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DOMINANCE OF STRONG ABSORPTION IN $^{9}Be + ^{28}Si$ ELASTIC SCATTERING*

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For several years we have been involved in a systematic study[1,2] of elastic scattering of light heavy ions from ^{28}Si. Our goal is to gain a better understanding of this relatively simple heavy ion interaction process. For example, we wish to know about the energy dependence of the optical potentials, whether we can determine the real or imaginary well depths, the "projectile dependence" of the interaction, and whether heavy ions show evidence for nuclear "rainbow" scattering (as is found[3] for light ion projectiles).

From our study of $^{16}O + ^{28}Si$ elastic scattering[1] we found that, in contrast to light ion behavior, the high energy data show no evidence for being dominated by rainbow scattering. Moreover, a shallow 6-parameter Woods-Saxon (WS) potential was found (E18) which is capable of fitting data from $E_L = 33$ to 215 MeV without explicit energy dependence. A similar study of the $^{12}C + ^{28}Si$ system[2] gave essentially the same results.

In contrast to these results, however, we found that the $^{6}Li + ^{28}Si$ system behaved in a qualitatively different fashion.[2] In particular, the ^{6}Li data at $E_L = 135.1$ MeV do exhibit the characteristic exponential fall-off of nuclear rainbow scattering. As is true for α-particle elastic

scattering[3], we found that a reasonable fit to the high energy data required a real well depth $V_o \gtrsim 100$ MeV. Furthermore, it was found to be impossible to fit ^{6}Li + ^{28}Si data over a large energy range with an energy independent WS potential. On the basis of the qualitative differences described above, we term the ^{6}Li + ^{28}Si system to exhibit "light ion" behavior while the ^{12}C + ^{28}Si and ^{16}O + ^{28}Si systems show "heavy ion" behavior.

Because the character of the scattering changes markedly from ^{6}Li to ^{12}C projectiles, we have undertaken a study of the ^{9}Be + ^{28}Si system to map out the transition region. Data were measured at 121.0 and 201.6 MeV using ^{9}Be(3+) and ^{9}Be(4+) beams from the LBL 88-inch cyclotron. In order to carry out global optical model searches, low energy ^{9}Be + ^{28}Si data, measured by other groups[4], were also utilized.

Compared with our results for the other projectiles,[1,2] we find that demanding an energy independent fit does not constrain the depth of the real potential in the case of ^{9}Be scattering. This is demonstrated by the wide variety of potentials listed in Table I, fits from some of which are illustrated in Fig. 1. For example, we note that potential sets G92 and G95 have essentially the same imaginary well but very different central well depths for the real potential. Clearly the fits in Fig. 1 are not very sensitive to the depth of the real well. There is some problem with most of the potentials listed in Table I in reproducing the trend of the back angle data ($\theta_{c.m.} \approx 25°$) at 201 MeV. This deficiency is improved (see Fig. 1) by using a potential such as G38.

One question we had hoped to answer in this study concerned the existence of rainbow scattering. We know that high energy light ion elastic scattering angular distributions, up to ^{6}Li,[2,3] do show behavior which is

dominated by nuclear rainbow scattering, while ^{12}C and ^{16}O projectiles do not.[1,2] The potentials in Table I have predicted rainbow angles ranging from -81° (G90) to -3° (G38). Thus, the data would be expected to show characteristic rainbow behavior (at least if V $\gtrsim$ 75 MeV) unless the absorption is too strong. It turns out that the absorptive strength required to fit the data is enough to remove the observable effects of the rainbow scattering in the calculated angular distributions. This is confirmed by model calculations which show that reducing the strength of the imaginary potential by a factor of 2 for set G92 gives rise to a factor of 10 increase in the back angle cross sections at 201 MeV, as well as giving rise to the smooth angular distribution which is typical[3] of nuclear rainbow scattering. Although the calculation with potential G38 does show some flattening out at back angles, this is <u>not</u> related to rainbow effects. For this potential a reduction of the imaginary strength by a factor of 100 (to W = 5 MeV) makes essentially no change in the magnitude of the predicted cross sections, although the phase of the oscillations shifts markedly.

In order to understand why the various projectiles behave differently, we have examined the potentials which fit the data. Figure 2 shows the radial form of the potentials for ^{6}Li, ^{9}Be, and ^{16}O elastic scattering from ^{28}Si. The "sensitive regions" shown in the figure were obtained from "notch perturbation" calculations.[5] (Potential parameters for ions other than ^{9}Be are given in Refs. 1 and 2.) Although we have used potentials having no <u>explicit</u> energy dependence, the different real and imaginary well geometries nonetheless give rise to an implicit energy dependence of the potential. This is demonstrated in Fig. 3, where we plot the ratio of V/W (evaluated at the radius of maximum sensitivity obtained in the notch

perturbation calculations) as a function of energy.

For the $^{16}O + ^{28}Si$ potential E18, we see that the ratio slopes downward as the energy increases, signifying a gradual increase in the strength of the imaginary compared with the real potential. Potential A23 of Ref. 1 is a deep real potential which was adjusted (by increasing the imaginary strength) to fit the high energy data. Clearly it will work less well at low energies. For comparison, the behavior of Satchler's "A-type" potential[6] is shown in Fig. 3. This potential has essentially the same real well as potential A23 but has an imaginary diffuseness which increases with energy. Looking at Fig. 3, it is not surprising that this potential does an equivalently good job at fitting the data.

In the case of $^{6}Li + ^{28}Si$, just the opposite trend is observed, with the V/W ratio increasing as the energy increases. For ^{6}Li it has not been possible to find an energy independent potential which fits the high and low energy data sets simultaneously; the curve marked "fits" is obtained from different potentials at each energy. Part of the problem is related to the very rapid change in the V/W ratio between $E_{c.m.}$ = 10 and 40 MeV. An energy independent WS potential has trouble following such a rapid variation; the curve for potential R22 is representative of about how well one can do with a WS shape. Potential Z8 is a shallow, surface transparent potential similar to the $^{16}O + ^{28}Si$ potential E18 and has entirely the wrong trend for the data.

Looking now at the $^{9}Be + ^{28}Si$ potentials, we see that the overall trend is quite flat, with the imaginary potential always stronger than the real. If we stretch our faith in the representation shown in Fig. 3, we can infer that for this particular system a 4-parameter WS potential (that is,

$r_R = r_I$, $a_R = a_I$) might be adequate over the whole energy range. This is indeed correct, since calculations with potential G05 in Table I yield fits equal in quality to those from the 6-parameter potentials.

If we look at these trends for the various projectiles, we see that the ^{16}O potential behaves in a rather intuitive way, that is, the imaginary potential gets more important as the energy increases. On the other hand, ^{6}Li behaves in the opposite fashion and ^{9}Be shows domination by the imaginary potential at all energies. Particularly in the case of ^{6}Li, it is tempting to ascribe the low energy behavior to breakup in the Coulomb field of the target. This mechanism has been demonstrated[7] for ^{6}Li at near-barrier energies, although even at the barrier the nuclear potential plays a role.[8] In addition, there is some evidence[9] that the breakup changes to a direct (presumably nuclear) process at high energies. We note again that Fig. 3 shows almost a discontinuity in the V/W ratio at low energies which makes these data difficult to fit along with the higher energy data even when using an explicitly energy dependent potential. However, it <u>is</u> possible to get fairly reasonable fits to the higher energy data sets (E_L = 46 - 135.1 MeV) with an energy independent potential.

In the ^{9}Be case, Fig. 3 does not indicate any anomaly in the low energy data. However there are some differences in ^{9}Be compared with ^{6}Li which might explain this fact. Although ^{6}Li breakup at low energies goes mainly through a single state (the 3^+ at 2.18 MeV), which is excited primarily via Coulomb excitation,[7] the ^{9}Be breakup[10] goes through a number of low-lying states. One of these states is reached by an E2 transition with a B(E2) similar to that for the ^{6}Li excited state, but the others are not reached by E2 transitions and might be predominantly excited by nuclear inelastic

scattering. Depending on which states dominate the breakup process, it is possible that the V/W ratio does not change much near the barrier.

In summary, we find that the elastic scattering of ^{9}Be from ^{28}Si is dominated at all energies by relatively strong absorption. This removes much of the sensitivity to the real potential and even elastic scattering data spanning a range of energies from 13 to 201 MeV do not allow a unique determination of the potential parameters. There is at least circumstantial evidence that ^{6}Li scattering at low energies (and by implication also ^{9}Be scattering) may be strongly influenced by breakup processes, although it is not entirely clear that the breakup mechanism is the same in both cases.

References

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1) J.G. Cramer, R.M. DeVries, D.A. Goldberg, M.S. Zisman, and C.F. Maguire, Phys. Rev. C 14, 2158 (1976).

2) R.M. DeVries, D.A. Goldberg, J.W. Watson, M.S. Zisman, and J.G. Cramer, Phys. Rev. Lett. 39, 450 (1977).

3) D.A. Goldberg, S.M. Smith, and G.F. Burdzik, Phys. Rev. C 10, 1367 (1974); D.A. Goldberg in Proceedings of the Symposium on Heavy Ion Elastic Scattering, University of Rochester, Oct. 25-26, 1977, p. 242 (unpublished).

4) J.S. Eck, T.J. Gray, and R.K. Gardner, Phys. Rev. C 16, 1873 (1977); D.P. Stahel, G.J. Wozniak, M.S. Zisman, B.D. Jeltema, and Joseph Cerny, Phys. Rev. C 16, 1456 (1977); R.M. DeVries et al., unpublished data.

5) J.G. Cramer, University of Washington Nuclear Physics Laboratory Annual Report, 1976, p. 115 (unpublished).

6) G.R. Satchler, Nucl. Phys. A279, 493 (1977).

7) D. Scholz, H. Gemmeke, L. Lassen, R. Ost, and K. Bethge, Nucl. Phys. A288, 351 (1977).

8) H.W. Wittern, Physics Lett. 32B, 441 (1970).

9) R. W. Ollerhead, C. Chasman, and D.A. Bromley, Phys. Rev. 134, 1374 (1963).

10) H. Werle, L. Van der Zwan, and K.W. Geiger, Z. Physik 259, 275 (1973); A.W. Obst, T.B. Grandy, and J.L. Weil, Phys. Rev. C 5, 738 (1972).

Table I. $^{9}Be + ^{28}Si$ Optical Potentials

Set	V (MeV)	r_R (fm)	a_R (fm)	W (MeV)	r_I (fm)	a_I (fm)	θ_R (deg)
G90	300.0	0.567	0.942	41.1	1.054	0.782	-81
G92	150.0	0.703	0.944	27.6	1.150	0.753	-46
G89	100.0	0.767	0.960	23.1	1.191	0.736	-31
G84	75.0	0.776	1.012	29.8	1.143	0.744	-22
G95	15.0	1.149	0.914	24.4	1.185	0.701	-2
G38	13.8	1.244	0.652	503.2	0.617	0.825	-3
Z06	13.8	1.243	0.655	323.5	0.691	0.818	-3
G05	13.8	1.232	0.729	16.9	1.232	0.729	-3

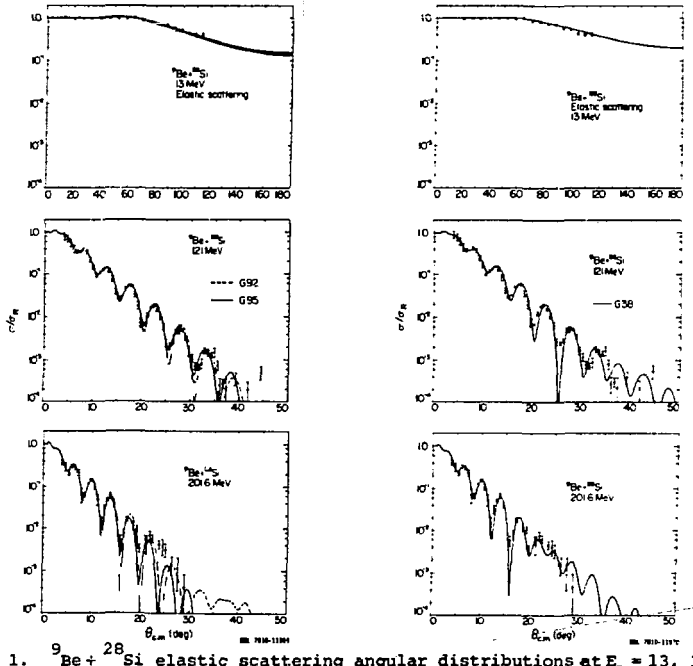

Fig. 1. $^{9}Be + ^{28}Si$ elastic scattering angular distributions at E_L = 13, 121 and 201.6 MeV. Optical potential parameters are listed in Table I.

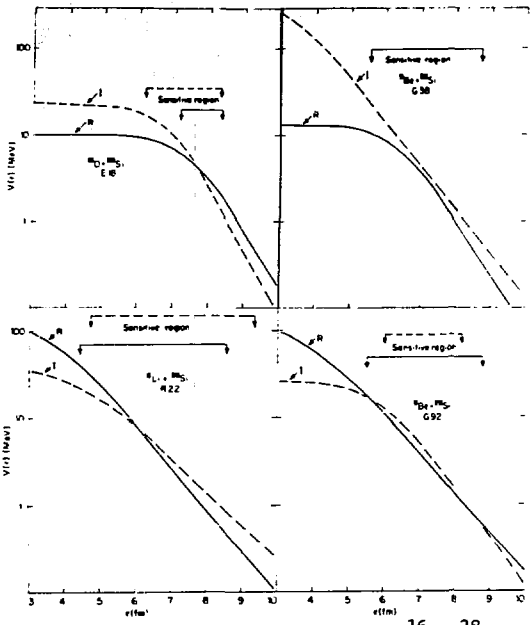

Fig. 2. Radial shapes of potentials found for $^{16}O + ^{28}Si$ (Ref. 1), $^{6}Li + ^{28}Si$ (Ref. 2), and $^{9}Be + ^{28}Si$ elastic scattering.

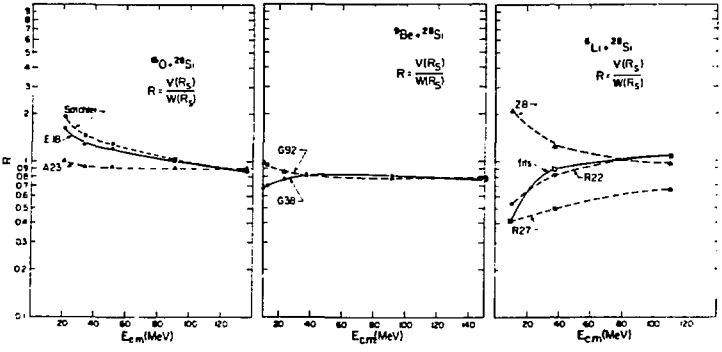

Fig. 3. Ratio of real to imaginary potential (evaluated at the radius of maximum sensitivity) for various heavy ion elastic scattering systems.

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