Kaon-nucleon and D-nucleon scattering in the quark model, including spin-orbit interactions

Noel Black
Department of Physics and Astronomy
University of Tennessee, Knoxville, TN, 37996, USA

Abstract.
Interactions of charmed and strange mesons with baryonic matter can be calculated in the nonrelativistic quark potential model. For $KN$ scattering data exists, and the theoretical results for S-waves are in approximate agreement with experiment. Here we apply the same model to the scattering of open-charm ($D$) mesons by nucleons, and give quark model predictions for $DN$ scattering amplitudes. Spin-orbit forces in $KN$ and $DN$ will also be discussed.

1. Introduction

$KN$ scattering is ideally suited for studying the origins of the nonresonant “nuclear” force. Conventional s-channel baryon resonance production is excluded because there is no valence annihilation, and one-pion exchange is forbidden because there is no three-pseudoscalar vertex. We may therefore study the nonresonant part of hadron scattering in relative isolation, uncomplicated by one-pion exchange. In this work we calculate $KN$ phase shifts at Born order in a quark exchange model with one gluon exchange (OGE) and linear scalar confinement. The dominant hyperfine term has given very good results in S-wave for $I=2 \pi\pi$ [1], $I=3/2 K\pi$ [2], $I=1 KK$ [1], $KN$ [3], and short-ranged $NN$ [4] scattering. Here we include the spin-orbit and subdominant spin-independent contributions, and give results for higher-L waves. $KN$ scattering is an excellent place to test our model since data exists and there is a large spin-orbit effect, especially evident in the P-waves. Understanding the spin-orbit effect here will be important for applications to other hadronic interactions, such as $DN$. $KN$ scattering is almost entirely elastic below $K\Delta$ threshold, and the Born approximation is expected to be relevant since the interaction is known experimentally to be relatively weak.

2. Experiment

There are some basic experimental features of $KN$ scattering which are generally agreed upon. The $I=1$ channel is relatively well determined from $K^+P$ scattering. Using the

$\S$ nblack@utk.edu
Kaon-nucleon and D-nucleon scattering in the quark model

conventional $L_{I, J}$ notation, the $S_{11}$ and $P_{11}$ channels are repulsive and the $P_{13}$ channel is attractive. $I=0$ is more in doubt because of inherent difficulties in the experimental analysis. The $I=0$ $K\,N$ scattering amplitudes have been extracted from $K\,d$ scattering, using models of the deuteron breakup process and form factors. It is clear, however, that the $P_{01}$ channel is strongly attractive (in fact anomalously so). Inelasticities are known to be large above inelastic thresholds, in particular in the $P_{01}$ wave. For reference, $K\Delta$ ($I=1/2$ $K\,N$ only) opens at $P_{\text{lab}} = 0.86$ GeV, $K^*\,N$ opens at $P_{\text{lab}} = 1.08$ GeV and $K^*\Delta$ opens at a much higher $P_{\text{lab}} = 1.74$ GeV.

3. Calculation

The fundamental interactions in QCD are between quark and gluon constituents. The quark-quark OGE $T_{\text{ff}}$ is derived as the nonrelativistic reduction to order $P^2/m^2$ of the Feynman amplitude for two quarks to exchange a gluon with phenomenological strength $\alpha_s$. The result is the usual Breit-Fermi Hamiltonian, which is well known from atomic physics, and includes the dominant spin-spin hyperfine interaction as well as Coulomb, spin-orbit, tensor, and subdominant spin-independent contributions. The confining interaction is modelled as a linear scalar interaction with strength $b$ (the string tension) between a pair of quarks, and yields linear and spin-orbit contributions, as well as smaller spin-independent terms. The quark-quark interaction is followed by quark interchange, so that the outgoing hadrons emerge as color singlets [5].

The scattering arises from the interactions between quarks in different hadrons, and the interaction Hamiltonian $H_{\text{int}}$ is the sum of quark-quark interactions between all such pairs of quarks. To Born order the scattering amplitude is given by the matrix element of $H_{\text{int}}$ between external hadron states, which ideally should be eigenstates of the respective free Hamiltonians. We approximate the true wavefunctions by Gaussian forms for calculational simplicity, as these lead to analytical results for the scattering amplitudes. This approximation has been tested in previous calculations [6]. The parameters are relatively well determined from quark-model phenomenology; we use a reasonably standard set (below) for our numerical evaluation.

\[
\begin{align*}
\alpha_s &= 0.6 & \text{strong coupling constant} \\
b &= 0.18 \text{ GeV}^2 & \text{string tension} \\
\beta &= 0.4 \text{ GeV} & \text{meson wavefunction length scale} \\
\alpha &= 0.4 \text{ GeV} & \text{baryon wavefunction length scale} \\
m_{u,d} &= 0.330 \text{ GeV} & \text{nonstrange constituent quark mass} \\
m_s &= 0.550 \text{ GeV} & \text{strange constituent quark mass}
\end{align*}
\]

(1)

The phase shifts are calculated from the scattering amplitudes and phase space factors in the usual way [6].
4. Results

Hashimoto [7] has performed the most recent comprehensive single-energy phase shift analysis we are aware of, and we take his data for comparison. We also compare our results with those of the recent resonating group method (RGM) calculation of Lemaire, et al [8]. In the $I=1$ channel, our results are in reasonable agreement with the RGM calculation. Both calculations agree at least qualitatively with the data except in the $P_{13}$ wave, for which they both give the wrong sign. In $I=0$, the absolute values of the calculated phase shifts are in general too small, especially in the remarkably large $P_{01}$ wave. The OGE spin-orbit contributions to our quark model $KN$ phase shifts are shown in Figure 3. The large $P_{01}$ amplitude evident there is perhaps an indication that we have included at least some of the correct physics. It is, however, not large enough by itself to account for the data, and is partially cancelled by the confinement spin-orbit contribution and the negative spin-spin hyperfine term.

Mukhopadhyay and Pirner [9] have found that the phase shifts calculated from the symmetric part of the OGE spin-orbit interaction agree reasonably well with the experimental phase shifts at low energies except in the $P_{01}$ wave, which they seriously underestimate. The antisymmetric part of the OGE spin-orbit interaction is omitted in their calculation because it gives rise to large splittings in the baryon spectroscopy which are not observed. They similarly conclude that the confinement spin-orbit interaction partially cancels the OGE spin-orbit contribution, and the inclusion of the spin-spin interaction actually makes the $P_{13}$ phase shift theoretically repulsive.

The opening of inelastic channels is known to be a very large effect in the $P_{01}$ wave, and may be responsible for the large experimental phase shift. Coupling to inelastic channels will be treated in a future calculation.

5. $DN$ scattering

Knowledge of vacuum $DN$ scattering amplitudes and observables is important for understanding open-charm hadronic interactions in hot, dense media, as occur in heavy ion collisions. We applied our $KN$ scattering model to obtain $DN$ elastic phase shifts, which are shown in Figure 4. (The only new parameter was the charmed quark mass, taken to be $m_c = 1.550$ GeV.) Inelasticities may well be large in $DN$, as in $KN$ scattering. In $I=1$, the linear and spin-spin hyperfine terms are roughly comparable, and dominate scattering in the waves shown. The spin-orbit splitting is small in comparison. It is notable that in $I=0$ the spin-independent terms (Coulomb and linear) are identically zero and the spin-orbit interactions dominate the scattering.

References

1 Barnes T and Swanson E S 1992 Phys. Rev. D46 131
2 Barnes T, Swanson E S, and Weinstein J 1992 Phys. Rev. D46 4868
3 Barnes T and Swanson E S 1994 Phys. Rev. C49 1166
Figure 1. Theoretical $I=1$ $KN$ phase shifts (red lines). The experimental phase shifts of Hashimoto [5] (blue triangles with error bars) and the RGM theoretical phase shifts of Lemaire et al [6] (green circles and squares, representing two wavefunctions) are shown for comparison.

Figure 2. $I=0$ $KN$ phase shifts, legend as in Figure 1.
Kaon-nucleon and D-nucleon scattering in the quark model

Figure 3. Theoretical \( KN \) OGE spin-orbit phase shifts.

Figure 4. Theoretical \( DN \) phase shifts.

4 Barnes T, Capstick S, Kovarik M D, and Swanson E S 1993 Phys. Rev. C48 539
5 One may wonder whether t-channel meson exchange should be included as a separate effect in the calculation. We note that our quark line diagrams are topologically \( q\bar{q} \) exchanges in t-channel, and hence may implicitly incorporate t-channel meson exchange effects. The connection between the two pictures is an interesting topic for future research.
6 Barnes T, Black N, and Swanson E S 2001 Phys. Rev. C63 025204
7 Hashimoto K 1984 Phys. Rev. C29 1377
8 Lemaire S, Labarsouque J, and Silvestre-Brac B 2001 Nucl. Phys. A696 497
9 Mukhopadhyay D and Pirner H J 1985 Nucl. Phys. A442 605