Quadrupole scattering of 135 MeV protons by ^{9}Be

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We have measured cross sections and analyzing powers for ^{9}Be(p,p') at $E_p = 135$ MeV, observing the $\frac{3}{2}^-$ and $\frac{5}{2}^-$ members of the ground-state rotational band. Folding model calculations were performed using a density-dependent effective interaction in the local density approximation. The quadrupole contribution to elastic scattering was evaluated in distorted wave approximation. We find the elastic quadrupole contribution to be important for $q > 1.5$ fm^{-1}, in good agreement with data. The effect on the elastic analyzing power data is quite large.

The quadrupole deformation of ^{9}Be is among the largest known, and hence can be expected to make an important contribution to elastic scattering. Nonspherical contributions to elastic scattering by odd-A nuclei have been studied by Satchler[1] and by Blair and Naqib,[2] who show that quadrupole cross sections due to a static deformation share a common shape and have strengths proportional to

$$\left\langle \begin{matrix} I_i & 2 \\ I_i & 0 \end{matrix} \middle| \begin{matrix} I_f \\ I_i \end{matrix} \right\rangle^2 ,$$

where I_i and I_f are the initial and final nuclear spins. This model was used by Geesaman *et al.*[3] to estimate from inelastic data the quadrupole contribution to the elastic scattering of pions by ^{9}Be. We report new data for the scattering of 135 MeV protons by ^{9}Be, for both the $\frac{3}{2}^-$ and $\frac{5}{2}^-$ members of the ground-state rotational band. Transition potentials based upon Cohen-Kurath wave functions[4] are computed in the folding model. The quadrupole contributions to both elastic and inelastic scattering are then evaluated in DWBA, using distorted waves generated by the spherical part of the elastic potential. We find that the quadrupole contribution to elastic scattering is important for momentum transfers q beyond 1.5 fm^{-1}. The effect upon the analyzing power is particularly dramatic and is in good agreement with the data.

The experiment was performed at the Indiana University Cyclotron Facility, using the quadrupole-dipole-dipole-multipole (QDDM) spectrometer and a standard focal-plane detector array consisting of a helical wire chamber and two plastic scintillators. Data were collected for several BeO targets ranging in thickness between 21 and 69 mg/cm^2. Half of the experiment was performed with an unpolarized beam. For the other half, the polarization was typically 0.75 and was monitored every 4–8 h using the low-energy ^{4}He polarimeter following the injector cyclotron. Forward angle data were collected with a small Faraday cup inside the scattering chamber and normalized against the large external Faraday cup used for $\theta \geq 24°$. The normalizations between targets and between the several runs comprising this experiment were consistent to better than $\pm 5\%$. Further details may be found in Ref. 5.

Collective normal-parity transitions may be described by potentials of the form

$$U_l(r) = U_l^Z + U_l^C + \nabla U^{LS} \otimes \frac{1}{i} \nabla \cdot \sigma \ , \tag{1}$$

where U_l^Z is the Coulomb potential and l is the multipolarity. The central and spin-orbit potentials

$$U_l^C(r) = \frac{2}{\pi} \int dq\, q^2 j_l(qr) \sum_\lambda \rho_{l\lambda}(q) t_{0\lambda}^C(q,\rho_G) \ , \tag{2}$$

$$U_l^{LS}(r) = \frac{2}{\pi} \int dq\, q^2 j_l(qr) \sum_\lambda \rho_{l\lambda}(q) t_\lambda^{LS}(q,\rho_G) \tag{3}$$

are obtained by folding the matter transition density $\rho_{l\lambda}$ with effective interactions $t_{0\lambda}^C$ and t_λ^{LS}, where $\lambda = 0$ or 1 denotes isospin. For simplicity, the dependence of the effective interaction upon the local ground-state density ρ_G is evaluated at the site of the projectile. Additional contributions due to spin and current densities were found to be negligible. This microscopic approach includes magnetic and other noncollective contributions, and thus is more general than the collective model calculations of Refs. 1 and 2.

We use the density-dependent effective interaction constructed by the Hamburg group from the Paris potential.[6] The Paris-Hamburg (PH) interaction has been found to provide a good description of elastic scattering of 100–400 MeV protons by spherical nuclei.[7] However, its description of inelastic scattering is less successful; the data seem to require stronger density dependence.[8] For the surface-peaked 2^+ state of ^{16}O, we found[9] that an adequate description of the scattering of 135 MeV protons could be obtained by multiplying the results of this model by $(0.86)^2$. The same factor is applied to the inelastic cross section for ^{9}Be.

Transition densities were computed from the p-shell wave functions tabulated by Lee and Kurath[4] using oscillator wave functions. The oscillator parameter $b = 1.67$ fm was chosen to reproduce the charge radius $\langle r^2 \rangle^{1/2} = 2.52$ fm.[10] Note that we correct for the finite nucleon size but do not apply a center-of-mass form factor. To reproduce the quadrupole moment $Q = 5.3$ fm^2 deduced from measurements of hyperfine structure,[11] it is

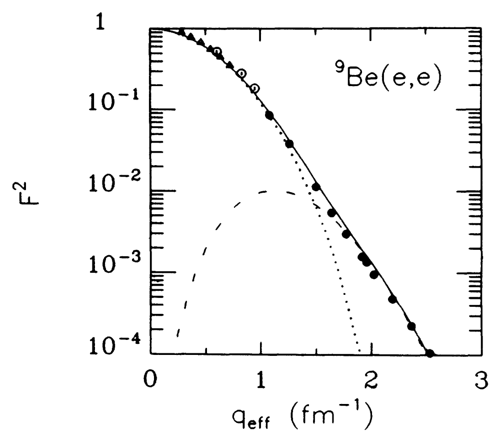

FIG. 1. Elastic electroexcitation form factor for ^{9}Be. The dotted curve gives the monopole and the dashed curve the quadrupole contributions to the total form factor (solid line). The data shown as triangles are from Ref. 10, the open circles from Ref. 12, and the solid points from Ref. 13.

then necessary to include a $C2$ effective charge $\delta_p = 0.58$. This model provides a good fit to the elastic form factor measurements[10,12,13] shown in Fig. 1, and to the data for the $\frac{5}{2}^-$ state (not shown).[13,14] Assuming that the core polarization is essentially isoscalar, we also use $\delta_n = \delta_p$, so that the isoscalar quadrupole density is enhanced by a factor of $e_0 = 2.16$. The (p,p') results are not very sensitive to the assumed isovector charge $e_1 = 1$. Spin and current densities were not enhanced.

The quadrupole contribution to the elastic scattering matrix $f(\theta)$ is evaluated in perturbation theory according to

$$f(\theta) = f_0(\theta) - \frac{\mu}{2\pi} \langle \chi_f^{(-)} | U_2 | \chi_i^{(+)} \rangle , \tag{4}$$

where f_0 is the exact elastic scattering produced by the spherical potential U_0 alone. The distorted waves χ are solutions to the "relativistic" Schrödinger equation

$$[\nabla^2 + k^2 - 2\mu U_0]\chi = 0 , \tag{5}$$

where μ is the reduced energy and k is the relativistic wave number.

The results for elastic scattering are shown in Fig. 2, where the solid curves include both spherical and deformed contributions and the dotted curves include only the spherical potential. The $M1$ and $M3$ contributions were found to be negligible. The quadrupole contribution to the cross section, shown as the dashed line, is most important for $q > 1.5$ fm^{-1}. The spherical part of the cross section falls well below the data in this region. The quadrupole cross section repairs this deficit quite nicely.

The most dramatic signature of quadrupole scattering is found in the analyzing power. Based upon the spherical potential alone, we would have expected to find a strong positive A_y peak near $q \sim 2$ fm^{-1}. Such a peak is characteristic of elastic scattering by spherical nuclei of protons in this energy regime. However, the observed analyzing power flattens out at small negative values for q between 2 and 3 fm^{-1}. The quadrupole contribution to

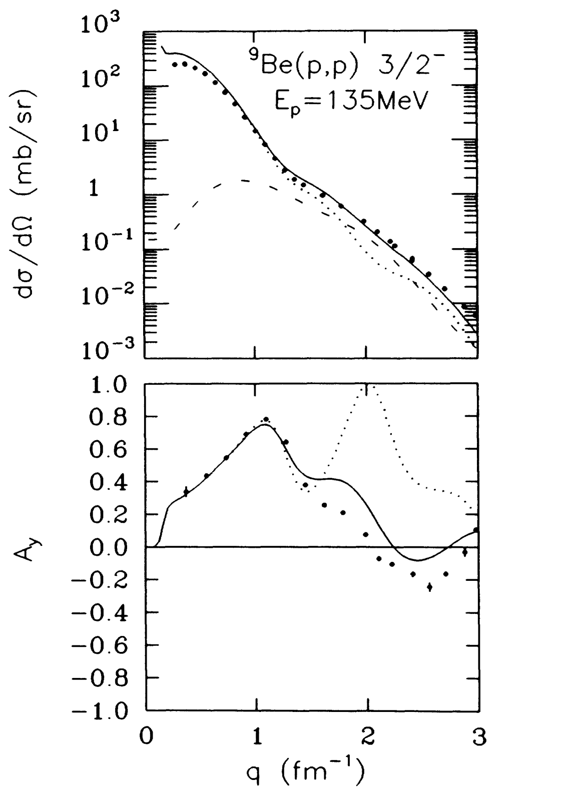

FIG. 2. Elastic scattering of 135 MeV protons by ^{9}Be. The dotted curves are computed for the spherical potential alone, the dashed curve gives the quadrupole contribution to the cross section, and the solid curves include the quadrupole contribution in DWBA. This calculation uses a density-dependent effective interaction.

elastic scattering reproduces this effect rather well.

The inelastic scattering results for the $\frac{5}{2}^-$ member of the ground-state rotational band are shown in Fig. 3. The cross section prediction agrees with the data very well over the entire angular distribution. Although these calculations are based upon the shell model, the relative strength of the inelastic and elastic quadrupole cross sections is in good agreement with the rotational model. The inelastic analyzing power is also in good qualitative agreement with the data.

The remaining discrepancies between the calculations and the data are attributable, in part, to known defects of the Paris-Hamburg effective interaction. The node in the inelastic analyzing power calculation occurs at somewhat larger momentum transfer than the node in the data. This same discrepancy has also been seen for normal-parity isoscalar transitions in other nuclei.[8] Had the inelastic analyzing power become negative sooner, then the elastic analyzing power would have been improved also. Furthermore, elastic cross sections predicted by this interaction are always somewhat too large at low q, as also observed here. Therefore, we can expect improvements of the effective interaction for spherical nuclei to also improve the quantitative accuracy of the present calculation and conclude that the model is essentially correct.

Similar effects have also been observed by Roy *et al.*[15]

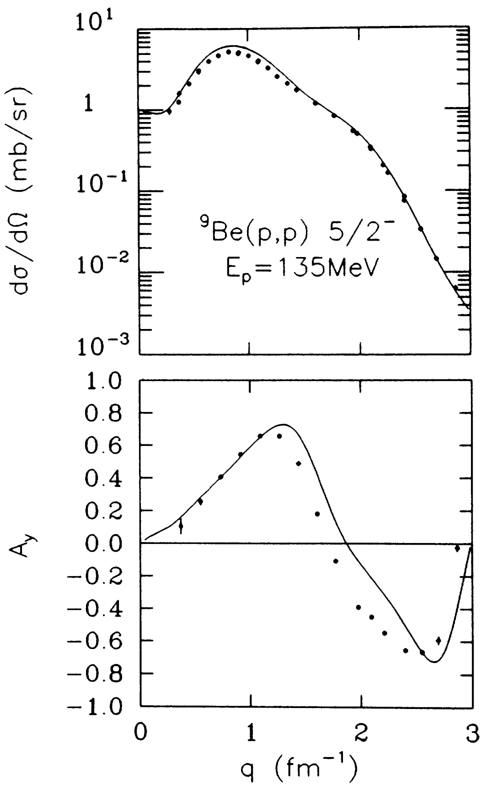

FIG. 3. Excitation of the $\frac{5}{2}^-$ rotational state of ^{9}Be by 135 MeV protons. The calculation uses Cohen and Kurath wave functions and a density-dependent effective interaction.

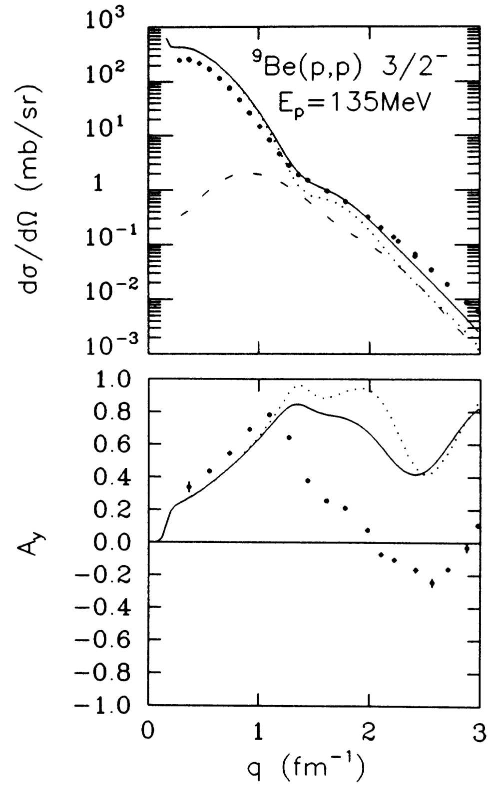

FIG. 4. Elastic scattering of 135 MeV protons by ^{9}Be is computed in the impulse approximation and shown with the same legend as Fig. 2. Density dependence is important even for ^{9}Be.

in the elastic scattering of 220 MeV protons. However, those authors chose to fit their data with spherical optical potentials of the Woods-Saxon type. The resulting strength and geometry parameters are rather peculiar. These potentials bear little resemblance to those predicted by the folding model or fitted to data for other light nuclei. Roy *et al.* then perform coupled-channels fits but do not display the effect of coupling beyond that implicit in our first-order model. Work by Carpenter *et al.*[16] demonstrates that the distorted wave approximation accurately reproduces the elastic scattering results obtained from the solution to the coupled equations, even for the large deformation of ^{9}Be. The agreement between these calculations is quantitative for the cross section and is semiquantitative for the analyzing power beyond 2 fm^{-1}. Hence, we believe that phenomenological coupled-channels analyses based upon unrealistic potentials serve little purpose.

Finally, we present in Fig. 4 an elastic scattering calculation based upon the density-independent interaction of Franey and Love.[17] Although the quadrupole contribution still helps, it is clear that the impulse approximation fails badly. Similar discrepancies are also found when inelastic scattering is computed in impulse approximation. Evidently, density dependence is important and appears to be well described by the local density approximation even for a nucleus as small as ^{9}Be.

We conclude that quadrupole scattering can make important contributions to elastic scattering by odd-A nuclei and is well described by the distorted wave approximation. We also conclude that the local density approximation provides an adequate description of the effective interaction in light nuclei.

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[1]G. R. Satchler, Nucl. Phys. **45**, 197 (1963).
[2]J. S. Blair and I. M. Naqib, Phys. Rev. C **1**, 569 (1970).
[3]D. F. Geesaman, C. Olmer, B. Zeidman, R. L. Boudrie, R. H. Siemssen, J. F. Amann, C. L. Morris, H. A. Thiessen, G. R. Burleson, M. J. Devereux, R. E. Segel, and L. W. Swenson, Phys. Rev. C **18**, 2223 (1978).
[4]T. S. H. Lee and D. Kurath, Phys. Rev. C **21**, 293 (1980).
[5]J. J. Kelly, Ph.D. thesis, Massachusetts Institute of Technolo-

gy, 1981.

[6]H. V. von Geramb, in *The Interaction Between Medium Energy Nucleons in Nuclei (Indiana Cyclotron Facility, Bloomington, Indiana),* Proceedings of the Workshop on the Interactions Between Medium Energy Nucleons in Nuclei, AIP Conf. Proc. No. 97, edited by H. O. Meyer (AIP, New York, 1982), p. 44.

[7]L. Rikus, K. Nakano, and H. V. von Geramb, Nucl. Phys. **A414**, 413 (1984).

[8]J. J. Kelly, in *Relations Between Structure and Reactions in Nuclear Physics,* edited by D. H. Feng, M. Vallieres, and B. H. Wildenthal (World Scientific, Singapore, 1987), p. 222.

[9]J. J. Kelly, W. Bertozzi, T. N. Buti, J. M. Finn, F. W. Hersman, M. V. Hynes, C. Hyde-Wright, B. E. Norum, A. D. Bacher, G. T. Emery, C. C. Foster, W. P. Jones, D. W. Miller, B. L. Berman, J. A. Carr, and F. Petrovich, Phys. Lett. **169B**, 157 (1986).

[10]J. A. Jansen, R. Th. Peerdeman, and C. deVries, Nucl. Phys. **A188**, 337 (1972).

[11]A. G. Blachman and A. Lurio, Phys. Rev. **153**, 164 (1967).

[12]A. G. Slight, T. E. Drake, and G. R. Bishop, Nucl. Phys. **A208**, 157 (1973).

[13]R. W. Lourie, W. Bertozzi, T. N. Buti, J. M. Finn, F. W. Hersman, C. Hyde, J. Kelly, M. A. Kovash, S. Kowalski, M. V. Hynes, B. E. Norum, and B. L. Berman, Phys. Rev. C **28**, 489 (1983).

[14]J. Glickman *et al.* (unpublished).

[15]G. Roy, H. S. Sherif, E. D. Cooper, L. G. Greeniaus, G. A. Moss, J. Soukop, G. M. Stinson, R. Abegg, D. P. Gurd, D. A. Hutcheon, R. Liljestrand, and C. A. Miller, Nucl. Phys. **A442**, 686 (1985).

[16]A. W. Carpenter, Ph.D. thesis, Florida State University, 1987; A. W. Carpenter, F. Petrovich, R. J. Philpott, and J. A. Carr (unpublished).

[17]M. A. Franey and W. G. Love, Phys. Rev. C **31**, 488 (1985).