Angular Distributions of Protons from the $^{28}\text{Si}(\alpha,P)^{31}\text{P}$ Reaction

Allen

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ANGULAR DISTRIBUTIONS
OF PROTONS FROM THE
$^{28}\text{Si}(\alpha,p)^{31}\text{P}$ REACTION

by

Susan Mary Allen

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment
of the
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Susan Mary Allen
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INTRODUCTION

In stripping and pickup reactions the shapes of the angular distributions of the outgoing particles usually depend mainly on the orbital angular momenta transferred by the stripped or picked-up particles. However a J-dependence, that is, a strong dependence of the shape of an angular distribution on the total angular momentum of the final state, is observed in some ($\alpha$,\(\Lambda\)) reactions.¹ This suggests that it may be possible to use the shape of an angular distribution to determine the total angular momentum of the final state. There is some qualitative agreement with distorted-wave Born-approximation (DWBA) calculations to support this argument. But there has not been an extensive study to establish the range in atomic numbers, incident energy, and excitation energy for which J-dependence might be a reliable technique for extracting spectroscopic information.

In the present study angular distributions of protons from the \(^{28}\text{Si}(\alpha,\Lambda)^{31}\text{P}\) reaction were obtained for alpha particles with a laboratory energy of 14.5 MeV to determine if the reaction proceeds by a direct mechanism. If this turned out to be the case, the angular distributions could then be studied to determine if J-dependence were present. Only two states, the ground state and the first excited state, showed a clear stripping pattern and for the first excited state a DWBA computer program was used to try to fit the experimental angular distribution. The two states which showed clear stripping patterns were studied to determine if J-dependence occurs at this mass and energy.

¹
THEORY

The optical model has been quite successful in predicting certain experimental results such as total neutron cross sections. In this model the nucleus is represented by a one-body potential which acts upon the incident particle. The optical potential has real and imaginary parts. The real part represents the average potential in the nucleus required by the nuclear shell model. The imaginary part is necessary to produce absorption, which describes the formation of the compound nucleus. While the optical model accounts for the absorption of part of the incoming wave, it does not predict the details of the decay of compound nuclear states.

Several parameters are used in the optical model. The general form of the optical potential function, the Woods-Saxon potential, is

\[ U(r) = -V_f(r, \rho, \sigma) + i \left[ W + W_d \frac{d}{dr} \right] f(r, \sigma) + V_{so} \frac{d}{dr} f(r, \sigma) \bar{s} \cdot \bar{L} + V_c(r_c) \]

where \( V, W, V_{so}, \) and \( V_c \) are the well depths for the real, imaginary, spin-orbit, and Coulomb terms respectively. The parameter \( W_d \) is the depth of the imaginary surface potential. The parameters \( \rho, \sigma \) are for the real and imaginary wells as indicated by the subscripts \( r \) and \( i \). The parameters \( \rho \) and \( \rho_i \) determine the radius of the real and imaginary wells respectively. The parameters \( \sigma \) and \( \sigma_i \) are a measure of the surface region in which the potential decreases smoothly to zero. If the incident particle is charged, a Coulomb potential must be included. In the optical model potential \( r_c \) is the Coulomb charge radius. It is
necessary to include a spin-orbit potential in the optical model because large polarizations are observed for the nucleons. In addition to improving the fits to polarization data it also improves fits to differential cross sections for large angular momentum transfer. A Thomas-type spin-orbit term with strength as a variable parameter is included in the optical model. In order to change the shape of the Woods-Saxon potential, derivatives of the Woods-Saxon potential are added to obtain the total potential function. For example, the first derivative of the imaginary term accounts for absorption near the nuclear surface. The optical model has been very successful in reproducing the elastic scattering cross sections for protons from various targets for energies that are not near isolated levels in the compound nucleus.

Direct reactions, which involve only a few internal degrees of freedom in the colliding system, are characterized by angular distributions which peak in the forward direction and usually oscillate sharply with angle. Stripping and pick-up reactions are both examples of direct reactions. In stripping reactions one or more nucleons from the incident particle are transferred to the target nucleus. The reverse process occurs in a pick-up reaction. The shapes of the angular distributions of stripping and pick-up reactions are dependent on the orbital angular momentum of the transferred particle and perhaps the total angular momentum of the transferred particle.
DWBA theory has been used to analyze the angular distributions of particles resulting from direct reactions. To account for the elastic scattering and absorption in the entrance and exit channels, optical potentials are used. The interaction producing the stripping or pick-up is then introduced as a perturbation. It is assumed that in a stripping or pick-up reaction the particles go into or come from simple shell model orbits. In particular, for the \((a, p)\) reaction it is assumed that a triton is transferred to a single shell. It is generally assumed that the effect of the target nucleus on the transferred particle can be approximated by a simple real potential, perhaps including a spin-orbit term.

Hence in a DWBA calculation, optical model parameters for the incident particle, outgoing particle, and the transferred particle must be specified. Of course an assumption must be made about the shell involved in the transfer. In the computer program used in the present work, lower (lower cut-off radius) and upper limits for the numerical integration must be specified.
From DWBA calculations and rather general geometrical arguments, forward-angle J-dependence for ($\alpha$, nucleon) reaction cross sections is predicted. J-dependence means that the shape of the angular distributions, for the same value of the orbital angular momentum, $\lambda$, of the transferred particle, depends on the total angular momentum of the final state. Usually the angular distributions for the state $J=\lambda-\frac{1}{2}$ oscillate sharply with angle, while the angular distribution for the state $J=\lambda+\frac{1}{2}$ decreases smoothly as the angle increases. (See figure 1.) J-dependence is predicted by direct reaction theory and will be present only if the major reaction mechanism is direct rather than compound nuclear. The precise range of bombarding energies in which direct-reaction mechanisms are dominant has not been systematically determined.

The dependence of the shape of the angular distribution of protons from ($\alpha$,P) reactions on the total angular momentum transfer, J, has been observed experimentally. In particular, experimental data for the ($\alpha$,P) reaction have been obtained for $\lambda=1$ and $\lambda=2$ transfers for various targets. First we shall consider the results of the $\lambda=1$ studies. Several groups have reported qualitative agreement between DWBA calculations and experimental data. (See figure 1.) The angular distributions of protons from the ($\alpha$,P) reaction on a spin zero target for a J=3/2 state is relatively smooth while the angular distribution for the J=1 state oscillates sharply with angle.
Figure 1.

The angular distributions of protons from the $^{62}\text{Ni}(\alpha,p)^{65}\text{Cu}$ reaction. The figure on the left shows angular distributions for the states $E_x=0.00$ MeV ($J^\pi=\frac{3}{2}^+$) and $E_x=0.77$ MeV ($J^\pi=\frac{1}{2}^+$) of $^{65}\text{Cu}$. The figure on the right shows DWBA fits for these states. The data were obtained from J.E. Glenn, C.D. Zafiratos, and C.S. Zaidins.5
While there is general qualitative agreement, some details are not predicted by the theory. For example, the relationship between bombarding energy and the J-dependence is not well understood. There is evidence\textsuperscript{6,7} that J-dependence in the $^{58}\text{Ni}$ and $^{60}\text{Ni(\alpha,P)}$ reactions is enhanced as the $\alpha$-particle energy increases from 18 MeV to 30 MeV. However, this effect is not observed for all reactions.

Second, we shall consider the results of the $l=2$ studies. The agreement between theory and experimental data does not seem to be as good as for a transfer of one unit of angular momentum. J-dependence was observed at 22.2 MeV for $^{28}\text{Si}$\textsuperscript{7} but had disappeared at 30 MeV\textsuperscript{6}. However by choosing a suitable lower cut-off radius it is possible to obtain a DWBA calculation that predicts such a disappearance. It is not yet known if the disappearance of the J-dependence is peculiar to the mass region $A \approx 28$\textsuperscript{8}. Another view is that J-dependence for the ($\alpha$,P) reaction is an unreliable spectroscopic technique\textsuperscript{8}. But for other targets ($^{35}\text{Cl}$ and $^{24}\text{Mg}$)\textsuperscript{8} qualitative agreement between experimental data and DWBA calculations for $l=2$ transfers has been obtained.

The present study attempted to obtain more detail about the $l=2$ transfers. The $^{28}\text{Si(\alpha,P)}^{31}_p$ reaction was investigated at a laboratory energy of 14.5 MeV.
EXPERIMENTAL PROCEDURE

A 14.5-MeV $^4\text{He}^+$ beam from the Western Michigan University EN-tandem Van de Graaff accelerator struck a thin $^{28}\text{SiO}_2$ target at the center of an ORTEC scattering chamber of 43.2-cm diameter. In general proton spectra were taken at 10-degree intervals to obtain angular distributions. However at angles less than 50 degrees, protons knocked out of the target (knock-on protons) by the incident $^4\text{He}^+$ beam obscured some of the proton groups. The energy of the knock-on protons changes rapidly as a function of scattering angle. Therefore to reduce the size of the gaps in the angular distributions of the protons obscured by the knock-on protons, five degree steps were taken at forward angles. Spectra within the range of 12 degrees to 170 degrees in the laboratory system were measured. Figure 2 shows the spectrum obtained at 30 degrees. The details of the scattering geometry used to obtain the spectra are shown in figure 3. The angular spread of the detector system was limited to ±0.65 degrees by a circular collimator one-eighth inch in diameter placed in front of the detector system.

The detector system consisted of two cooled ORTEC surface barrier detectors. The $\Delta E$ detector was a 150-micron thick barrier detectors. The sensitive volume of the E detector was 1500 microns thick. The signals from both detectors were applied to the inputs of preamplifiers and amplifiers before the pulses were shaped for analysis by the particle identifier. The particle identifier can be used to distinguish among various types of charged
Figure 2.
Spectrum at 30 degrees.
The states of $^{31}\text{p}$ are identified and the excitation values are
given in Table I. The proton group marked with an arrow is due to
knock-on protons and has been reduced by a factor of ten.
<table>
<thead>
<tr>
<th>Number of peak</th>
<th>Ex (MeV)</th>
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<tbody>
<tr>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>1</td>
<td>1.226</td>
</tr>
<tr>
<td>2</td>
<td>2.223</td>
</tr>
<tr>
<td>3</td>
<td>3.133</td>
</tr>
<tr>
<td>4</td>
<td>3.295</td>
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<tr>
<td>5</td>
<td>3.414</td>
</tr>
<tr>
<td>6</td>
<td>3.505</td>
</tr>
<tr>
<td>7</td>
<td>$^{12}<em>{\text{C}}(\alpha,\text{p}^* )^{15}</em>{\text{N}}$</td>
</tr>
<tr>
<td>8</td>
<td>4.260</td>
</tr>
<tr>
<td>9</td>
<td>Knock-on protons</td>
</tr>
<tr>
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<td>5.015</td>
</tr>
<tr>
<td>11</td>
<td>5.116</td>
</tr>
<tr>
<td>12</td>
<td>Unidentified</td>
</tr>
<tr>
<td>13</td>
<td>5.530, 5.557</td>
</tr>
<tr>
<td>14</td>
<td>5.672</td>
</tr>
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<td>15</td>
<td>5.770</td>
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<td>16</td>
<td>5.892</td>
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<tr>
<td>17</td>
<td>6.050</td>
</tr>
<tr>
<td>18</td>
<td>6.180, 6.240</td>
</tr>
<tr>
<td>19</td>
<td>6.380, 6.400</td>
</tr>
<tr>
<td>20</td>
<td>6.593, 6.610</td>
</tr>
<tr>
<td>21</td>
<td>6.844</td>
</tr>
<tr>
<td>22</td>
<td>$^{16}_{\text{O}}(\alpha,\text{p}<em>0 )^{19}</em>{\text{F}}$</td>
</tr>
<tr>
<td>23</td>
<td>7.150</td>
</tr>
</tbody>
</table>
Figure 3.
Scattering Geometry
particles, such as protons, deuterons, $^3\text{He}^{++}$, and $^4\text{He}^{++}$. This identification is possible because different types of particles with the same energy lose energy at different rates in an absorber. If $R$ is the range of a particle in an absorber, $E_i$ is the incident particle energy, $a$ a constant depending on the type of particle, and $b$ another constant (approximately 1.73), then $R = a E_i^b$.

Applying this power law to the $E$ and $\Delta E$ detectors yields

$$R = a E_i^{1.73} = a (E + \Delta E)^{1.73} = T + a E^{1.73}.$$ 

Rearranging the above equation the ratio $T/a$ is obtained.

$$T/a = (E + \Delta E)^{1.73} - E^{1.73}.$$ 

where $T$ is the thickness of the $\Delta E$ detector and $E_i = E + \Delta E$. The ratio, $T/a$, is characteristic of each type of particle (figure 4). The particle identifier produces a pulse proportional to $T/a$; thus a particle may be identified.

A block diagram of the electronics is shown in figure 5. The signals from the two detectors and the timer-scaler are required to be in coincidence. After the collection of 240 microcoulombs, the timer-scaler does not generate a pulse and the coincidence requirement fails, terminating a run. If the three signals are in coincidence, the gate and delay generator sends an enable pulse to the particle identifier. The enable pulse gates the particle identifier so that it can receive the signals from the $E$ and $\Delta E$ detectors. Since the $^4\text{He}^{++}$ particles are stopped in the $\Delta E$ detector, the coincidence requirement greatly decreases the number of pulses that must be analyzed by the particle identifier.
Figure 4.

**Range-Energy relationships.**
The data are taken from ORTEC manual.
Figure 5.  
**Block Diagram of electronics.**  
The abbreviations used in the diagram are as follows: ADC - analog-to-digital converter and PDP 15-computer.
AE
TIMING SINGLE CHANNEL ANALYZER
LINEAR GATE AND STRETCHER
INTEGRATOR CURRENT COINCIDENCE
SPECTROSCOPIC AMPLIFIER
SATE ENABLE OSCILLOSCOPE
TIMING SINGLE CHANNEL ANALYZER
LINEAR GATE AND STRETCHER
CURRENT INTEGRATOR TIMER SCALER UNIVERSAL COINCIDENCE GATE AND DELAY GENERATOR PARTICLE IDENTIFIER ADC PDP 15 DELAY AMPLIFIER DELAY AMPLIFIER
When the coincidence requirement is satisfied, the $E$ and $\Delta E$ signals from the linear gate and stretcher are applied to the particle identifier. The particle identifier produces two analog signals: one is a measure of $T/a$ and the other measures the energy of the particle, $(E + \Delta E)$. The $T/a$ pulses which correspond to protons are used to gate the analog-to-digital converter. The digital form of the $(E+\Delta E)$ signal is stored in a PDP-15 computer. The data in the computer can be displayed on a storage oscilloscope. After each run the data are transferred from the computer core to DEC tape.
RESULTS

The differential reaction cross section, \( \left( \frac{d\sigma}{d\Omega} \right)_{\exp} \), for each proton group which could be resolved was calculated using the relationship

\[
N_{\exp} = \left[ N_{Si} \Omega N_i' \right] \left( \frac{d\sigma}{d\Omega} \right)_{\exp}
\]

with \( N_i = Q/2e \). The total charge collected for each run is represented by \( Q \), the electron charge by \( e \), the number of silicon scattering centers per unit area by \( N_{Si} \), and the solid angle of the detector system by \( \Omega \). A Rutherford scattering experiment was performed to determine the quantity in square brackets. The Rutherford scattering data were taken at 40, 60, and 80 degrees in the laboratory and with laboratory energies of 3.464 MeV and 3.962 MeV. Low energies and forward angles were used so that the \(^4\text{He}^{++}\) particles would not penetrate the Coulomb barrier with any significant probability. Nuclear force interactions can therefore be neglected. Using the equation for Rutherford scattering and the relationship

\[
N_{\text{Ruth}} = \left[ N_{Si} \Omega N_i' \right] \left( \frac{d\sigma}{d\Omega} \right)_{\text{Ruth}}
\]

\( N_{Si} \Omega N_i' \) can be determined. (See figure 6.) In the \((\alpha,p)\) reaction \( Q=240 \) microcoulombs while in the Rutherford scattering experiment \( Q_R=2.4 \) microcoulombs, thus \( N_i=100N_i' \). Therefore,

\[
\left( \frac{d\sigma}{d\Omega} \right)_{\exp} = \frac{N_{\exp}}{[N_{Si} \Omega N_i']_{100}}
\]

substituting the value of \( [N_{Si} \Omega N_i'] \) from the Rutherford scattering experiment

\[
\left( \frac{d\sigma}{d\Omega} \right)_{\exp} = 3.195 \times 10^{-5} N_{\exp} \pm (a^2 + (bc)^2)^{1/2} \frac{m_b}{s\pi}
\]

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Figure 6.

\[
\frac{\frac{d\sigma}{d\Omega}}{N_{\text{RUTR}}} \quad \text{vs.} \quad \Theta_{\text{LAB}}
\]
\[ \frac{d \sigma}{d \Omega} \text{RUTH} \] vs. \( \theta_{\text{LAB}} \)

- \( E_{\text{LAB}} = 3.962 \text{ MEV} \)
- \( E_{\text{LAB}} = 3.463 \text{ MEV} \)
where \( a \) is the statistical error in \( N_{\text{exp}} \).

Using eq. (1) it is possible to determine the areal density of the target.

\[
N_{s_i} = \frac{N_{\text{RUTH}}}{Q \Omega} \frac{d\sigma_{(\text{MCW})}}{d\Omega} \left( \frac{\text{mb}}{\text{sr}} \right) = \frac{N_{\text{RUTH}}}{Q} \frac{3.2 \times 10^{14}}{\Omega} \frac{\text{particles}}{\text{cm}^2}
\]

Substituting the ratio \( \frac{N_{\text{RUTH}}}{Q} \), the areal density of the target was found to be \( 46 \pm 5 \) micrograms per centimeter squared. The result was reasonable since the target is nominally 100 micrograms per centimeter squared. In addition to the hydrogen in the target, which was previously mentioned, the target contained carbon and oxygen. The proton group from the \(^{12}\text{C}(\alpha, P)_{^{15}}\text{N}\) reaction obscured several proton groups from the \(^{28}\text{Si}(\alpha, P)_{^{31}}\text{P}\) reaction.

The angle between the target and the incident beam was 60 degrees for most of the runs. (See figure 3.) For scattering angles of 40, 50, and 60 degrees \( N_{\text{exp}} \) was normalized to a target angle of 60 degrees since the target angle for these runs was 90 degrees.

For some proton groups it was necessary to subtract a background to obtain \( N_{\text{exp}} \). For the states of \(^{31}\text{P}\) with low excitation energies the background subtraction was negligible while for high excitation energies the background correction was less than 15% of the total number of counts for most proton groups. The correction for \( N_{\text{exp}} \) was determined by averaging the background on both sides of a particular proton group. The angular distributions obtained are given in figure 7. 

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Figure 7.
Angular distributions at 14.5 MeV.
DISCUSSION AND CONCLUSION

Most of the angular distributions obtained at 14.5 MeV (figure 7) do not have the forward peaking that is characteristic of direct reactions. The angular distributions\(^5,8,9,10\) at four other energies are given in figure 8. Comparing the angular distributions reveals that the first maximum for the first excited state of \(^{31}\text{P}\) \((J^\pi=\frac{3^+}{2})\) does not occur at the same angle for the various energies. Direct reaction theory predicts that above a certain energy where the reaction mechanism is predominately direct, the angular distributions will vary slowly as a function of increasing energy. Since the angular distributions change significantly in the region of interest, compound nucleus formation must play an important role. Thus direct reaction theory cannot be applied to most of the states of \(^{31}\text{P}\) formed in the \((\alpha,P)\) reaction with 14.5 MeV alpha particles.

Nevertheless a crude attempt was made to obtain a fit for the first excited state of \(^{31}\text{P}\) \((\text{Ex}=1.226\text{ MeV})\) which has \(J^\pi=\frac{3^+}{2}\). The proper method to treat a three-nucleon transfer is to consider each nucleon separately. But as an approximation in the calculation the three transferred nucleons were treated as a single triton with spin \(\hbar/2\). This assumption has been justified in some cases since the crude calculation has roughly fit some of the experimental data in the literature\(^5\). In the present case, it may not be valid to assume that all of the nucleons in a triton go into the same shell. The computer program DWUCK\(^{11}\) was used to obtain a theoretical fit.
Figure 8.

**Angular distributions at various energies.**
They were obtained from the following sources: 14.8 MeV - Zelenskaya, N.S., et al\textsuperscript{10}, 22.2 MeV - Yamazahi, T., et al\textsuperscript{9}, 28.8 MeV - August, L.S., et al\textsuperscript{8}, 35.5 MeV - Glenn, J.E., et al\textsuperscript{5}.
The optical model parameters used for the alpha and proton channels were obtained from August, Shapiro, and Cooper. They did not list the parameters used for the transferred particle. Therefore it was necessary to estimate them in order to do the calculations. The parameters used are given in table II.

The radial cutoff, which determines the distance the incoming particle penetrates the target nucleus, drastically affects the shape of the theoretically predicted curve. The peak in the angular distribution is a sensitive function of the radial cutoff. (See figure 9.) The curves are the result of using real volume potentials for the alpha particle, the proton, and the transferred particle. In addition to the radial cutoff, the spin-orbit interaction affects the magnitude of the predicted cross sections. For a given angular momentum, $\ell$, the spin-orbit interaction causes the magnitude of the cross section for the state $J = \ell - \frac{1}{2}$ to decrease.

In conclusion, the present study was not able to obtain a good theoretical fit to the angular distributions. Most of the states were not the result of a direct reaction. Therefore, it was impossible to apply direct reaction theory. The angular distributions for the first excited state of $^{31}$P had the shape characteristic of a direct reaction but an acceptable theoretical fit was not obtained. It may be that the parameters used in DWUCK (especially the triton parameters) were not correct. The present study does not indicate that there is $J$-dependence for the $^{28}$Si($\alpha$,P)$^{31}$p reaction with a 14.5-MeV alpha particle.
<table>
<thead>
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<th>V (MeV)</th>
<th>W (MeV)</th>
<th>r_{or} (F)</th>
<th>a_R (F)</th>
<th>r_c (F)</th>
<th>W_D^* (MeV)</th>
<th>r_{oi} (F)</th>
<th>a_i (F)</th>
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<tbody>
<tr>
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<td>187.3</td>
<td>13.8</td>
<td>1.66</td>
<td>0.466</td>
<td>1.4</td>
<td>....</td>
<td>....</td>
<td>....</td>
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<tr>
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<td>5.44</td>
<td>1.1</td>
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<td>1.2</td>
<td>1.79</td>
<td>1.442</td>
<td>0.500</td>
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<tr>
<td>Triton</td>
<td>15.668†</td>
<td>....</td>
<td>1.2</td>
<td>0.6</td>
<td>1.25</td>
<td>....</td>
<td>....</td>
<td>....</td>
</tr>
</tbody>
</table>

* Multiply by 4 for use in DWUCK

\[ ^{28}_{\text{Si}} \text{M} + ^{3}_{\text{He}} \rightarrow ^{31}_{\text{P}} - \text{Ex} \]

Ex: Excitation Energy
Figure 9. Radial Cutoff
BIBLIOGRAPHY


