I INTRODUCTION

The neutralino is one of the most promising dark matter candidates [1]. It could be detected indirectly by observation of energetic neutrinos from neutralino annihilation in the Sun and/or Earth. Energetic neutrinos are produced by decays of neutralino annihilation products. These neutrinos can be detected by neutrino detectors such as AMANDA and super-Kamiokande [2], which observe the upward muons produced by the charged-current interactions in the rock below the detector. For the models which can be tested by the current or next generation of detectors, an equilibrium of accumulation and annihilation is reached, so the annihilation rate is determined by the capture rate in the Sun or Earth. The event rate is proportional to the second moment of the neutrino energy spectrum, so it is this neutrino energy moment weighted by the corresponding branching ratio that determines the detection rate.

By now, the cross sections for annihilation have been calculated for all two-body final states that arise at tree level. Roughly speaking, among the two-body channels the $b\bar{b}$ and $\tau^+\tau^-$ final states usually dominate for $m_\chi < m_W$. Neutralinos that are mostly higgsino annihilate primarily to gauge bosons if $m_\chi > m_W$, because there is no s-wave suppression mechanism for this channel. Neutralinos that are mostly gaugino continue to annihilate primarily to $b\bar{b}$ pairs until the neutralino mass exceeds the top-quark mass, after which the $t\bar{t}$ final state dominates, as the cross section for annihilation to fermions is proportional to the square of the fermion mass.

Three-body final states arise only at higher order in perturbation theory and are therefore usually negligible. However, some two-body channels easily dominate the cross section when they are open because of their large couplings; for example the $W^+W^-$ for the higgsinos and $t\bar{t}$ for gauginos. This suggests that their corresponding three-body final states can be important just below these thresholds. Moreover, the neutrinos produced in these three-body final states are generally much more energetic than those produced in $b$ and $\tau$ decays. Recently, we calculated the s-wave
Below the top pair threshold, the neutralino may annihilate via a virtual top quark: $\chi\chi \to tt^* \to tWb$. The Feynman diagrams for this process are shown in Fig. 1. Like annihilation to $t\bar{t}$ pairs, annihilation to this three-body final state takes place via $s$-channel exchange of $Z^0$ and $A^0$ (pseudo-scalar Higgs bosons) and $t$- and $u$-channel exchange of squarks. Although there are additional diagrams for this process, such as those shown in Fig. 2, these are negligible for the gaugino because of the small coupling. On the other hand, for higgsinos the gauge boson channel dominates and the $tt^*$ would be unimportant anyway. In the $v_{rel} \to 0$ limit

$$\sigma_{v_{rel}} = \frac{N_c}{128\pi^3} \int_{x_{4min}}^{x_{4max}} dx_4 \int_{x_{6min}}^{x_{6max}} dx_6 \frac{1}{4}|M|^2,$$

the amplitude is given by $M = M_t - M_u + M_s$.

The three-body cross section for a series of typical models are shown in Fig. 3. In these models the neutralino is primarily gaugino. As expected, the three-body cross section approaches the two-body value above the top threshold (we take $m_t = 180 \text{ GeV}$). Below the top mass it is non-zero but drops quickly. The flux of upward muons is proportional to the second moment of the neutrino energy spectrum weighted by branching ratios, which is given by

$$B_F \left\langle N z^2 \right\rangle = \frac{3}{128\pi^3} \int dx_4 dx_6 |M|^2 \left( \left\langle N z^2 \right\rangle_t x_4^2 + \left\langle N z^2 \right\rangle_W x_5^2 + \left\langle N z^2 \right\rangle_b x_6^2 \right),$$

in the three-body case. Although the three-body cross section is small except just below the $tt$ threshold, its contribution to the the second moment, $B_F \left\langle N z^2 \right\rangle$, may be important, as illustrated in Fig. 4. This is because the $\left\langle N z^2 \right\rangle$ for top quarks and $W$ bosons is significantly larger than that for the light fermions.

Below the $W^+W^-$ threshold, the neutralino can annihilate to a real $W$ and a virtual $W$. The $W$-bosons then decay independently into a fermion pair $ff'$, which
can be $\tau \nu$, $\mu \nu$, $e \nu$, $cs$, or $ud$. About 10% of these decay into a muon (or anti-muon) and a muon anti-neutrino (or neutrino).

The $WW^*$ calculation is similar to the $tWb$ calculation. In the $v \to 0$ limit, only chargino exchange in the $t$ and $u$ channels shown in Fig. 5 are important. Neutrinos can be produced either by the virtual $W^*$ or by decay of the real $W$. The neutrinos produced by decay of the muon or other fermions can be neglected, and the real $W$ boson has a probability $\Gamma_{W-\mu \nu}$ to decay to a muon neutrino. On the other hand this $W$ boson is produced in all $\chi \chi \to Wf\bar{f}'$ channels, and each of these channels has approximately the same cross section, so the contribution has a weight of $n_{\text{chan}} \Gamma_{W-\mu \nu} \approx 1$. The cross section and second moment for annihilation in the Earth are shown in Fig. 6 and Fig. 7. Below $m_W/2$, the four-body channel might become significant, and may smooth the jump in much the same fashion as the three-body channel does near the two-body channel threshold, but we will not consider it here.

### III CONCLUSIONS

The contributions of these three-body channels are important only in a limited region of parameter space. However, they may produce a large effect. In fact, our calculation shows that although the cross sections of these annihilations are significant only just below the two-body channel threshold, due to the high energy of the neutrinos they produce, they can enhance the neutrino signal by many times and actually dominate the neutrino signal far below the two-body threshold. Furthermore, the regions in question may be of particular interest. For example, motivated by collider data, Kane and Wells proposed a light higgsino [5], and recent DAMA results [6] suggest a WIMP candidate with $m_x \approx 60$ GeV (but see [7]). There are also arguments that the neutralino should be primarily gaugino with a mass

![FIGURE 3. total annihilation cross section.](image1)

![FIGURE 4. Detection Rate for neutrinos from the core of Earth. Dashed curves show two-body only result, solid curves includes three-body contribution.](image2)
somewhere below but near the top-quark mass [8].

There are many parameters in the minimal supersymmetric model. The results shown in Figs. 4 and 7 are of course model dependent, and these effects might be more or less important in models with different parameters.

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REFERENCES

2. For a review, see, e.g. the talks of L. Roszkowski and L. Bergstrom in this volume.