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Nuclear Excitation by Neutral Weak Currents†

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ABSTRACT

The use of neutrino excitation of nuclear levels to study weak neutral currents is examined.

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Recent experiments[1] have indicated the possible presence of neutral currents in strangeness conserving semi-leptonic weak interactions. These results, yet to be confirmed, have aroused great interest, since neutral weak currents play an important role in certain unified theories of weak and electromagnetic interactions, such as those proposed by Weinberg[2], Salam and Ward[3] and others, and shown to be renormalizable by t'Hooft and others[4]. In this Letter, we point out that such currents would lead to a new class of experiments in which nuclear energy levels could be excited through the inelastic scattering of neutrinos. If neutral currents do indeed exist, then neutrino excitation can yield important information about their structure. We shall describe the mechanism of excitation, consider several nuclei as examples, and discuss experimental implications.

The usual charge-changing semi-leptonic weak Hamiltonian has the form

$$H_W = \frac{iG}{\sqrt{2}} \left[\bar{\psi}_e \gamma_\lambda (1 + \gamma_5)\, \psi_{\nu_e} + \bar{\psi}_\mu\, \gamma_\lambda\, (1 + \gamma_5)\, \psi_{\nu_\mu}\right] \mathscr{J}_\lambda^{(+)} + \text{h.c.}$$

The nuclear current has the structure $\mathscr{J}_\lambda = J_\lambda + J_{\lambda_5}$ consisting of a vector and axial-vector part. The electromagnetic current is known to consist of an isoscalar and isovector part $J_\lambda^\gamma = J_\lambda^S + J_\lambda^{V_3}$. The conserved-vector-current theory identifies the charge raising and lowering parts of the vector current entering into the weak interaction with the isovector part of the electromagnetic current through the following relation: $J_\lambda^{(\pm)} = J_\lambda^{V_1} \pm i\, J_\lambda^{V_2}$. The axial-vector current is also an isovector operator and has the structure $J_{\lambda_5}^{(\pm)} = J_{\lambda_5}^{V_1} \pm i\, J_{\lambda_5}^{V_2}$.

In Weinberg's theory, the charge-changing semi-leptonic part of the weak Hamiltonian is unchanged. However, there is an additional neutral current interaction with neutrinos of the form

$$H_\nu = \frac{iG}{\sqrt{2}} \left[\bar{\psi}_{\nu_e} \gamma_\lambda (1 + \gamma_5) \, \psi_{\nu_e} + \bar{\psi}_{\nu_\mu} \gamma_\lambda (1 + \gamma_5) \, \psi_{\nu_\mu} \right] \mathscr{J}_\lambda^{(0)}$$

giving rise to neutrino scattering processes. According to Weinberg, the isospin structure of the neutral hadronic current is

$$\mathscr{J}_\lambda^{(0)} = \mathscr{J}_\lambda^{V_3} - 2 \sin^2 \theta_W \, J_\lambda^\gamma = J_\lambda^{V_3} + J_{\lambda_5}^{V_3} - 2 \sin^2 \theta_W \, (J_\lambda^S + J_\lambda^{V_3}) \, .$$

Weinberg points out that in principle the matrix elements of $\mathscr{J}_\lambda^{V_3}$ can be obtained from the corresponding charge-changing processes using isospin invariance, and the matrix elements of J_λ^γ can be obtained directly from electron scattering. Thus one can, in principle, make predictions for the neutral processes which are independent of the strong interactions structure of the target.

The effective Hamiltonian for the neutral weak interactions of leptons with nucleons may be taken over directly to nuclear processes, using the general analysis of charge-changing semi-leptonic weak interactions in nuclei, which has recently been carried out in close analogy with the analysis of electron scattering from nuclei[5)]. A multipole analysis is made of the weak nuclear current, and the selection rules on the multipoles, as well as their long wavelength reductions, are given. Expressions are derived for the rates for general β-decay and μ-capture processes and for cross sections for neutrino and anti-neutrino reactions. A prescription is also given for constructing the nuclear many-body current operators in terms of measured single-nucleon matrix elements.

If we are interested in low-energy nuclear processes initiated by the $\bar{\nu}_e$ obtained from a nuclear reactor, we require only the long wavelength limit of the neutrino cross section. The only independent non-vanishing multipoles remaining in the limit $qR \to 0$ are $\hat{\mathcal{M}}_0$ and $\hat{\mathcal{L}}_1$. For allowed Fermi transitions corresponding to the selection rules $|\Delta\vec{J}|=0$, $\Delta\pi=$no:

$$\hat{\mathcal{M}}_0^{(0)} = \frac{1}{\sqrt{4\pi}} \int d\vec{x}\, \hat{J}_0^{(0)}(\vec{x}) = \hat{T}_3 - 2\,\hat{Q}\,\sin^2\theta_W .$$

This operator is diagonal in the nuclear Hilbert space and cannot cause nuclear transitions. For allowed Gamow-Teller (G-T) transitions with $|\Delta\vec{J}| = 1, \Delta\pi =$ no, the longitudinal multipole is independent of the Weinberg mixing angle θ_W and has the form:

$$\hat{\mathcal{L}}_{1M}^{(0)} = \frac{i}{\sqrt{12\pi}} \int d\vec{x}\, \hat{J}_5\, (\vec{x})_{1M}^{V_3} .$$

If β-decay rates between the analog states are known, then isospin invariance and the Wigner-Eckart theorem directly give us the necessary matrix elements of this operator.

As examples,[6] consider the β-decay transition $^6He(0^+1) \to {}^6Li(1^+0)$ and the electron capture transition $^7Be\ (\frac{3}{2}^-\frac{1}{2}) \to {}^7Li^*\ (\frac{1}{2}^-\frac{1}{2},\ 0.478\ \text{MeV})$. The corresponding inelastic neutrino scatterings involve the allowed G-T transitions $^6Li(1^+0) \to {}^6Li^*\ (0^+1,\ 3.562\ \text{MeV})$ and $^7Li(\frac{3}{2}^-\frac{1}{2}) \to {}^7Li^*(\frac{1}{2}^-\frac{1}{2},\ 0.478\ \text{MeV})$. These transitions satisfy two important criteria: (1) they have large matrix elements and (2) they involve light nuclei, so that the total cross section <u>per nucleon</u> is large. In contrast, in heavy nuclei the cross section per nucleon is smaller, since only valence nucleons contribute to spin-flip transitions. The solid curves in Figure 1 show the inelastic neutrino cross sections for these nuclei. The anti-neutrino spectrum at the Savannah River Plant reactor[7] is also indicated. The dashed curves show the inelastic neutrino scattering cross sections weighted by the $\bar{\nu}_e$ spectrum. When integrated over the spectrum, these yield total cross sections of 5.2×10^{-46} cm^2/nucleon/$\bar{\nu}_e$ for ^{6}Li and 3.3×10^{-45} cm^2/nucleon/$\bar{\nu}_e$ for ^{7}Li.

Another interesting case (see below) involves the transition $^{19}F\ (\frac{1}{2}^+\frac{1}{2}) \rightarrow {}^{19}F^*\ (\frac{3}{2}^+\frac{1}{2},\ 1.554\ \text{MeV})$. The total cross section integrated over the $\bar{\nu}_e$ spectrum is 6.3×10^{-44} B cm^2/nucleon/$\bar{\nu}_e$ where B is the branching ratio for the β-decay of the $\frac{1}{2}^+\frac{1}{2}$ ground state of ^{19}Ne to the $\frac{3}{2}^+\frac{1}{2}$ excited state of ^{19}F. Only the ground state to ground state β-decay rate has been measured and so we must use a nuclear model to estimate the branching ratio. In particular we use the single-particle Nilsson model with a $K=\frac{1}{2}$ band[9] and four adjustable parameters (the three intrinsic matrix elements and g_R) to fit the $\frac{1}{2}^+$ and $\frac{5}{2}^+$ (0.197 MeV) magnetic moments of ^{19}F, the $\frac{3}{2}^+ \rightarrow \frac{1}{2}^+$ M1 γ-decay rate in ^{19}F and the $^{19}Ne\ (\frac{1}{2}^+\frac{1}{2}) \rightarrow {}^{19}F\ (\frac{1}{2}^+\frac{1}{2})$ β-decay rate. The $\frac{1}{2}^+, \frac{5}{2}^+, \frac{3}{2}^+$ energy spectrum of ^{19}F, the $\frac{3}{2}^+ \rightarrow \frac{5}{2}^+$ M1 γ-decay rate in ^{19}F and the $\frac{1}{2}^+$ magnetic moment of ^{19}Ne which are then predicted are in good agreement with experiment. This model then yields a branching ratio B = 0.010 ± 0.009% for the β-decay to the excited state of ^{19}F. It should be emphasized the once the β-decay branching ratio is measured, the $\bar{\nu}_e$ cross section is model-independent to the extent of the isospin purity of the levels involved and that only then will the prediction of the neutrino scattering cross section be free from nuclear uncertainties.

Detection of neutrino excitation of nuclear levels entails the observation of a very weak γ-ray signal associated with the operation of a nuclear reactor or accelerator. The excitation of the .478 MeV level of ^{7}Li appears to be a favorable case because of the large matrix element and low mass and the large natural abundance of ^{7}Li. With a reactor of the Savannah River type (2×10^{13} $\bar{\nu}_e/cm^2$/sec), this reaction would produce 4 γ's/day/kg ^{7}Li.

Note that since mass absorption coefficients at these energies are approximately equal for all elements, the counting rate per kg of γ detector will be lower than the event rate per kg of target. The problem, then, is to distinguish neutrino induced γ's from background. It appears possible to shield the apparatus adequately from reactor associated neutrons and γ's. The dominant source of background would be residual radioactivity in the target or the photon detector themselves, and in the surrounding shielding, as well as cosmic ray induced events. In a search for neutrinoless double-beta decay, Fiorini, et.al.[10)] observed 2.4 counts/day/2 KeV at .478 MeV in a well-shielded 25 cm^3 Ge(Li) detector. If ten such detectors were surrounded by several γ absorption lengths of ^7Li, they would count 1.2 $\bar{\nu}_e$ events/day. This implies a signal/noise ratio of 1/20 assuming 2 keV resolution. The use of ^6Li as a target would result in substantially lower counting rates, but improved signal/noise, as the background falls steeply with energy.

To avoid the background problems associated with single γ experiments one would like to find a neutral current reaction which allows one to use a delayed coincidence technique. Munsee and Reines[11)] have done this in a search for the reaction $\bar{\nu}_e + d \rightarrow n + p + \bar{\nu}_e$, where the neutron provides a delayed coincidence γ-ray after capture in Gd-loaded liquid scintillator. Another possibility is excitation of the 2.43 MeV $(\frac{5}{2}^- \frac{1}{2})$ state in ^9Be, which decays by neutron emission to ^8Be, which then decays to two α's. The excitation of the $\frac{3}{2}^+$, 1.554 MeV state in ^{19}F is an interesting case[12)], since this level decays 93% of the time to the $\frac{5}{2}^+$ level at .197 MeV, which in turn decays to the ground state with a half-life of 87 nsec. The counting rate for this reaction is about a factor of 600 less than for ^7Li, but by making use of the delayed coincidence, signal/noise can be greatly improved.

The advantages of this approach are best discussed with respect to a specific experimental arrangement. Consider a large hexagonal array of 300 cylinders of a scintillator[13] such as $BaF_2(Eu)$, each 5 cm in diameter and 50 cm long, weighing a total of 1400 kg. Should a neutrino excitation of ^{19}F occur in a particular cylinder, the .197 MeV γ-ray would likely be detected in that cylinder, while the 1.36 MeV γ-ray would be detected in one of the six cylinders surrounding the "source" cylinder, in delayed coincidence. With 30% overall detection efficiency, this array would produce .7 coincidence events/day. If the $BaF_2(Eu)$ has the same background singles rate as does $NaI(T\ell)$, the accidental coincidence rate would produce a signal/noise ratio of 1:1.

In order to compute the neutrino excitation cross section at accelerator energies, that is at higher values of qR, we need the nuclear densities from which we can compute all the contributing multipole matrix elements and corresponding cross sections and rates. These higher energy regions are of more interest for experiments possible at LAMPF[14], where the neutrinos have energies up to 53 MeV. Although at full intensity the neutrino flux will be 10^{-5} of that near a large reactor, the increased energy partially compensates for this loss of flux. Note that for low energy muon neutrinos the neutral current reactions are the only way they can interact. The general form of the single nucleon matrix elements needed to construct the nuclear currents as well as the remaining necessary theoretical analysis is presented in detail in Ref. 5. When qR is not small it is important to carry out a unified analysis of semi-leptonic weak and electromagnetic interactions in nuclei. There we find that electron scattering data at all q^2 provides a test of nuclear wave functions, allowing us to have some confidence in predictions for new processes and serving in many cases to eliminate nuclear physics uncertainties in examining the basic structure of the weak interaction itself. Indeed, if sufficiently accurate electron scattering data is available, it is frequently possible to use inelastic electron scattering to determine the one-body density matrix for the nuclear transition and then to use this to calculate the weak processes in an essentially model-independent fashion. In a series of recent papers[15], these ideas have been developed and applied to several specific cases. Here we extend these calculations to include the inelastic neutrino cross sections. In Fig. 2 we give these cross sections for neutral current excitation by ν and $\overline{\nu}$ (either electron or muon neutrinos and anti-neutrinos) of the 0^+1, 3.562 MeV excited state in ^6Li and the 1^+1, 15.11 MeV excited state in ^{12}C. These curves are shown for two values of the Weinberg angle, 0^o and 35^o. At very low energies where $qR << 1$ only the axial vector dipole operator contributes significantly and, as a consequence, the ν and $\overline{\nu}$ cross sections are equal and are independent of the Weinberg angle. The other extreme of very high energies appropriate to NAL and CERN is indicated by arrows on the right hand edge of Fig. 2. There the cross sections are peaked towards forward angles and again the interference term which yields the ν-$\overline{\nu}$ difference goes to zero. However, in the intermediate energy region shown in Fig. 2 the cross sections differ considerably for ν and $\overline{\nu}$ and are sensitive to the value of the Weinberg angle. The ^{12}C reaction is particularly interesting, in that it seems to be free of neutron or cosmic-ray induced background. An array of 10 5"x5" NaI(Tℓ) detectors, each surrounded by several γ absorption lengths of liquid scintillator, would have a counting rate of 1 per day, assuming a flux of $10^8\ \nu/cm^2/sec$ of each type at LAMPF. Here one gains a factor of two in counting rate because of the higher mass absorption coefficient of NaI(Tℓ) at 15 MeV.

In conclusion, if neutral weak currents in fact exist, it should be possible to detect γ-rays from nuclear excitation caused by neutrinos with either reactor neutrinos or those from an accelerator such as LAMPF. By making use of nuclear selection rules, one can isolate particular spin and isospin components of the neutral weak current for detailed examination, as in the allowed Gamow-Teller transitions discussed above. As examples of experimental possibilities, counting rates and signal/noise ratios of typical experiments to detect neutral current excitation in ^{6}Li, ^{12}C and ^{19}F have been described. Such investigations are of considerable interest, in that they represent experimental conditions of a totally different nature than those which search for muon-less ν_μ induced events at high energy accelerators, and in that they allow determination of the weak neutral current coupling constant independent of the Weinberg angle at reactor energies, but are sensitive to the Weinberg angle at intermediate energies.

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References and Footnotes

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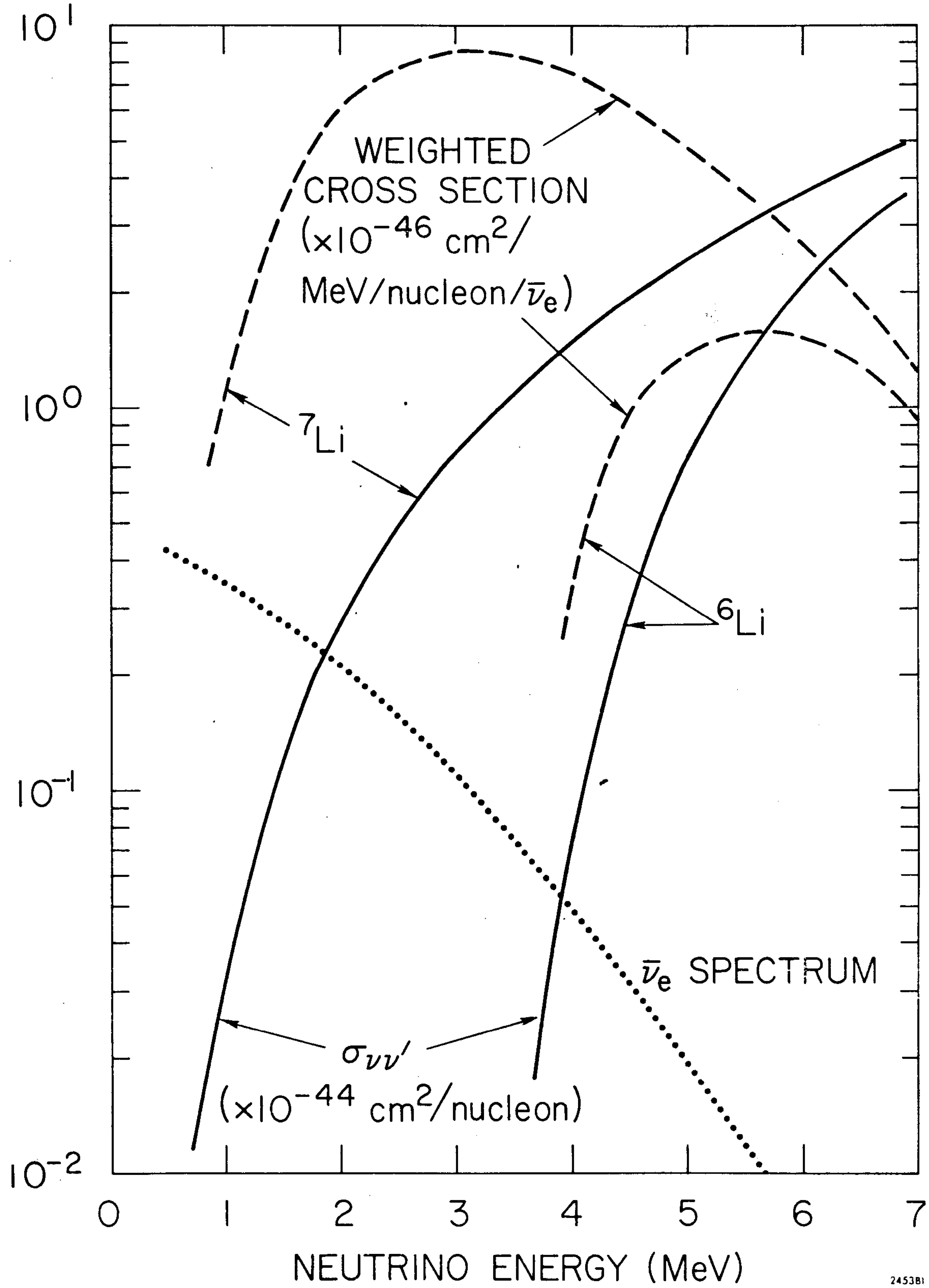
Figure Captions

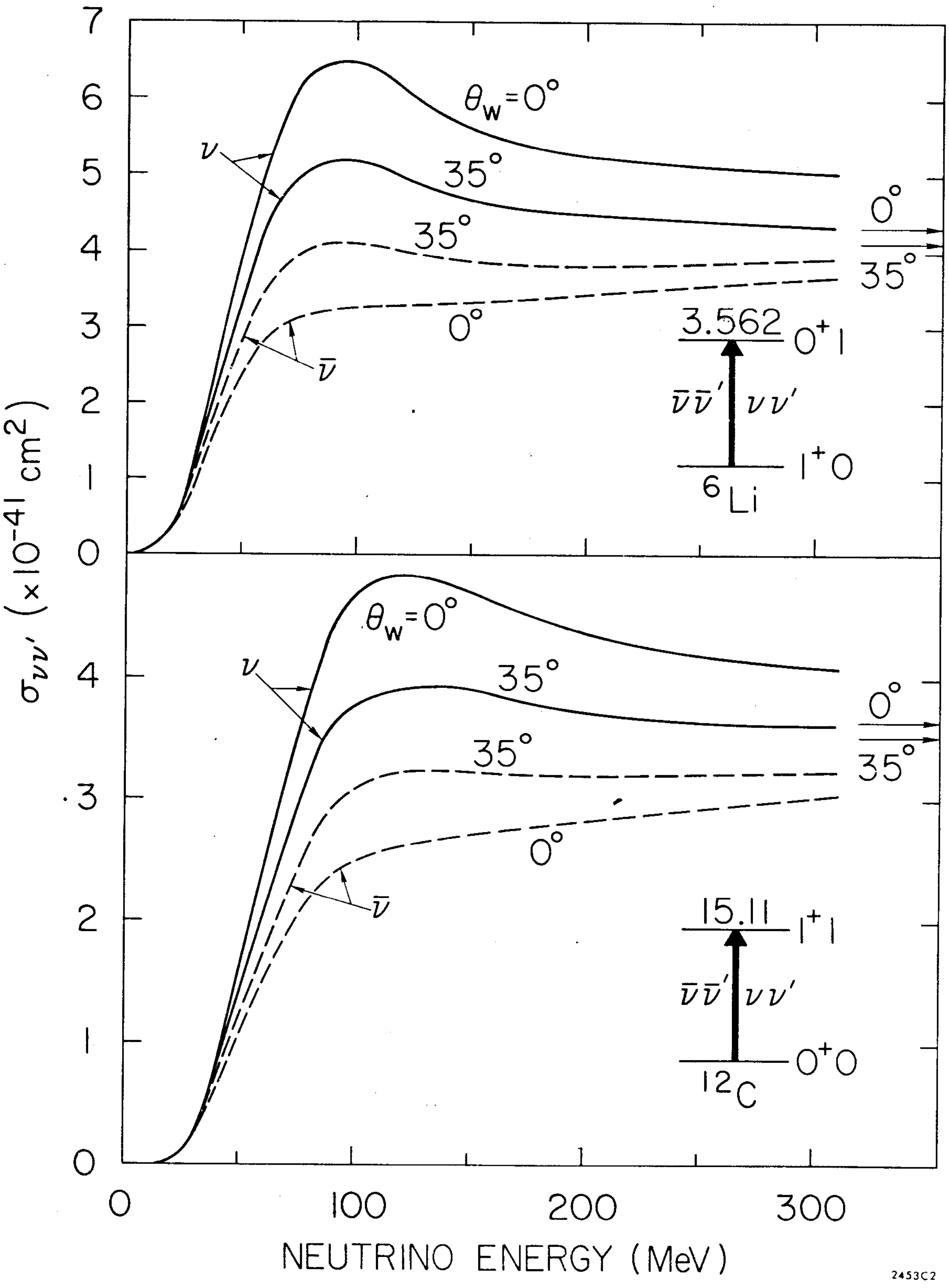
1. The inelastic neutrino scattering cross sections for excitation of the 0^+1(3.562 MeV) state in ^{6}Li and the $\frac{1}{2}^-\frac{1}{2}$ (0.478 MeV) state in ^{7}Li are shown as solid curves. The $\bar{\nu}_e$ spectrum from Ref. 6 normalized to unity when integrated over all neutrino energies is shown as a dotted curve. The total effective cross sections per unit energy obtained by folding the $\bar{\nu}_e$ spectrum with the solid curves are shown as dashed curves.

2. Inelastic neutrino scattering cross sections for excitation of the 0^+1 (3.562 MeV) state in ^{6}Li and the 1^+1 (15.11 MeV) state in ^{12}C. The solid curves are for neutrinos and the dashed curves for anti-neutrinos. The cross sections are shown for two values of the Weinberg angle, $\theta_W = 0^\circ$ and 35°. The asymptotic cross sections are indicated by arrows at the right-hand edge of the figure.



WEIGHTED CROSS SECTION
($\times 10^{-46}$ cm^2/ MeV/nucleon/$\bar{\nu}_e$)
^{7}Li
^{6}Li
$\bar{\nu}_e$ SPECTRUM
$\sigma_{\nu\nu'}$
($\times 10^{-44}$ cm^2/nucleon)
10^1
10^0
10^{-1}
10^{-2}
0
1
2
3
4
5
6
7
NEUTRINO ENERGY (MeV)
2453B1

Fig. 1



7
6
5
4
3
2
1
0
$\theta_W = 0°$
35°
35°
0°
ν
$\bar{\nu}$
0°
35°
3.562
$0^+ 1$
$\bar{\nu}\bar{\nu}'$
$\nu\nu'$
$1^+ 0$
^{6}Li
$\sigma_{\nu\nu'}$ $(\times 10^{-41}\ \mathrm{cm}^2)$
4
3
2
1
0
$\theta_W = 0°$
35°
35°
0°
ν
$\bar{\nu}$
0°
35°
15.11
$1^+ 1$
$\bar{\nu}\bar{\nu}'$
$\nu\nu'$
$0^+ 0$
^{12}C
0
100
200
300
NEUTRINO ENERGY (MeV)
2453C2

Fig. 2