Quadrupole effects in ^{7}Li scattering at 88 MeV

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Calculations for ^{7}Li elastic scattering at 88 MeV have been made explicitly including a quadrupole term in the optical potential resulting from folding of an effective nucleon-nucleon interaction with the quadrupole deformation of ^{7}Li. Data for ^{48}Ca could be fitted without a renormalization of the folded potential, but this was not possible for lighter targets which required a renormalization of about 0.6 even when the quadrupole potential was included.

[NUCLEAR REACTIONS $^7\mathrm{Li} + {}^{24,26}\mathrm{Mg}$, ^{40,48}Ca, $E=88$ MeV. Double-folding model analysis, quadrupole potentials.]

The double folding model,[1] in which the optical potential is obtained from the convolution of an effective nucleon-nucleon interaction with the projectile and target distributions, is now widely used in the analysis of heavy-ion elastic and inelastic scattering data. Specifically, the folded potential is given by

$$V_F(\vec{r})=\int d\vec{r}_P \int d\vec{r}_T \rho_P(\vec{r}_P)\rho_T(\vec{r}_T) \times v(\vec{r}-\vec{r}_P+\vec{r}_T), \tag{1}$$

where $\rho_P(r)$ and $\rho_T(r)$ are the projectile and target densities, and $v(r)$ is the effective interaction which is commonly taken to be the $S=T=0$ component of the M3Y interaction determined by Bertsch *et al.*,[2] modified[1] to account for single nucleon exchange

$$v(r)=7999\frac{e^{-4r}}{4r}-2134\frac{e^{-2.5r}}{2.5r}-262\delta(\vec{r}). \tag{2}$$

This model has been successfully applied for heavy ions with $A \geq 10$, but for the lighter projectiles ^{6,7}Li and ^{9}Be the potential needs to be multiplied[1,3–7] by a renormalization or "unhappiness factor" of about $\frac{1}{2}$. It has been suggested[5] that the anomalous behavior of these projectiles is associated with their small breakup energies. Another explanation[8] offered for ^{7}Li and ^{9}Be was that their large static quadrupole moments introduce additional terms in the optical potential which could be important. Coupled-channels calculations[8,9] for ^{7}Li at 34 MeV and ^{9}Be at 40 MeV were able to reproduce the data without a renormalization of the real folded potential when the quadrupole effects were explicitly included. This paper considers the role of the quadrupole coupling term in $^7\mathrm{Li} + {}^{24,26}\mathrm{Mg}$, ^{40,48}Ca elastic scattering at 88 MeV where the data[10] exhibit deep oscillations and are likely to be more sensitive to such a term than at the lower energies of the previous studies.

At first the 88 MeV ^{7}Li data were fitted with just the monopole part of the optical potential. The real potential was obtained by folding the effective interaction of (2) with spherical projectile and target densities using the momentum-space folding code DFPOT.[11] A harmonic oscillator form[12] was used for the ^{7}Li density

$$\rho_P^0(r)=(A+\mathrm{B}r^2)e^{-\alpha^2 r^2} \tag{3}$$

with $A=0.13865$ fm^{-3}, $B=0.02316$ fm^{-1}, and $\alpha=0.578$ fm^{-1}. The target densities were obtained from the liquid drop model[13] after unfolding the nucleon charge distribution. A phenomenological Woods-Saxon form was used for the imaginary monopole potential. The optical model search program HERMES,[14] which also has the ability of solving the coupled equations when the quadrupole term is included, was used for the calculations in which the normalization of the real potential and the imaginary potential parameters were varied to fit the data. The fits are shown as the full lines in Fig. 1 and the parameters are given in Table I (Part a). For all four targets a renormalization of about 0.6 was required to fit the data.

The real part of the quadrupole potential was calculated by folding the effective interaction with the

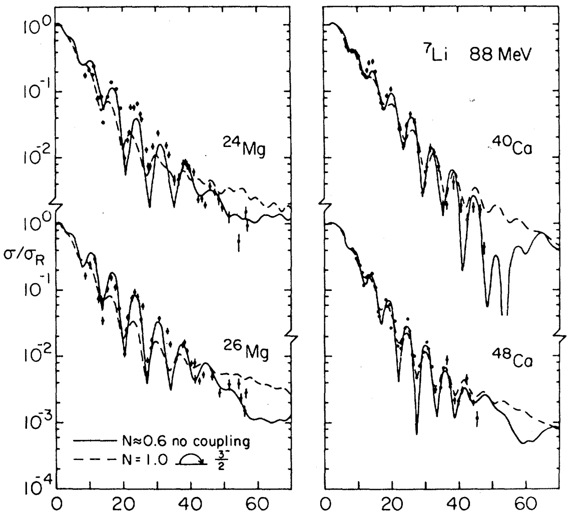

FIG. 1. Angular distributions for ^{7}Li elastic scattering at 88 MeV compared with calculations with (dashed lines) and without (full lines) the reorientation coupling of the projectile ground state. N was allowed to vary in the fits without coupling, but was fixed at $N=1.0$ in the fits with coupling. The data are from Ref. 10 and the potential parameters are given in Table I, Parts (a) and (c).

quadrupole density of the projectile and the spherical density of the target. The projectile quadrupole was assumed to have a derivative form

$$\rho_P{}^2(r)=\delta_2 d\rho_P^0(r)/dr, \tag{4}$$

where the quadrupole deformation length δ_2 (-3.4 fm) was determined by normalization to the intrinsic quadrupole moment Q_{20} of ^{7}Li

$$(16\pi/5)^{1/2}\int \rho_P{}^2(r)r^4dr=(A/Ze)Q_{20}. \tag{5}$$

Assuming a rotational model for ^{7}Li the intrinsic quadrupole moment Q_{20} is related to the experimental value[15] of the static moment $Q_2=-4.5 \pm 0.5e$ fm^2 by $Q_{20}=-5Q_2$. The real quadrupole potential was multiplied by the same renormalization factor N as the real monopole potential. A Woods-Saxon derivative form was used for the imaginary quadrupole potential, with an independently variable deformation length δ_I.

Calculations were now made with both the monopole and quadrupole parts of the optical potential, adjusting all six parameters with $N\approx 0.6$ to fit the data, resulting in the parameters of Table I (Part b). In all four cases N changed only very slightly from the fits with the spherical potential alone and the imaginary potential parameters were similar, with deformation lengths rather much smaller than the value obtained from the static quadrupole moment. The fits, judged by the values of χ^2 per point, were better when the quadrupole potential was included, mainly due to a filling in of the deep diffractive minima. However, this by itself does not necessarily show that a quadrupole term is an important addition to the optical potential, since a similar effect results from folding in the experimental angular ac-

TABLE 1. Optical-potential parameters and quadrupole deformation lengths for ^{7}Li elastic scattering at 88 MeV. The potential has a double folded real part, renormalized by the factor N, and a Woods-Saxon imaginary part.

Target	N	W (MeV)	r_I[a] (fm)	a_I (fm)	δ_I (fm)
		(a) No coupling			
^{24}Mg	0.57	28.0	1.63	1.19	0.0
^{26}Mg	0.59	25.6	1.75	0.93	0.0
^{40}Ca	0.63	16.4	1.95	0.72	0.0
^{48}Ca	0.61	21.5	1.66	1.01	0.0
		(b) With coupling			
^{24}Mg	0.56	25.8	1.70[b]	1.16	-0.4
^{26}Mg	0.55	27.1	1.70[b]	0.97	-0.3
^{40}Ca	0.58	22.1	1.82	0.81	-1.4
^{48}Ca	0.64	23.7	1.62	1.05	-1.6
		(c) With coupling			
^{24}Mg	1.0	76.6	0.89	1.65	-4.6
^{26}Mg	1.0	57.9	1.34	1.50	-8.3
^{40}Ca	1.0	31.8	1.78	0.96	-5.8
^{48}Ca	1.0	36.3	1.60	1.15	-6.2

[a] $R_I=r_I A_T{}^{1/3}$; charge radius $R_c=1.3A_T{}^{1/3}$ fm.

[b] r_I was kept fixed at 1.7 fm to avoid a continuous ambiguity between W and r_I.

ceptance of about 0.8° with the theoretical calculations.

To determine whether the data can be described with the folded potential without renormalization when the quadrupole terms are included, further calculations were made with N fixed at unity and the imaginary deformation length δ_I equal to the quadrupole deformation length of the projectile δ_2. The imaginary Woods-Saxon parameters were varied to improve the fits, which were of poor quality except for ^{48}Ca. The fits which resulted when δ_I was also varied were better and are shown as the dashed lines in Fig. 1 with the parameters given in Table I (Part c). The fit for ^{48}Ca with $N=1.0$ and the quadrupole potential included is almost as good as that for the spherical potential alone with $N \approx 0.6$, but the fits become progressively worse as the target becomes lighter. In particular, there is not enough structure in the cross sections at small angles and the magnitudes of the peaks are underpredicted. Thus it would appear that inclusion of the quadrupole term for heavy targets enables the renormalization factor to be dispensed with if a deeper imaginary potential is used with an imaginary deformation length much larger than calculated from the quadrupole moment. However, the same mechanism does not work well for lighter targets where the fits result in very unusual imaginary parameters. Finally, calculations were made varying N as well, starting from unity. For ^{40,48}Ca N changed by only ± 0.05 from unity and resulted in only small improvements to the fits, whereas for ^{24,26}Mg N decreased to about 0.6 in order to fit the data.

In conclusion, for ^{7}Li scattering at 88 MeV it is not possible to describe the data for ^{24,26}Mg with an unrenormalized folded potential when the quadrupole part is included, although this works better for ^{40}Ca and well for ^{48}Ca. Since ^{7}Li has a strongly excited $\frac{1}{2}^-$ state at 0.478 MeV this could have an important effect on the elastic scattering channel. However, coupled-channels calculations for ^{24,26}Mg carried out here and in Ref. 16 explicitly including this state, although resulting in improved fits to the elastic cross section when $N \approx 0.6$, were unable to fit the data with $N=1.0$. It is more likely that the failure to fit the data for the Mg isotopes is due to a larger amount of projectile breakup from light targets compared to heavier ones. The first α decaying state for ^{7}Li occurs at 4.63; 2.16 MeV above the $\alpha+t$ breakup threshold. Experimentally[17] the breakup of 70 MeV ^{7}Li scattered from ^{12}C proceeds sequentially through the 4.63 MeV $\frac{7}{2}^-$ state in ^{7}Li, whereas when scattered from ^{208}Pb the projectile breakup occurs as a direct one-step process in the nuclear field of the target. It is this changing nature of the breakup process which we believe results in our different conclusions for the Mg and Ca targets. Nagarajan *et al.*[18] recently published adiabatic breakup calculations for the $^7\text{Li}+{}^{40,48}\text{Ca}$ data analyzed here using an $\alpha+t$ Watanabe cluster model. They found that whereas the ^{7}Li quadrupole moment and projectile excitation had only small effects on the elastic scattering, the inclusion of p and f wave breakup decreased the magnitude of the cross section when $N=1.0$ to obtain better agreement with the data. However, although the phasing of the peaks was good, their magnitude was underestimated. Since their analysis enables a distinction to be made between direct and sequential breakup it would be worthwhile to repeat the work for the Mg targets to confirm whether our hypothesis is correct.

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