01 Oct 1990

Angular Distribution of Auger Electrons Emitted through the Resonant Transfer and Excitation Process Following O^{5+}+He Collisions

Malika Benhenni

Stephen M. Shafroth

J. K. Swenson

Michael Schulz
Missouri University of Science and Technology, schulz@mst.edu

et. al. For a complete list of authors, see https://scholarsmine.mst.edu/phys_facwork/1318

Recommended Citation

M. Benhenni et al., "Angular Distribution of Auger Electrons Emitted through the Resonant Transfer and Excitation Process Following O^{5+}+He Collisions," *Physical Review Letters*, vol. 65, no. 15, pp. 1849-1852, American Physical Society (APS), Oct 1990.
The definitive version is available at https://doi.org/10.1103/PhysRevLett.65.1849

Angular Distribution of Auger Electrons Emitted through the Resonant Transfer and Excitation Process following O^{5+} + He Collisions

M. Benhenni,[(1)] S. M. Shafroth,[(1)] J. K. Swenson,[(2),(a)] M. Schulz,[(2),(b)] J. P. Giese,[(2),(b)] H. Schöne,[(2)] C. R. Vane,[(2)] P. F. Dittner,[(2)] and S. Datz[(2)]

[(1)]*Department of Physics and Astronomy, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina 27599-3255*

[(2)]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831*

(Received 1 May 1990)

This Letter reports the first measurements of the angular distribution of Auger electrons emitted from the decay of the $(1s2s2p^2)^3D$ O^{4+**} doubly excited state formed predominantly through resonant transfer and excitation (RTE) in collisions of 13-MeV O^{5+} projectiles with He. The $(1s2s2p^2)^3D$ angular distribution is strongly peaked along the beam direction in agreement with recent calculations of the RTE angular-dependent impulse approximation. Furthermore, interference effects between the RTE and the elastic target direct-ionization channels are observed.

PACS numbers: 34.70.+e

High-resolution projectile-electron spectroscopy has become an increasingly attractive tool for studies of ion-atom collision processes.[1] These studies have usually been performed at zero degrees because the kinematic broadenings are minimal.[1] However, information concerning the magnetic substate populations cannot be obtained from such measurements alone. In order to obtain this information, one has to perform angular distribution measurements.[2] Such studies are important in ion-atom collision physics because they give a more complete picture of the collision mechanism and the distortion of the electron cloud in the field of the target. Measurements of electron spectra at various ejection angles are also necessary in order to obtain total cross sections for the different excitation processes. Finally, angular distribution measurements can give important information on the interference effects between processes giving rise to the same final state.[3-6] Such angular distribution measurements have not previously been possible due to the severity of the kinematic or Doppler broadening at high projectile energies. The recent development of a kinematic "refocusing" parallel-plate electron spectrometer[7] has made these measurements possible.

Processes such as transfer and excitation (TE) have been shown to proceed via different mechanisms. One such mechanism, resonant TE (RTE), is a correlated two-electron process where the projectile electron is excited by an interaction with the captured target electron. In a second TE process, nonresonant transfer and excitation (NTE), the doubly excited states are populated by two uncorrelated processes where the projectile-electron excitation is induced by the target nucleus, independently of the target-electron capture. For a Li-like projectile $P^{(Z-3)+}$ incident on a target T, the TE process can be represented, assuming single ionization of the target, as follows:

$$P^{(Z-3)+}(1s^2 2s)+T \rightarrow P^{(Z-4)+**}(1s2s2p^2)+T^+ \rightarrow P^{(Z-3)+}(1s^2 2s)+e+T^+ \quad \text{(TE)}.$$

$$\downarrow \text{-----------} \xrightarrow[\text{(direct ionization)}]{} \text{-----------} \uparrow$$

Furthermore, electrons emitted via the direct ionization of the target, known as the binary-encounter (BE) electrons,[8] contribute a broad background whose centroid coincides with the energy of Auger electrons formed through RTE when the resonance condition $E_{\text{Auger}} = (m_e/M_{\text{ion}})E_{\text{beam}} - E_{\text{binding}}$ is met. This alternate channel is shown as the dashed line in the above expression for TE. Therefore, the electrons emitted through the RTE, NTE, and the BE channels might show interference effects. For Li-like ions, the $(1s2s2p^2)^3D$ state formed through the transfer and excitation processes RTE and NTE might show such interference effects. This has already been observed at 0° in such collisions,[9,10] where the Auger line shape showed a pronounced "Fano" profile.[11] When such interference occurs, angular distribution studies are important in order to extract the resonance cross section from the coherently summed emission amplitudes of the different interfering channels.

Both RTE and NTE have been studied intensively in the last decade[3-6,9,10,12-23] in the x-ray as well as in the Auger decay channel. In these experiments, good agreement with theory was found in the resonance energy and the shape of the total cross sections versus projectile energy, which served to validate the impulse approximation model for RTE. However, in absolute magnitude, various discrepancies between the theoretical and experimental total cross sections of TE were found, especially in the Auger decay channel. In these earlier measurements of TE, Auger electrons or x rays were detected at a fixed emission angle and an isotropic angular distribution was assumed in order to compare the measured RTE

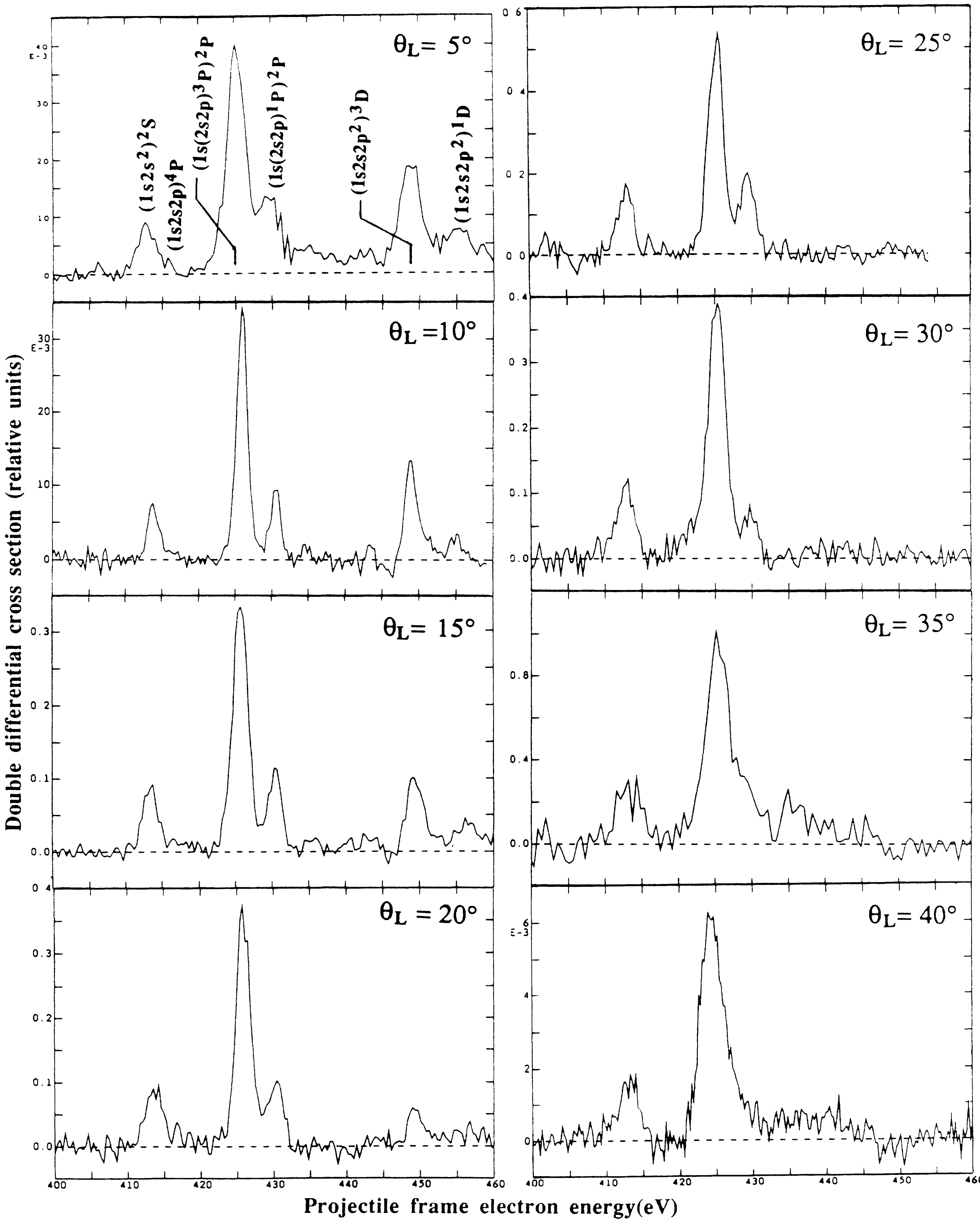

FIG. 1. Electron spectra in the projectile frame at 5°, 10°, 15°, 20°, 25°, 30°, 35°, and 40° laboratory angle θ_L for $O^{5+}+He$ collisions at 13-MeV projectile energy.

differential cross sections with the calculated total cross sections since theoretical cross sections differential in angle were not available.

This Letter gives the first evidence for a strong anisotropy of the angular distribution of Auger electrons emitted in the decay of the states $(1s2s2p^2)\,^3D$ populated via RTE. We observe a differential cross section strongly peaked along the beam direction which indicates a nonstatistical magnetic substate population. We also observe an angular-dependent Fano line shape for this state, indicating interferences between the Auger and binary-encounter electrons. These results are in good agreement with recent calculations by Bhalla[3] for the angular-dependent impulse-approximation model for RTE. Our data allow a more direct comparison of the measured cross section with the theory and help improve the agreement between theory and experiment.

The experiment was performed at the Oak Ridge National Laboratory EN tandem Van de Graaff accelerator. After collimation, the Li-like O^{5+} ions passed through a differentially pumped gas cell and finally were collected and integrated in a suppressed Faraday cup. The gas cell consists of two concentric slotted cylinders containing helium in the inner one of 25-mm diameter. Linearity of electron yield versus target gas pressure ensured single-collision conditions at 10-mTorr He gas pressure. Electrons emitted following 13-MeV $O^{5+}+\mathrm{He}$ collisions were detected with a high-resolution projectile-electron spectrometer[7] at angles ranging from 5° to 40° in the laboratory frame (corresponding to 10° to 80° in the projectile frame) in steps of 5°. The length of the target viewing region varied from 25 mm at 5° to 0.8 mm at 40°. The emitted electrons exit the gas cell through radial slots and were decelerated typically to one-fourth of their initial laboratory energy to enhance their energy resolution. They were then energy analyzed by a two-stage refocusing 30° parallel-plate analyzer and detected by an $8\times50\text{-mm}^2$ microchannel plate equipped with a resistive anode encoder at a position proportional to their energy. The Doppler-broadening effects caused by the variation of the observation angle, $\Delta\theta_L=\pm0.4°$, permitted by the spectrometer entrance slit width become more severe as the observation angle increases. They are eliminated to first order through refocusing of the projectile electrons on the detector which is remotely positioned along the shifted focal line. Details concerning the spectrometer and the refocusing technique have been reported previously.[7]

Figure 1 displays the different Auger electron spectra for laboratory observation angles ranging from 5° to 40°, obtained following 13-MeV O^{5+} on He collisions after relative efficiency correction, background subtraction, and kinematic transformation to the projectile frame. The state of interest $(1s2s2p^2)\,^3D$ at 449 eV, formed through RTE,[10] is clearly seen at 5°, 10°, 15°, 20°, and 25° and is almost not discernible at 30°, 35°, and 40°. The $(1s2s2p^2)\,^1D$ state at 454 eV, also populated via RTE,[10] is well resolved from the ^3D state. However, the ^1D cross section was too small to get good statistics, but it is clear from Fig. 1 that the ^1D ground-state-decay angular distribution is also forward peaked. An asymmetric Fano line shape[11] due to the interference of the RTE Auger (RTEA) process with the binary-encounter channel is observed for the ^3D state (Fig. 1). Moreover, Fig. 1 shows that the ^3D line shape varies from a weakly asymmetric peak in the forward direction to a "dip" at larger emission angles. This is in good agreement with recent calculations by Bhalla.[3] The remaining lines observed in the spectra are Li-like transitions which are formed through various excitation mechanisms.[24] Of these lines, the $(1s2s^2)\,^2S\rightarrow(1s^2)\,^1S$ transition at 412 eV, clearly discernible at each angle, is used to normalize the measured electron intensity at each observation angle, since this line decays isotropically. Thus, it is possible to eliminate the solid-angle, target-density, and beam-current-integration uncertainties in the ^3D differential-cross-section data by studying the ratio $[d\sigma/d\Omega(^3D)]/[d\sigma/d\Omega(^2S)]$ as a function of observation angle, where $d\sigma/d\Omega(^3D)$ and $d\sigma/d\Omega(^2S)$ are the respective Auger ground-state-decay differential cross sections of the ^3D and ^2S excited states. The nearest state to the ^2S is the metastable state $(1s2s2p^2)\,^4P$ at 416 eV, which mostly decays outside the gas cell at 13-MeV projectile energy and therefore does not contribute significantly to the spectra.

In Fig. 2, the ratio $[d\sigma/d\Omega(^3D)]/[d\sigma/d\Omega(^2S)]$ is plotted as circles versus laboratory angle, obtained from the spectra in Fig. 1. The represented error bars in the data are due to background subtraction and counting statistics. The solid line represented in Fig. 2 is the recent calculation by Bhalla[25] for our collision system $O^{5+}+\mathrm{He}$ obtained by use of the RTEA angular-

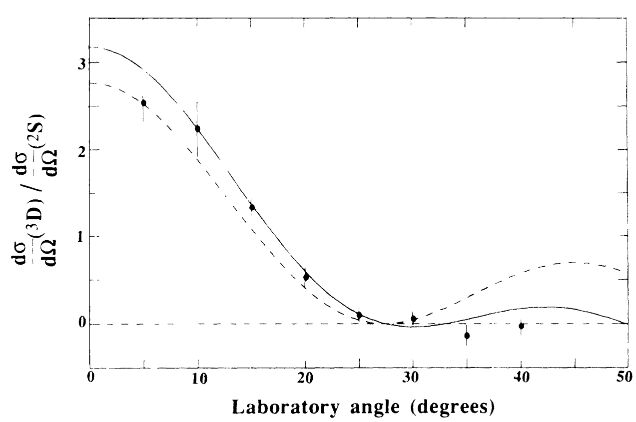

FIG. 2. The circles are the experimental ratios $(d\sigma/d\Omega)(^3D)/(d\sigma/d\Omega)(^2S)$ vs laboratory angle for 13-MeV projectile O^{5+} on He. The solid line represents Bhalla's theory (Ref. 25) as given by Eq. (1), normalized to experiment at $\theta_L=10°$. The dashed line is the resonance contribution $C_R(E_R,\theta_L)$ to the RTEA differential cross section, excluding the interference between RTEA and BE.

dependent impulse approximation[3] and given by

$$\left[\frac{d\sigma}{d\Omega}(^3D)\right]_{\mathrm{RTEA}}=C_R(E_R,\theta_L)+C_I(E_R,\theta_L)\,, \qquad (1)$$

where $[d\sigma/d\Omega(^3D)]_{\mathrm{RTEA}}$ is the difference between the total differential cross section for electron emission and the binary-encounter differential cross section. The term C_R represents the contribution of the Auger angular distribution of the RTEA resonance and C_I is the contribution from the interference between RTEA and the elastic binary-encounter channel. E_R and θ_L are the resonance energy and the laboratory emission angle, respectively. The dashed curve in Fig. 2 is a plot of the resonance term C_R alone, which corresponds to a pure spherical harmonic $|Y_{20}|^2$. Thus the observed anisotropy of the RTEA angular distribution results from the fact that the ^3D state is exclusively populated with the magnetic substate $m_l=0$. This is expected since in RTE, the exchange of angular momentum takes place solely between two electrons and the transferred target electron carries no net angular momentum into the collision. Since we measured a ratio of cross sections, the theory has been scaled by a factor of 0.56 to normalize the theory to the data at 10°. By comparing the solid and the dashed curves, relatively small constructive interference between RTEA and the elastic binary-encounter channels is indicated in the forward direction, while strong destructive interference occurs when θ_L is greater than 25°.

Earlier measurements of RTEA performed at 0° emission angle show that the total RTEA cross section for the system $O^{5+}+\mathrm{He}$, after very careful spectrometer efficiency determination[26] and assuming isotropy of the angular distribution, is larger by a factor of 3.5 than theory.[27] After correction for measured anisotropy of the RTEA angular distribution, the total cross section σ_t, given by $[4\pi/(2l+1)]d\sigma/d\Omega$ $(\theta_L=0°,m_l=0)$, becomes lower than theory by a factor of 0.7. Thus an improved agreement between experiment and theory is obtained when the measured angular distribution for the state in question is used.

In summary, we have measured the angular distribution of the $(1s2s2p^2)\,^3D$ Auger ground-state decay at the resonance energy for 13-MeV O^{5+} energy. The data show an angular distribution strongly peaked along the beam axis direction. Furthermore, at this resonance energy, the data show a small constructive interference between the RTEA and the elastic binary-encounter channels in the forward direction and strong destructive interference at laboratory angles greater than 25°. Our results are in good agreement with Bhalla's recent calculations of the RTEA angular-dependent impulse approximation.

The correction of earlier RTEA measurements for anisotropy in the angular distribution improves the agreement between the experiment and theory and gives a stringent test of the impulse approximation.[7]

Finally, it will be of interest to perform further angular distribution measurements at a collision energy where RTE and NTE have comparable amplitudes, since this may provide information on possible interferences between these two processes, and at a collision energy where NTE predominates.

The authors are grateful to C. P. Bhalla for communicating his calculations for our collision system, and to E. Merzbacher and T. Zouros for helpful discussions. Also, we are thankful to N. Jones and C. J. Gaither for experimental assistance. Finally we acknowledge support by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Chemical Sciences, under Contracts No. DE-AC05-840R21400 and No. DE-FG05-87ER40361 with Martin Marietta Energy Systems, Inc. and the University of North Carolina Research Council.

(a)Present address: L 421, Lawrence Livermore National Laboratory, Livermore, CA 94450.

(b)Present address: Department of Physics, Kansas State University, Manhattan, KS 66506.

1N. Stolterfoht, Phys. Rep. **146**, 315 (1987).

2B. Cleff and W. Mehlhorn, J. Phys. B **7**, 593 (1974); W. Mehlhorn, University of Aarhus lecture notes, 1978 (unpublished), p. 107.

3C. P. Bhalla, Phys. Rev. Lett. **64**, 1103 (1990).

4J. M. Feagin *et al.*, At. Mol. Phys. **117**, 1057 (1984); J. Phys. B **17**, 1057 (1984).

5T. Reeves, in *Electronic and Atomic Collisions,* Invited papers of the International Conference on the Physics of Electronic and Atomic Collisions, edited by H. B. Gilbody, W. R. Newell, F. H. Read, and A. C. H. Smith (North-Holland, Amsterdam, 1988), p. 685.

6W. Fritch and C. D. Lin, Phys. Rev. Lett. **61**, 690 (1988).

7J. K. Swenson, Nucl. Instrum. Methods Phys. Res., Sect. B **10/11**, 899 (1985).

8N. Stolterfoht *et al.*, Phys. Rev. Lett. **33**, 59 (1974).

9A. Itoh *et al.*, J. Phys. B **18**, 4581 (1985).

10J. K. Swenson *et al.*, Phys. Rev. Lett. **57**, 3042 (1986).

11U. Fano, Phys. Rev. **124**, 1866 (1961).

12D. Brandt, Phys. Rev. A **27**, 1314 (1983).

13D. Brandt, Nucl. Instrum. Methods Phys. Res. **214**, 93 (1983).

14J. A. Tanis *et al.*, Phys. Rev. A **31**, 4040 (1985).

15M. Clark *et al.*, Phys. Rev. Lett. **54**, 544 (1985).

16P. L. Pepmiller *et al.*, Phys. Rev. A **31**, 734 (1985).

17J. K. Swenson *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **24/25**, 184 (1987).

18J. M. Anthony *et al.*, J. Phys. (Paris), Colloq. **48**, C9-301 (1987).

19M. Schulz *et al.*, Phys. Rev. Lett. **58**, 1734 (1987).

20T. J. M. Zouros *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **40/41**, 17 (1989).

21T. J. M. Zouros *et al.*, Phys. Rev. A **40**, 6246 (1989).

22M. Schulz *et al.*, Phys. Rev. A **38**, 5454 (1988).

23M. Schulz *et al.*, Phys. Rev. Lett. **62**, 1738 (1989).

24N. Stolterfoht *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **24/25**, 168 (1987).

25C. P. Bhalla (private communication).

26D. H. Lee *et al.*, Phys. Rev. A **41**, 4816 (1989).

27T. J. M. Zouros *et al.*, Phys. Rev. A **42**, 678 (1990).