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Quadrupole scattering of pions by ^{9}Be

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The results for $\pi^\pm + {}^9$Be elastic scattering at $E_{\text{lab}} = 162$ MeV are shown to provide evidence for quadrupole contributions to the elastic scattering of pions. The strong-coupling rotational model is used to relate the measured inelastic scattering cross sections to the elastic scattering cross sections.

[INTERMEDIATE ENERGY $\pi^\pm + {}^9$Be elastic and inelastic scattering, $E_{\text{lab}}=162$ MeV, optical-model analysis, quadrupole scattering.]

I. INTRODUCTION

The importance of multipole contributions in the elastic scattering of projectiles from odd-A nuclei has been discussed for many years.[1-3] The effects are, in general, observed to be quite weak in proton and α-particle elastic scattering. To date, only one theoretical study, for the $\pi + {}^7$Li reaction, has estimated multipole contributions to pion elastic scattering.[4] In a recent paper,[5] we presented the results of a study of pion elastic scattering at an incident energy of 162 MeV on targets of ^{9}Be, Si, ^{58}Ni, and ^{208}Pb. Reasonable agreement with the results for the three even-even nuclei was obtained with a first-order optical-potential calculation. However, the data for $\pi^\pm$ scattering by ^{9}Be could not be explained in this manner. While the angular distributions for the even-even targets show strong diffractive structure characteristics of strong absorption, the ^{9}Be angular distributions vary much more smoothly. In this paper, we will show that the inclusion of quadrupole contributions can account for the $\pi^\pm + {}^9$Be elastic scattering angular distributions.

II. MULTIPOLE CONTRIBUTIONS TO ELASTIC SCATTERING

If the target has spin J, then all multipoles through order $2J$ must be considered in the elastic scattering of a projectile by this target. Furthermore, our understanding of nuclear collectivity would lead us to expect that only those multipoles with $(-1)^\lambda = 1$ are important. In general, the evaluation of these contributions would require calculations similar to those required for inelastic scattering where the multipole contributions are solely responsible for the scattering. However, in the strong-coupling model, since the intrinsic state of all members of a rotational band is the same, the scatterings from a given mutlipole to states within a band are related[1-3] by angular momentum coupling coefficients. Blair and Naqib[3] have shown that, in the adiabatic approximation, the cross section to any member of the ground-state rotational band is

$$\frac{d\sigma}{d\Omega}(I\to I') = \delta_{I,I'}\frac{d\sigma}{d\Omega}(\lambda=0) + \sum_{\substack{\lambda\neq 0\\ \text{even}}} \langle IK\lambda 0|I'K\rangle^2 \frac{d\sigma}{d\Omega}(\lambda=L)\,. \qquad (1)$$

In this expression, $I(I')$ is the initial (final) state spin and $(d\sigma/d\Omega)(\lambda=0)$ and $(d\sigma/d\Omega)(\lambda=L)$ are the elastic and in-band inelastic cross sections for scattering from a spin-zero nucleus whose intrinsic deformation and optical parameters are the same as those of the odd-mass nucleus in its rotational band. Thus the measured inelastic scattering cross sections determine $(d\sigma/d\Omega)(\lambda=L)$. The various multipole contributions add incoherently, a result well known for the inelastic scattering case.

III. ^{9}Be ELASTIC SCATTERING

The elastic angular distributions for $\pi^\pm + {}^9$Be scattering at $E_{\rm lab} = 162$ MeV measured by Zeidman *et al.*[5] are shown in Figs. 1 and 2. The solid lines are optical-model calculations based on folding the pion-nucleon t matrix with a nuclear-matter density obtained from electron scattering analyses.[6] The momentum-space optical-model code PIPIT[7] was used to generate these calculations. A more complete discussion of these calculations, together with those for pion scattering by ^{12}C, ^{28}Si, ^{58}Ni, and ^{208}Pb, is presented in Ref. 5. We point out that the optical model used here is strictly valid only for even-even nuclei, since the pion-nucleon interaction is averaged over the nucleon spin coordinates. This is, however, appropriate for calculating the monopole term, $(d\sigma/d\Omega)(\lambda=0)$.

Numerous studies of light-ion inelastic scattering from ^{9}Be have definitively identified the $K=\frac{3}{2}$ ground-state rotational band. Votava *et al.*[8] have performed a coupled-channels analysis of the proton elastic and inelastic scattering within this band using a deformed optical-model potential and the strong coupling model. The resulting deformation parameter, β_2, is 1.1, in reasonable agreement with the value ($\beta_2 \sim 1.3$) necessary to explain the ^{9}Be ground-state quadrupole moment.

In the pion inelastic scattering work of Ref. 5, intense transitions to both the $J^\pi = \frac{5}{2}^-$ (2.43-MeV) and $\frac{7}{2}^-$ (6.76-MeV) members of the ground-state rotational band of ^{9}Be were observed with strengths

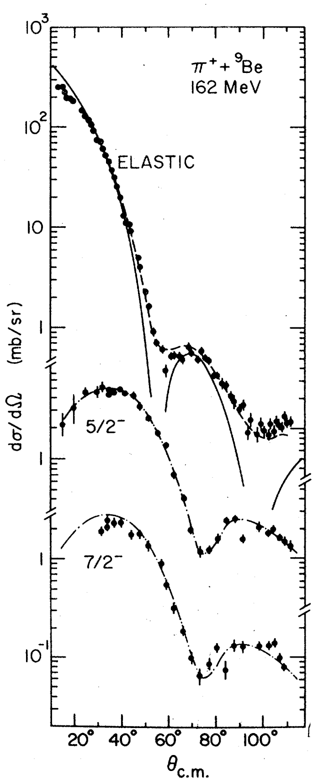

FIG. 1. Angular distributions for $\pi^\pm + {}^9$Be elastic and inelastic scattering to the 2.43-MeV $\frac{5}{2}^-$ state and the 6.76-MeV $\frac{7}{2}^-$ state. The solid curve is an optical-model calculation. The dot-dashed curve is the smooth curve used for the inelastic cross section for computing the quadrupole contribution to the elastic scattering. The dashed curve is

$$\frac{d\sigma}{d\Omega}(\text{optical model}) + \frac{\langle \frac{3}{2}\frac{3}{2}20|\frac{3}{2}\frac{3}{2}\rangle^2}{\langle \frac{3}{2}\frac{3}{2}20|\frac{5}{2}\frac{3}{2}\rangle^2}\frac{d\sigma}{d\Omega}(\tfrac{5}{2}^-,\ 2.43\ \text{MeV}).$$

The curve for the $\frac{7}{2}^-$ state is that drawn for the $\frac{5}{2}^-$ level corrected by the appropriate angular momentum coupling coefficients relating the two states.

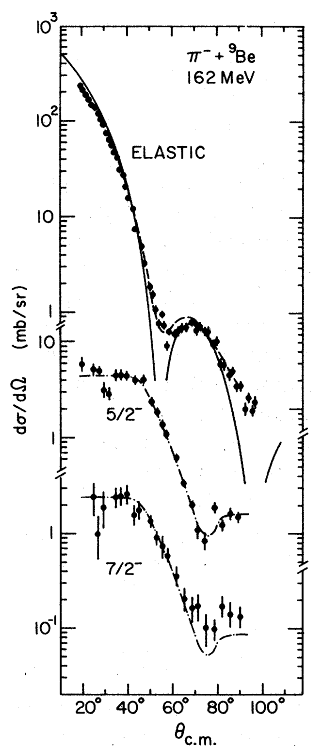

FIG. 2. Angular distributions for $\pi^- + {}^9$Be elastic and inelastic scattering. The curves have the same meaning as in Fig. 1.

comparable to that of the elastic scattering. Angular distributions for these two transitions are displayed in Figs. 1 and 2. The shapes of the inelastic scattering angular distributions are quite similar, and the relative intensities of these transitions are consistent with those predicted by Eq. (1) assuming only quadrupole scattering (only $\lambda = 2$ contributions). Owing to the large (~2-MeV) width of the $\frac{7}{2}^-$ state, the uncertainties in the cross sections for this state are somewhat larger than those for the $\frac{5}{2}^-$ state.

A smooth curve drawn through the experimental angular distribution for the $\frac{5}{2}^-$ state was used to determine the inelastic scattering contribution to the elastic scattering via Eq. (1)

$$\frac{d\sigma}{d\Omega}(\lambda=2)=\langle \tfrac{3}{2}\,\tfrac{3}{2}\,2\,0|\,\tfrac{5}{2}\,\tfrac{3}{2}\rangle^{-2}\frac{d\sigma}{d\Omega}(\tfrac{3}{2}\to\tfrac{5}{2})\,, \tag{2a}$$

$$\frac{d\sigma}{d\Omega}(\tfrac{3}{2}\to\tfrac{3}{2})=\frac{d\sigma}{d\Omega}(\lambda=0)+\langle \tfrac{3}{2}\,\tfrac{3}{2}\,2\,0|\,\tfrac{3}{2}\,\tfrac{3}{2}\rangle^{2}\frac{d\sigma}{d\Omega}(\lambda=2)\,. \tag{2b}$$

The π^+ and π^- data were treated separately.

If the monopole term $(d\sigma/d\Omega)(\lambda=0)$ is taken from the optical-model calculation, the predicted elastic scattering cross section $(d\sigma/d\Omega)(\frac{3}{2},\frac{3}{2})$ is determined. The results are compared with the experimental data in Figs. 1 and 2.

IV. DISCUSSION

The successful application of Eq. (1) to pion elastic scattering by ^{9}Be indicates the importance of quadrupole scattering for this system. However, the quantitative agreement with the data may be somewhat fortuitous. Several potentially important features have been neglected, of which the most obvious are the unusual structure of ^{9}Be, and the possibilities of spin-flip transitions and coupled-channels effects. The ^{9}Be system is extremely weakly bound, and shows some evidence for α-α-n cluster structure.[9] The simple Woods-Saxon matter distribution used in the optical-model calculation does not reflect these features. Angular distributions calculated with different density distributions do not, however, exhibit shallow diffraction minima. Thus it is unlikely that the elastic scattering can be explained in this manner. These observations, of course, depend on the choice of the optical model of Ref. 6 which is based on the fundamental pion-nucleon interaction. If, for example, a Kisslinger potential is used with parameters which are adjusted to fit the $\pi^\pm$ elastic scattering data, adequate fits can be obtained. In this phenomenological approach, the physical effects are absorbed into the adjusted parameters whose underlying physical significance is not readily discernible.

Without detailed calculations, it is quite difficult to estimate the importance of spin-flip amplitudes in pion-elastic scattering. One might expect such contributions to be important in pion scattering on ^{6}Li, which has a very small quadrupole moment and thus is not affected by the quadrupole scattering of concern here. Preliminary results have been obtained for 163-MeV $\pi^- + {}^6$Li elastic scattering.[10] These data seem to be reasonably well described by the optical-model calculations, and suggest that the spin-flip correction for ^{9}Be elastic scattering is probably less than 20% of the quadrupole contribution.[9]

Landau[11] and Sparrow[4] have calculated the spin-flip contributions to the elastic scattering of $\pi^\pm + {}^3$He and $\pi^+ + {}^7$Li, respectively. Extrapolating their results to the ^{9}Be scattering, we again estimate spinflip to be ~10% of the quadrupole contribution.

Since the states of the rotational band are strongly excited, coupled-channels effects are probably important for a complete description of the scattering of pions from ^{9}Be just as it was necessary to include such effects for protons. However, two-step processes should also contribute to the excitation of the $\frac{7}{2}^-$ level. Since the relative strengths of the $\frac{5}{2}^-$ and $\frac{7}{2}^-$ transitions are correctly predicted by Eq. (1), two-step effects do not seem to cause large modifications of the individual angular distributions in the rotational band. This is not to say two-step processes are unimportant, but that the transitions to all states in the band are affected in a similar manner.

V. CONCLUSIONS

In this paper we have shown that quadrupole contributions to pion elastic scattering appear to be quite important in the $\pi + {}^9$Be system. While the quantitative importance of several other possible effects is not well understood, it seems clear that the quadrupole contributions must be included. We should point that the $\pi + {}^9$Be interaction at the energy considered here is probably the best candidate for showing such effects. The elastic angular distributions in the vicinity of the $T=\frac{3}{2}$, $J=\frac{3}{2}$ pion-nucleon resonance tend to be diffractive in nature, and the ^{9}Be target also has an extremely large quadrupole deformation. Pion elastic scattering measurements on other deformed nuclei, in particular ^{7}Li and ^{25}Mg, should be explored to determine the general importance of quadrupole effects.

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