PION PRODUCTION AS A PROBE OF TWO-NUCLEON AXIAL CHARGE AND CURRENT*

J.A. NISKANEN

Department of Physics
P.O. Box 9, FIN-00014 University of Helsinki, Finland
E-mail: Jouni.Niskanen@helsinki.fi

(Received October 9, 1996)

Some aspects of axial charge and current in pion production and absorption are reviewed. In addition to recent new mechanisms proposed to explain threshold $pp \to pp\pi^0$, the role of the $\Delta(1232)$ isobar is reiterated also in the two-nucleon axial charge.

PACS numbers: 13.60. Le

1. Introduction

Several recent experiments on threshold pion production [1–4] have revived also theoretical activity in this field. Advances in beam technology provide the necessary high resolution of the beam energy. Thin targets on the other hand make possible the detection of recoil nucleons or nuclei rather than very slow pions. For example Ref. [1] gives the first cross section data very near threshold for the reaction $np \to d\pi^0$, which, unlike the corresponding charged particle reaction $pp \to d\pi^+$, is unhampered by the Coulomb interaction and problems associated with it. Together with analyzing power data for A_y close to threshold [5] (however for $pp \to d\pi^+$), these provide strong constraints to a single interesting amplitude, s-wave pions. Another experiment by Meyer *et al.* [2] on $pp \to pp\pi^0$ in turn gave a surprisingly large cross section as compared with theoretical expectations, which underestimated the cross section by a factor of ~ 5 [2, 6]. Even adding the $\Delta(1232)$ contribution increased the cross section only by some 30 % [7]. Very recently the experiment was confirmed and extended closer to threshold in Ref. [4].

To explain $pp \to pp\pi^0$ a completely new mechanism was proposed by Lee and Riska [8]. This consisted of a heavy meson exchange (HME) combined

* Presented at the "Meson 96" Workshop, Cracow, Poland, May 10–14, 1996.

with an $N\bar{N}$ pair formation and pion production vertex, applied earlier to weak interactions in nuclei [9]. Use of conventional nucleon-meson coupling constants from the Bonn and Paris potentials in this short-ranged mechanism brought the cross section to the experimentally observed region. The general theory of Ref. [8] in terms of NN-interaction invariants was cast into the form of explicit meson exchanges in Refs [10, 11].

As it would be, soon another possibility was suggested. S-wave rescattering of the pions is normally considered to be the dominant mechanism in threshold production. This can be described phenomenologically as

$$H_s = 4\pi\frac{\lambda_1}{\mu}\,\vec{\phi}\cdot\vec{\phi} + 4\pi\frac{\lambda_2}{\mu^2}\,\vec{\tau}\cdot\vec{\phi}\times\vec{\pi}.$$

However, in $pp \to pp\pi^0$ only the isoscalar (isospin symmetric) amplitude λ_1 enters, which is suppressed in threshold scattering by chiral symmetry. This is the reason for the theoretical smallness of the cross section. In Ref. [12] Hernandez and Oset proposed using simple models that in off-shell πN scattering this suppression is removed, and rescattering may be massive. Later a more sophisticated Jülich-Bonn model of pion-nucleon scattering showed this effect to be smaller but still substantial [13]. So threshold pion production has become a very interesting field of short-range NN and off-shell πN interaction studies.

Threshold studies concentrate naturally on s-wave pion production, on the typical contribution of the axial charge. This talk aims to point out that threshold production should not be separated from the main body of data and theoretical results, which may change due to the new contributions to the axial charge. Perhaps one might consider it as luck that *e.g.* the heavy meson exchange effect is suppressed by another relativistic factor [14] in the case of axial current as compared with the axial charge, so that effects there would not be expected to be as massive. Axial current like pion coupling (along with the $\Delta(1232)$-isobar) has been considered well known. Another important point is that the Δ, a typical part of the axial current, can also contribute significantly to the two-baryon axial charge.

2. Reaction $pp \to d\pi^+$

In pion production the condensation of data is by far highest in the reaction $pp \to d\pi^+$. As a two-body reaction it is simple to analyze, and in theory the bound state is easier to handle numerically than a continuum state. The data extend now from threshold to about 1 GeV in proton laboratory energy and in some observables higher. Theory seems to describe the data best around and just below the Δ region, *i.e.* $E_p = 400 - 600$ MeV indicating that a major part of the dominant Δ is correctly described. This is normally included in p-wave production by incorporating explicit ΔN admixtures to the NN wave functions or using a corresponding two-body operator acting in the NN space. Particularly important are the chains ${}^1D_2(NN) \to {}^5S_2(\Delta N) \to p_2$ and ${}^3F_3(NN) \to {}^5P_3(\Delta N) \to d_3$. Without these the cross section in the Δ region would be underestimated by a factor of 10 as compared with data. There is no other known mechanism to bring the cross section up by this factor.

However, it is less known that the $\Delta(1232)$ isobar contributes significantly also to s-wave pion production even at threshold. S-wave pions are produced from the ${}^3P_1$ pp state, which can be coupled to ΔN intermediate states ${}^3P_1$, ${}^5P_1$ and ${}^5F_1$. Although the centrifugal barrier in the P-wave baryon states suppresses the Δ components to some extent, these components persist also to lower energies, to pion threshold and as a virtual off-shell effect even below. As shown *e.g.* in Ref. [15], the decay of the Δ in these states can give rise to s- and d-wave pions. The primary decay is to relative p-wave pions, but similarly to the case with nucleonic production the pion can suffer an s-wave rescattering from the second nucleon. In integration over the intermediate momenta the momentum operator inherent in the first production vertex transforms to the relative coordinate of the nucleons together with a derivative of a Yukawa function arising from the pion propagation. In this way the parity and angular momentum are taken care of by the internal momentum transfer of the pion. The contribution from the direct decay is very small, since there parity and angular momentum conservation require the second term $j_1(qr/2)$ of the plane wave expansion of the pion to appear in the overlaps. Therefore, with rescattering the p-wave nature of the resonance is not reflected in the external momentum dependence.

The ΔN components are generated via an exchange of isovector mesons $\pi + \rho$ by the coupled channels method, on which details can be found *e.g.* in Ref. [15]. This coupled channels method treats the Δ isobar on the same basis as the nucleons in a coupled system of Schrödinger equations. Since solving this system automatically generates attractive ΔN box diagrams, phenomenologically fitted NN potentials must be modified to avoid doubly counting this effect. Furthermore, energy dependence is allowed for s-wave pion rescattering to fit on-shell πN scattering, but except for the virtual $N\Delta$ admixtures, at threshold the model reduces to the old formalism of Koltun and Reitan [16]. (A monopole form factor with $\Lambda = 700$ MeV is included to account for off-shell rescattering.)

Comparing the solid and dashed curves in Fig. 1 it can be seen that even for threshold s-wave pions the isobar effect is strong and its inclusion triples the cross section. Therefore, in a model including the Δ the threshold cross section is actually *overestimated* before the addition of the HME effect, in contrast to the assumption in Ref. [10]. As discussed above, by far most of this increase in s-wave pion production comes from the normal elementary p-wave emission of the pion from the Δ followed by strong s-wave rescattering from the second nucleon. In contrast, the moderate isobar effect of only an increase by 30% in $pp \to pp\pi^0$ [7] reflects in part the strongly suppressed s-wave rescattering in that reaction.

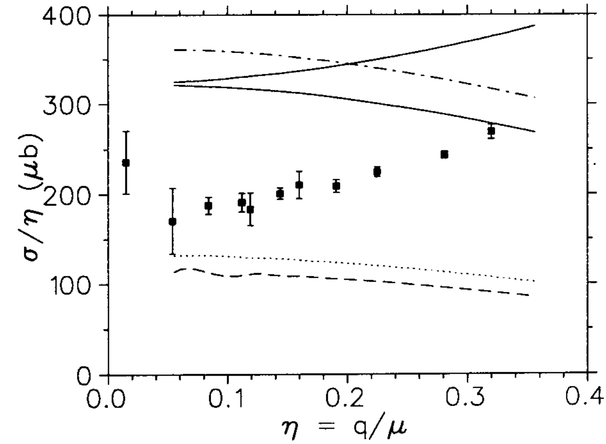

Fig. 1. Low-energy $pp \to d\pi^+$ cross section divided by $\eta = q_\pi/m_{\pi^+}$. The solid curves show the starting point before the addition of HME with the Δ included in all partial waves (the lower one is the s-wave contribution), while the dashed curve is the s-wave contribution without the Δ. The dotted and dash-dot curves have also the HME added to these calculations of the s-wave. The data are from Ref. [1].

Now it would be of great interest to see the effect of HME in this reaction. The σ meson exchange leads to the operator of the form

$$\mathcal{M}_{fi} \propto \frac{\boldsymbol{\sigma}_i \cdot (\boldsymbol{p}' + \boldsymbol{p})}{2M} \frac{1}{M} \frac{g_\sigma^2}{m_\sigma^2 + \boldsymbol{k}^2} \tau_{i0}$$

for each nucleon i. Except for the σ propagator this is similar to the Galilean invariance (axial charge) part of the direct production operator. Exchange of the other important ω meson has an additional spin-changing part $\propto \boldsymbol{\sigma}_1 \times \boldsymbol{\sigma}_2$, which does not contribute to s-wave production here. Eventually this operator leads to radial integrals [17]

$$J_\sigma = \frac{g_\sigma^2}{4\pi} \int_0^\infty \Big[\Big(\frac{d}{dr} - \frac{1}{r}\Big) v(r)\, j_0\Big(\frac{qr}{2}\Big) \Big(\frac{e^{-m_\sigma r}}{2Mr}\Big)\, u_{11}(r)$$
$$- v(r)\, j_0\Big(\frac{qr}{2}\Big) \Big(\frac{e^{-m_\sigma r}}{2Mr}\Big) \Big(\frac{d}{dr} + \frac{1}{r}\Big) u_{11}(r) \Big] dr$$

for the deuteron S-wave part $v(r)$ and

$$J_\sigma = \frac{g_\sigma^2}{4\pi}\int_0^\infty \Big[\Big(\frac{d}{dr}+\frac{2}{r}\Big)w(r)j_0\Big(\frac{qr}{2}\Big)\left(\frac{e^{-m_\sigma r}}{2Mr}\right)u_{11}(r)$$

$$- w(r)\,j_0|big\Big(\frac{qr}{2}\Big)\left(\frac{e^{-m_\sigma r}}{2Mr}\right)\Big(\frac{d}{dr}-\frac{2}{r}\Big)u_{11}(r)\Big]dr$$

for the D-wave $w(r)$, with the derivatives acting only on the nearest wave function. Similar equations are valid also for ω exchange.

As seen from Table I, there is a significant amount of cancelling between the deuteron S- and D-state contributions and the final result is moderately small. With ΔN there are slight changes in the short-range part of the NN wave function reflected in HME as seen in the second line of Table I, decreasing each individual contribution but increasing the total result. In this work HME is included only in the nucleon sector. The addition of HME slightly increases the overestimation as shown by the dash-dot curve in Fig. 1. The dotted curve gives the change in the purely nucleonic case. On one hand it is unfortunate that the HME does not remove the overestimation of the cross section. On the other hand one may be happy that a massive effect does not destroy old successes in describing observables at higher energies as could have happened.

TABLE I

Integrals (in $\mathrm{fm}^{-1/2}$) for σ and ω exchanges and S and D final states for $\eta = 0.1424$. The total result has also a factor $1/\sqrt{2}$ multiplying the D state as required by angular momentum algebra [16].

Model	σ, S	ω, S	σ, D	ω, D	Total
NN	-0.0284	-0.0202	0.0162	0.0119	-0.0287
$N\Delta$	-0.0260	-0.0181	0.0059	0.0037	-0.0373

Let us next see the effects caused in observables at higher energies from varying models at threshold. There the data are sufficient to basically fix the amplitudes. The analyzing power A_y between 500 and 600 MeV is very sensitive to the s-wave pion amplitude. The use of a smaller s-wave amplitude to fit the threshold cross section would produce too high an analyzing power, whereas a larger one would yield too deep a minimum in it. Again it is fortunate that the HME effect is small in this reaction, as can be seen comparing with the 515 MeV data [18] in Fig. 2. Further, since the low energy analyzing power data of Ref. [5] in Fig. 3, due to the s- and p-wave interference, can be easily fitted by simply scaling with the factor $\sqrt{\sigma(\mathrm{th})/\sigma(\mathrm{exp})}$,

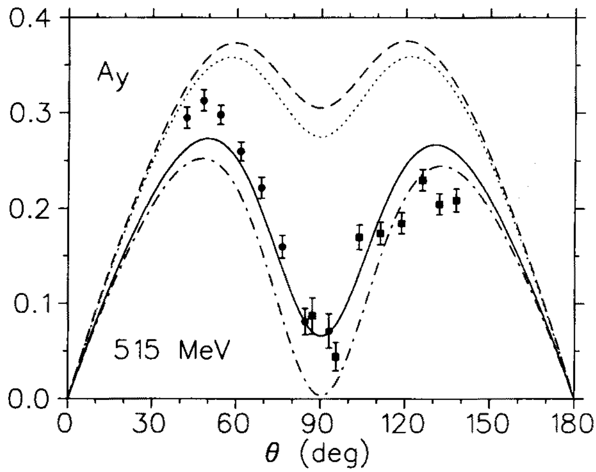

Fig. 2. The analyzing power A_y in $pp \to d\pi^+$ at 515 MeV. The different curves differ in their treatment of the s-wave pion production amplitude as in Fig. 1. The other partial waves have always the same full model as the solid curve also has for the s wave. The data are from Ref. [18].

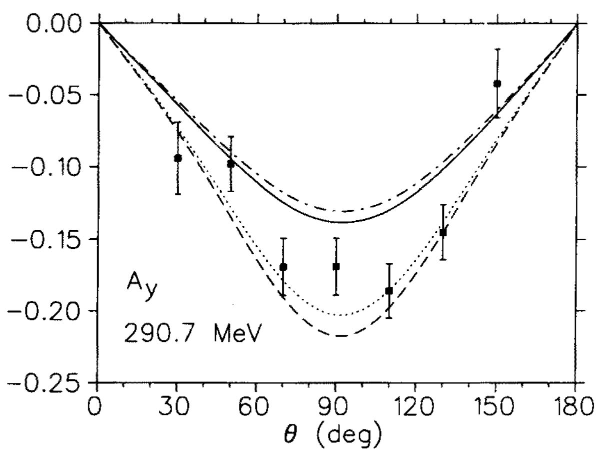

Fig. 3. The analyzing power A_y in $pp \to d\pi^+$ at 290.7 MeV. The different curves as in Fig. 2. The data are from Ref. [5].

which compensates for the overestimation of the s-wave amplitude in the cross section, one may conclude that apparently the p-wave amplitude is under control also close to threshold. The same conclusion can be drawn from the slope of the cross section in Fig. 1.

The overestimation of the threshold cross section by the full model, which agrees well with the data in the Δ region, poses a problem indicating that either the energy dependence of off-shell pion rescattering is not properly incorporated or some physical mechanism is still missing in the present models of pion production.

One could speculate on the possibility of off-shell rescattering effects. In this case the dominant part is the isovector (isospin antisymmetric) πN amplitude λ_2, where exchange of the ρ meson contributes most. In this exchange at low energies the main contribution comes from a term $\propto (s-u)/4M$. At threshold this changes kinematically to 3/4 of the on-shell situation, if one assumes only 1/2 of the energy to be carried by the intermediate pion. This elementary argument is supported by a similar decrease of the Jülich-Bonn πN interaction [19]. At threshold this would be enough to bring the cross section down to the experimental value. However, if one simply scales the appropriate πN amplitude by this constant factor, the analyzing power at higher energy becomes intolerably positive, rather similar to the dotted curve in Fig. 2. The energy dependence of this off-shell effect to the overall pion production amplitude has not been properly studied, yet.

3. Strength of $NN \to \Delta N$ transition

One might ask about the reliability of the strength of the ΔN components. How can one fix the transition potential? Are the relevant coupling constants reasonable? The transition potential itself is perfectly conventional with a tensor and spin-spin parts arising as in OPE or ρ exchange in NN scattering.

The $\pi N\Delta$ coupling constant can be extracted from the free width of the Δ and is $f_{\pi N\Delta}/4\pi = 0.35$ vs. $f_{\pi NN}/4\pi = 0.076$. The ρ meson cuts the more important tensor part at short distances. Its coupling constant with ΔN can be related to the NN coupling by the quark model $f_{\rho\Delta N} = \sqrt{\frac{72}{25}} f_{\rho NN}$, with the latter taken from literature. Using monopole form factors with the cut-offs $\Lambda_\pi = 1000$ MeV and Λ_ρ=1050 MeV one can get a very good fit to the $pp \to d\pi^+$ cross section at the Δ peak as seen in Fig. 4 (solid curve). For comparison also the transition potential with the Bonn parametrization is used. Here the $\pi N\Delta$ coupling is related to the πNN coupling also by the quark model. This leads to a significantly weaker coupling even though the form factor is harder. This is shown by the dashed curve, where the weaker coupling is also used for the final pion production vertex. The effect of the transition potential alone is shown by the dotted curve: there the final vertex was obtained from the free width, but the transition potential from the Bonn parametrization. The Bonn potential has been very successful in describing elastic NN scattering. However, its parameters have been

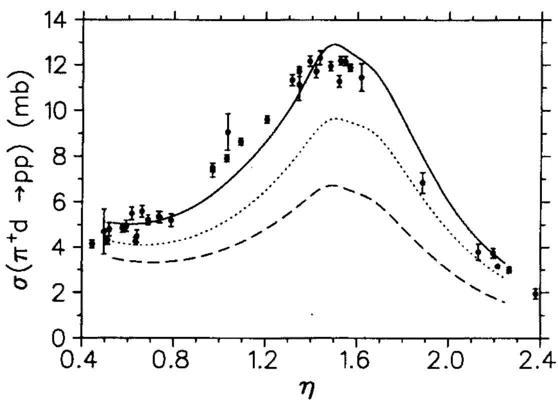

Fig. 4. The total cross section for pion absorption on the deuteron as a function of η. Solid: the strong $\pi N \Delta$ coupling; dashed: the Bonn $\pi N \Delta$ coupling; dotted: the Bonn coupling used in the transition potential but the Δ width value for the coupling of the external pion to the nucleon and Δ.

fitted just to do that. It seems that elastic scattering is not necessarily sensitive enough to the coupling to the Δ, but some of the coupling can be simulated by other meson exchange processes. Rather, one could use the simplest pion production reaction overwhelmingly dominated by the Δ to fix the transition potential for use in other reactions and phenomena. One such reaction is photon absorption on the deuteron, where the agreement with data is improved by use of the stronger coupling [20]. It is likely that this would also help in solving the problem of missing inelasticity in the ${}^1D_2$ and ${}^3F_3$ "dibaryon" waves in the extension of the Bonn potential above pion threshold [21].

4. Reaction $pn \to (pp)_S\pi^-$

The $NN \to d\pi$ amplitudes with different parities are also distinguished by spin, so the unpolarized cross section is symmetric about 90° in the CMS. However, in pion production with a final singlet pair ${}^1S_0$ all initial states are triplets with unnatural parity ($L \neq J$); of course, different parities have also different isospins, so mixing of opposite parity amplitudes is possible only in np collisions. In spite of the ΔN admixtures being forbidden in the isospin 0 states ${}^3S_1 -{}^3 D_1$ and ${}^3D_1 -{}^3 S_1$, p-wave pions dominate also here [22]. An admixture of the s wave causes an asymmetry about 90° seen earlier in π^- absorption on an ${}^1S_0(pp)$ pair in ^{3}He. There is no doubt that the amplitude ${}^3P_0 \to{}^1 S_0 s$ needs an enhancement because of $pp \to pp\pi^0$. This should also be observable here [23].

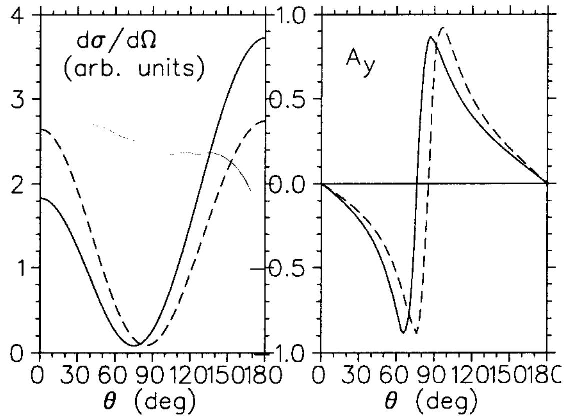

Fig. 5. The angular distribution and analyzing power A_y for $pn \to (pp)_S\pi^-$ 55 MeV above threshold (CMS) with HME (solid) and without (dashed).

A recent experiment E460 at TRIUMF has measured quasifree $pn \to (pp)_S\pi^-$ in the few-body reaction $pd \to (pp)_S\pi^- p_{\rm spec}$. In addition to the angular distribution also the analyzing power A_y is measured. If the dominant p-waves from the isospin 0 states were the sole contributors, A_y would be antisymmetric about 90°. However, a clear deviation from this was seen already earlier in Ref. [24]. Preliminary results from E460 [25] show a deviation of A_y from antisymmetry of a magnitude, which is not reproduced without some new contribution to the s-wave amplitude, such as HME needed in $p \to pp\pi^0$. The two theoretical curves are shown in Fig. 5. Also the experimental angular distribution is closer to the one with enhanced s-wave production than that obtained by conventional direct and s-wave rescattering. Probably off-shell scattering effects [12, 13] would be very similar to HME.

5. Conclusion

The role of HME in the reaction $pp \to d\pi^+$ is rather small, in spite of its dramatic effect in $pp \to pp\pi^0$. However, it is significant in the axial charge part of $pn \to (pp)_S\pi^-$, where its effect is moderated by the dominance of the axial current. Also the proposed off-shell pion rescattering could influence in the same way, and the two mechanisms cannot be distinguished with the present data. The Δ isobar can contribute strongly at threshold in $pp \to d\pi^+$, if it is combined with a subsequent s-wave rescattering, and probably also in the related $pp \to np\pi^+$. There may be a problem in joining threshold data with those in the Δ region. The energy dependence of the off-shell rescattering in pion production should be cleared up.

REFERENCES

[1] D.A. Hutcheon *et al.*, *Nucl. Phys.* **A535**, 618 (1991).
[2] H.O. Meyer *et al.*, *Phys. Rev. Lett.* **65**, 2846 (1990); H.O. Meyer *et al.*, *Nucl. Phys.* **A539**, 633 (1992).
[3] W.W. Daehnik *et al.*, *Phys. Rev. Lett.* **74**, 2913 (1995).
[4] A. Bondar *et al.*, *Phys. Lett.* **B336**, 39 (1996).
[5] E. Korkmaz *et al.*, *Nucl. Phys.* **A535**, 637 (1991).
[6] G.A. Miller, P.U. Sauer, *Phys. Rev.* **C44**, 1725 (1991).
[7] J.A. Niskanen, *Phys. Lett.* **B289**, 227 (1992).
[8] T.-S.H. Lee, D.O. Riska, *Phys. Rev. Lett.* **70**, 2237 (1993).
[9] M. Kirchbach, D.O. Riska, K. Tsushima, *Nucl. Phys.* **A542** , 616 (1992).
[10] C.J. Horowitz, *Phys. Rev.* **C48**, 2920 (1993).
[11] C.J. Horowitz, H.O. Meyer, D.K. Griegel, *Phys. Rev.* **C49**, 1337 (1994).
[12] E. Hernández, E. Oset, *Phys. Lett.* **B350**, 158 (1995).
[13] C. Hanhart, J. Haidenbauer, A. Reuber, C. Schütz, J. Speth, *Phys. Lett.* **B358**, 21 (1995).
[14] K. Tsushima, D.O. Riska, *Nucl. Phys.* **A549**, 313 (1992).
[15] J.A. Niskanen, *Nucl. Phys.* **A298**, 417 (1978); *Phys. Lett.* **141B**, 301 (1984).
[16] D.S. Koltun, A. Reitan, *Phys. Rev.* **141**, 1413 (1966).
[17] J.A. Niskanen, *Phys. Rev.* **C53**, 526 (1996).
[18] E. Aprile *et al.*, *Nucl. Phys.* **A379**, 369 (1982).
[19] C. Hanhart, private communication.
[20] J.A. Niskanen, P. Wilhelm, *Phys. Lett.* **B359**, 295 (1995).
[21] Ch. Elster *et al.*, *Phys. Rev.* **C37**, 1647 (1988); *Phys. Rev.* **C38**, 1828 (1988).
[22] J.A. Niskanen, *Phys. Rev.* **C43**, 36 (1991).
[23] J.A. Niskanen, *Phys. Rev.* **C49**, 1285 (1994).
[24] C. Ponting *et al.*, *Phys. Rev. Lett.* **63**, 1792 (1989).
[25] F. Duncan, PhD thesis, University of British Columbia, 1993.