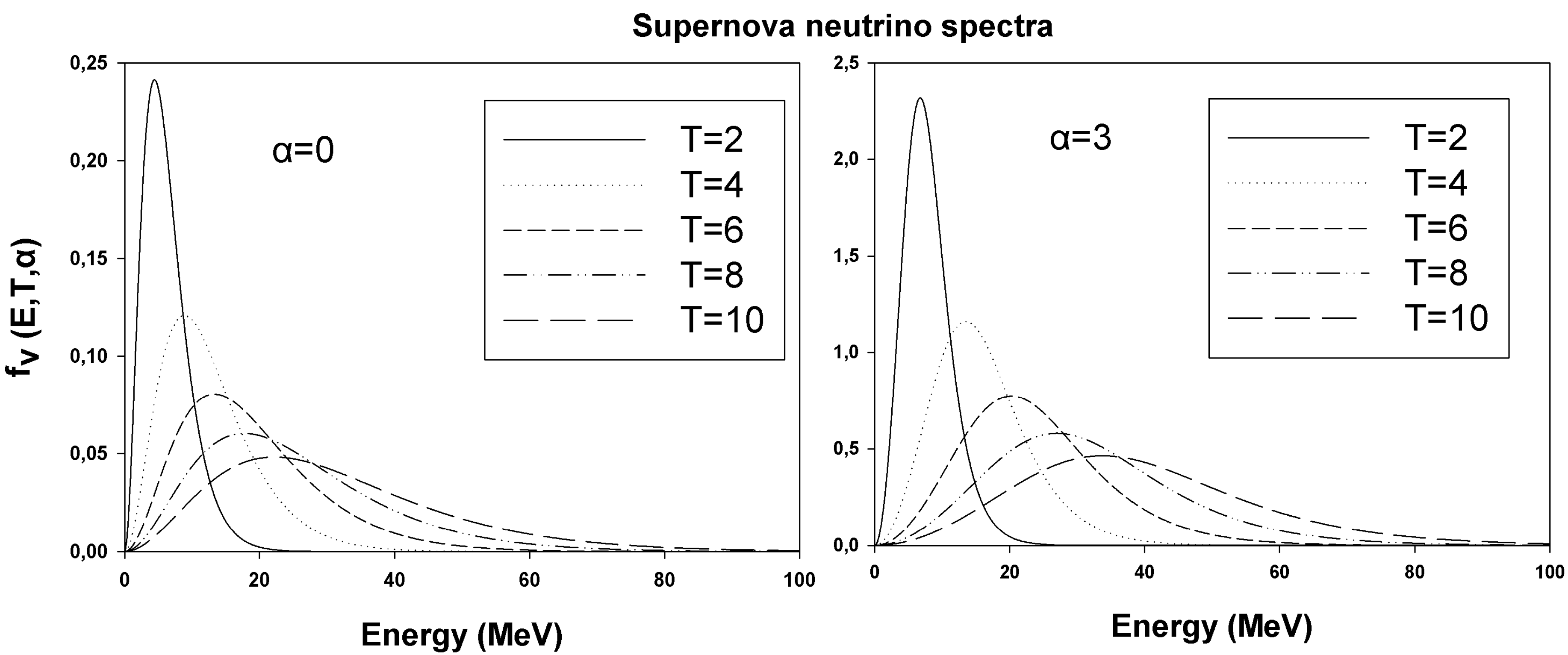
J. Serreau, C. Volpe: Phys.Rev. C70 (2004) 055502

Supernova-neutrino spectra

Fermi-Dirac distribution

$$f(E_\nu) = \frac{1}{F_2(\alpha)T^3}\frac{E_\nu^2}{exp[(E_\nu/T) - \alpha] + 1}$$

T = Neutrino Temperature α = Chemical Potential



Summary and Conclusions

The Nucleus is a good micro-laboratory in low-threshold experiments as:

(i) Direct detection of CDM-candidates

(ii) Low-energy neutrinos searches

i. Neutrino production Sources

ii. Solar, SN neutrino production

iii. Neutrino detection by terrestrial experiments

For such studies reliable neutrino-nucleus reaction cross sections are required

Nuclear Response to various ν-Spectra

i. Low energy beam neutrinos in SN- ν searches
- Reactor neutrino spectra
- Beta - beam neutrino spectra

Recent and future nuclear recoil experiments, with very low threshold energy,

could measure CNO (and pep) solar neutrinos as well as direct CDM events

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