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THE SENSITIVITY OF THE FORWARD CROSS SECTION IN TRANSFER REACTIONS BETWEEN HEAVY IONS TO THE EDGE OF THE NUCLEAR FIELD†

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The ratio of the cross section for two nucleon transfer in heavy ion reactions measured at forward angle and at the grazing angle depends very sensitively on the location of the edge of the imaginary potential compared to the real.

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In this note we focus attention on the cross section in heavy ion reactions at angles smaller than the grazing angle, θ_g. Under classical sub-coulomb conditions, such scattering events would correspond to large impact parameters or distant collisions where the field is weak and causes little deflection. Of course, distant orbits cannot very effectively contribute to nucleon transfer reactions, especially when more than one nucleon is transferred, because of the exponential decay of the bound state wave functions. However, in the classical scattering of particles in a field, such as that which acts

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between heavy ions, there exist also small impact parameter orbits which lead to forward scattering, for energies above the barrier, as was pointed out long ago by Ford and Wheeler [1]. Nuclei on such orbits can very easily transfer particles. They are, however, subject to absorption, because of their close encounter. However, this is precisely our interest in them. We claim that forward angle scattering in transfer reactions can be used as a very sensitive probe of the edge of the nuclear potential acting between heavy ions.

The situation is illustrated schematically in fig. 1. The distant orbit, a, is only slightly deflected by some small angle, θ, say. A closer orbit, b, since it feels a stronger repulsive field, is scattered to a larger angle. However, the two closer orbits c and d ($d < c$) feel a net attraction and scatter to the same angle θ as a. The orbits such as c and d are the ones of interest here.

In fig. 2 we show calculated cross sections for the reaction

$$^{120}\mathrm{Sn}(^{18}\mathrm{O},{}^{16}\mathrm{O})^{122}\mathrm{Sn}$$

leading to the ground and collective 2^+ state in ^{122}Sn, for $E = 100$ MeV, an energy significantly above the coulomb barrier (~ 60 MeV). The solid lines correspond to the optical model parameters listed in table 1. The ground state cross section shows the characteristic peak at the grazing angle while the 2^+ cross section exhibits a dip there due to destructive interference between direct and indirect modes of producing this state. This we have discussed separately [2]. The comparison we wish to make is with the dashed curve, which corresponds to a 5% increase in the radius of the imaginary potential. We see that this very modest change in potential results in a difference in the ratio of forward to grazing angle cross section of more than a factor 10, which is a very large amplification factor. (If the forward angle cross section for the ground state is hard to measure experimentally, because of low cross section, we suggest a wide angle counter to integrate out the ripples and speed up data taking.)

Of course the question immediately comes to mind as to whether the effect of changing the radius of the imaginary potential relative to the real might not be more easily detected in the elastic cross section. This is not the case as shown in fig. 3 where we see a high precision experiment would be required to distinguish the two cross sections. Even then the multiple ambiguities in the optical model fit to elastic cross sections might not yield a unique determination. Nor would inelastic cross sections, or one nucleon transfer reactions be as appropriate for the measurement of this effect. For in such reactions, distant orbits, a, would make a larger contribution to the forward angle cross section, thus masking the effect produced on the close orbits c and d by the edge of the nuclear potential.

Since the de Broglie wave length of the relative motion between heavy ions in typical collisions is very short compared to the nuclear dimensions, there is a close correspondence between impact parameter and angular momentum. This makes it especially interesting to examine the S matrix elements as a function of L. We anticipate being able to relate rather directly, changes in such a plot to changes in the interaction region, such as potential radii or slope of the tail of bound state wave functions of transferred particles. Such a plot for the transfer reaction leading to the ground state of ^{122}Sn is shown in fig. 4, and corresponds to the cross section shown by a solid line in fig. 2.

The absolute value of the S matrix element is plotted versus integer values of L. These points are joined exhibiting a very smooth behavior of S. The sudden fall on the low side of the peak corresponds to the sudden onset of absorption.* The slower fall off on the high L side is governed by the tail of the transfer form factor. The points plotted on the figure indicate S matrix values in the case where the imaginary radius has been increased by 5% (dotted line of fig. 2). Here as anticipated we see the lower L region is effected but not the higher region.

It is also noteworthy that the peak in the S matrix is very little effected by the change in imaginary radius whereas, our calculations (not shown) indicate a considerable shift if the real radius is also increased. We conclude that the trajectories are principally determined by the real potential, while the imaginary potential produces little deflection.

The forward angle ripples in the differential cross section are, we believe, the result of interference between pairs of close impact orbits from opposite sides of the nucleus, such as c and d in fig. 1. This phenomenon is likely to be very general for heavy ion transfer reactions, especially where more than one nucleon is transferred, for it depends only on a sufficiently high localization in L. The frequency of the ripples is determined by the angular momentum L_o corresponding to the peak in the S-matrix (angle between peaks is $\Delta\theta \simeq \pi/L_o$). Indeed, if the S-matrix were a delta function $\delta(L - L_o)$, then the angular distribution would be given by $|Y_{L_o}(\theta)|^2$. The ripples will be damped according

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*We use absorption only to mean loss to other channels than the elastic, inelastic and transfer channels explicitly treated in the calculation: We do not imply fusion!

to the width ΔL of S. So, for example, we see that the ripples are more damped in the dotted curve of fig. 2 corresponding to widths at half maximum of $\Delta L = 14$ and 11, respectively, for the dotted and solid S-matrix shown in fig. 4.

To summarize, the ratio of the cross sections of two-nucleon transfer reactions, measured at forward angle and at the grazing angle, is a very sensitive probe of the relationship between the radius of the real and imaginary nuclear potentials. Such measurements should prove very useful in determining the details of the potential at the edge, which is of decisive importance in predicting cross sections of heavy ion reactions. The location of the edge of the imaginary potential relative to the real is also important in connection with the question of nuclear molecules. However, this kind of measurement should be made for the 0^+ state since it is very little effected by second-order processes. In contrast, second-order processes can strongly alter the forward cross-section, and are responsible for the forward peak in the 2^+ state [2].

References

1. K. W. Ford and J. A. Wheeler, Ann. of Physics (N.Y.) 7 (1959) 259.

2. R. J. Ascuitto and N. K. Glendenning, Symposium on Heavy-Ion Transfer Reactions, Argonne (1973) 513; Phys. Letters 45B (1973) 85.

Table 1. Optical Potential Parameters: The radius of the nuclear part is $r_o(A_P^{1/3} + A_T^{1/3})$ and the charge radius $r_c\ A_T^{1/3}$.

V	W	r_o	a	r_c
-40	-15	1.31	.45	1.2

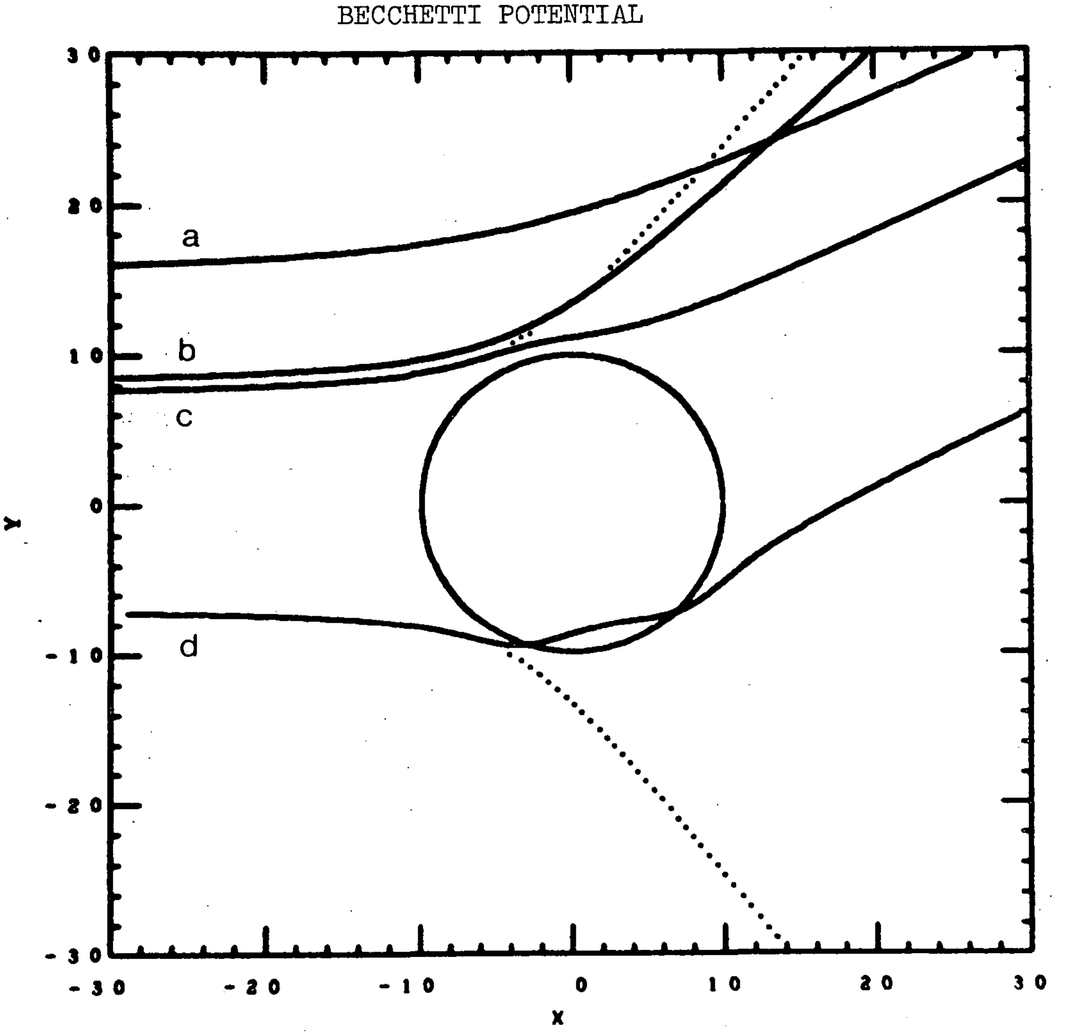

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Fig. 1. Four classical orbits in the real part of the potential of table 1 are plotted, three of which, having impact parameters a, c and - d, (d < c) scatter to the same angle θ. The orbit b feels a stronger repulsion than a and therefore scatters to a larger angle. The circle marks the half value of the Woods-Saxon nuclear potential. The orbits are for ^{18}O scattered by ^{120}Sn at 100 MeV lab energy. Dotted lines show pure Coulomb orbits.

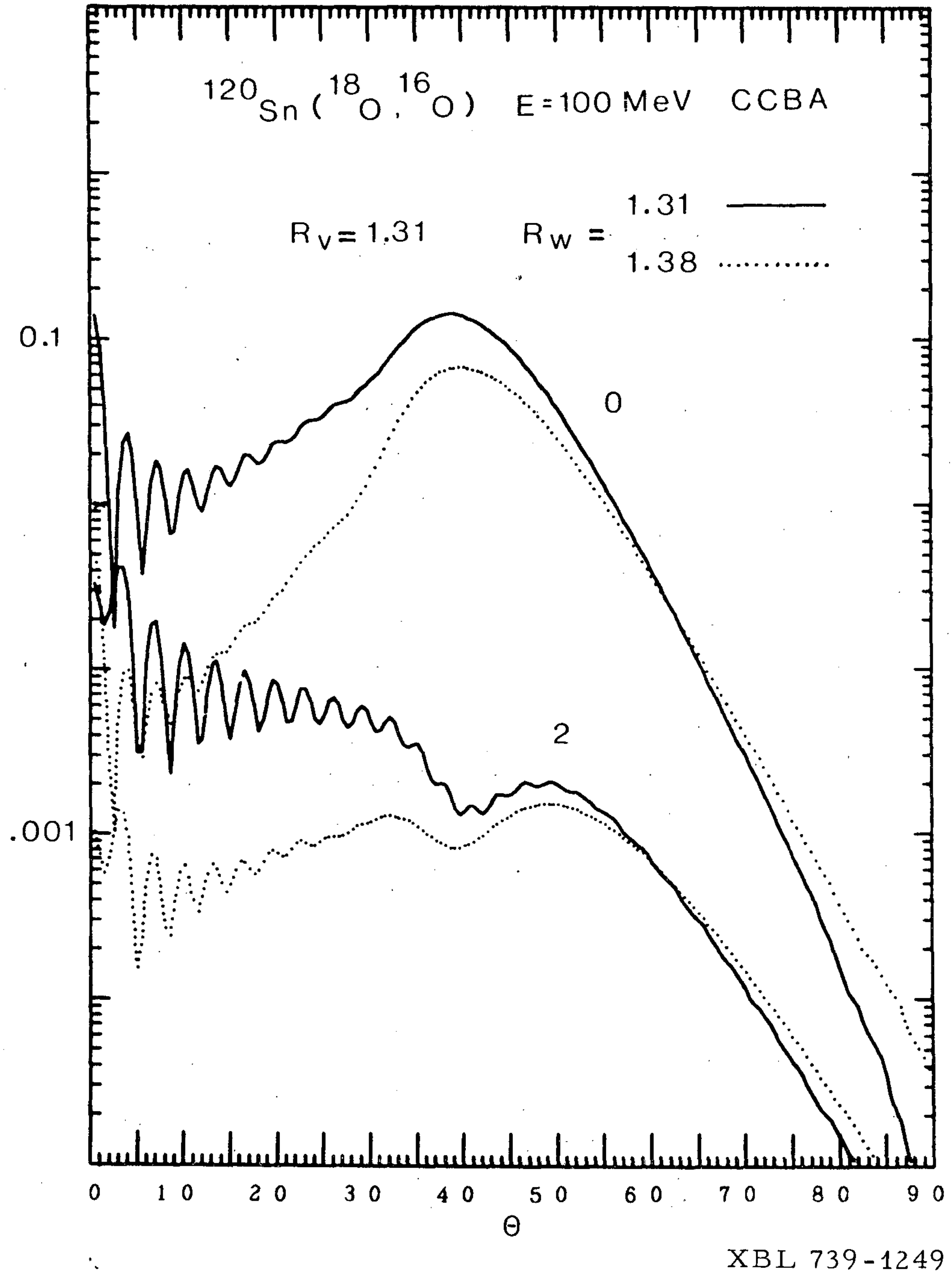

Fig. 2. Differential cross sections for the 0^+ and 2^+ state are compared for two values of the radius of the imaginary potential one of which (dotted curve) is 5% larger than the other. The shape of the 2^+ cross section has been strongly altered from the classical shape exhibited by the 0^+ by strong two-step processes which interfer destructively with the direct for stripping reactions as discussed in ref. 2. Cross sections are in mb./sr. and the two scales refer respectively to the 0^+ and 2^+ states.

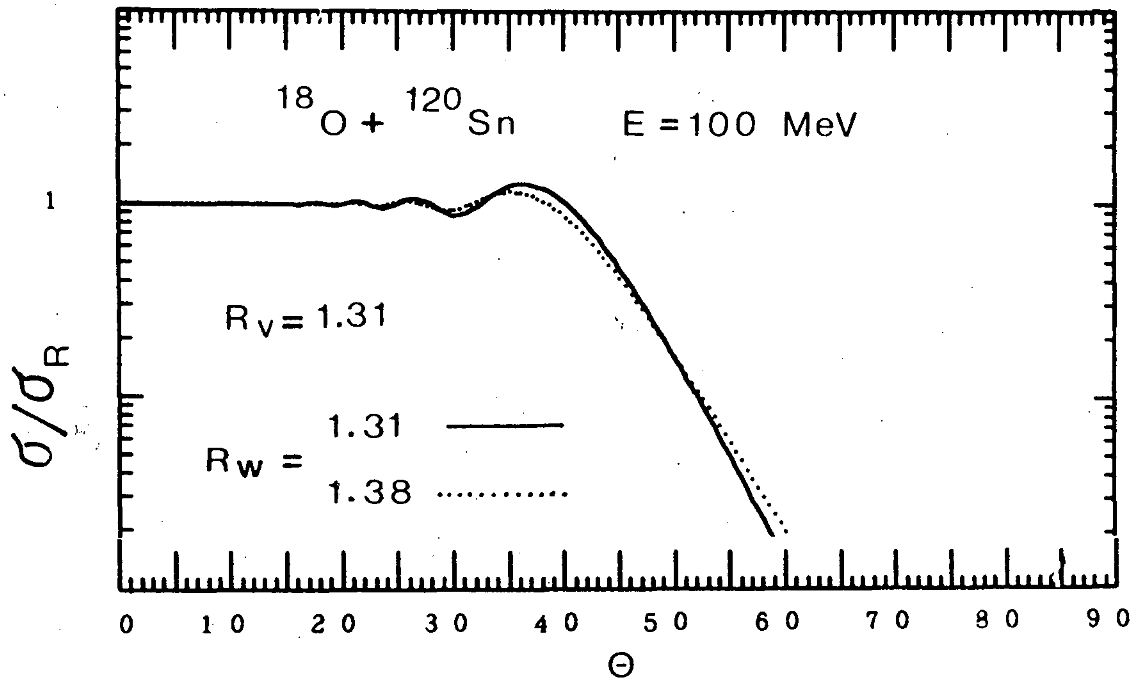

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Fig. 3. The elastic cross sections in the entrance channel corresponding to the reaction of fig. 2 for the two cases there, showing the weak sensitivity of the elastic cross section to R_V - R_W compared to the two-nucleon transfer cross section. The optical model parameters are listed in table 1 for the solid line.

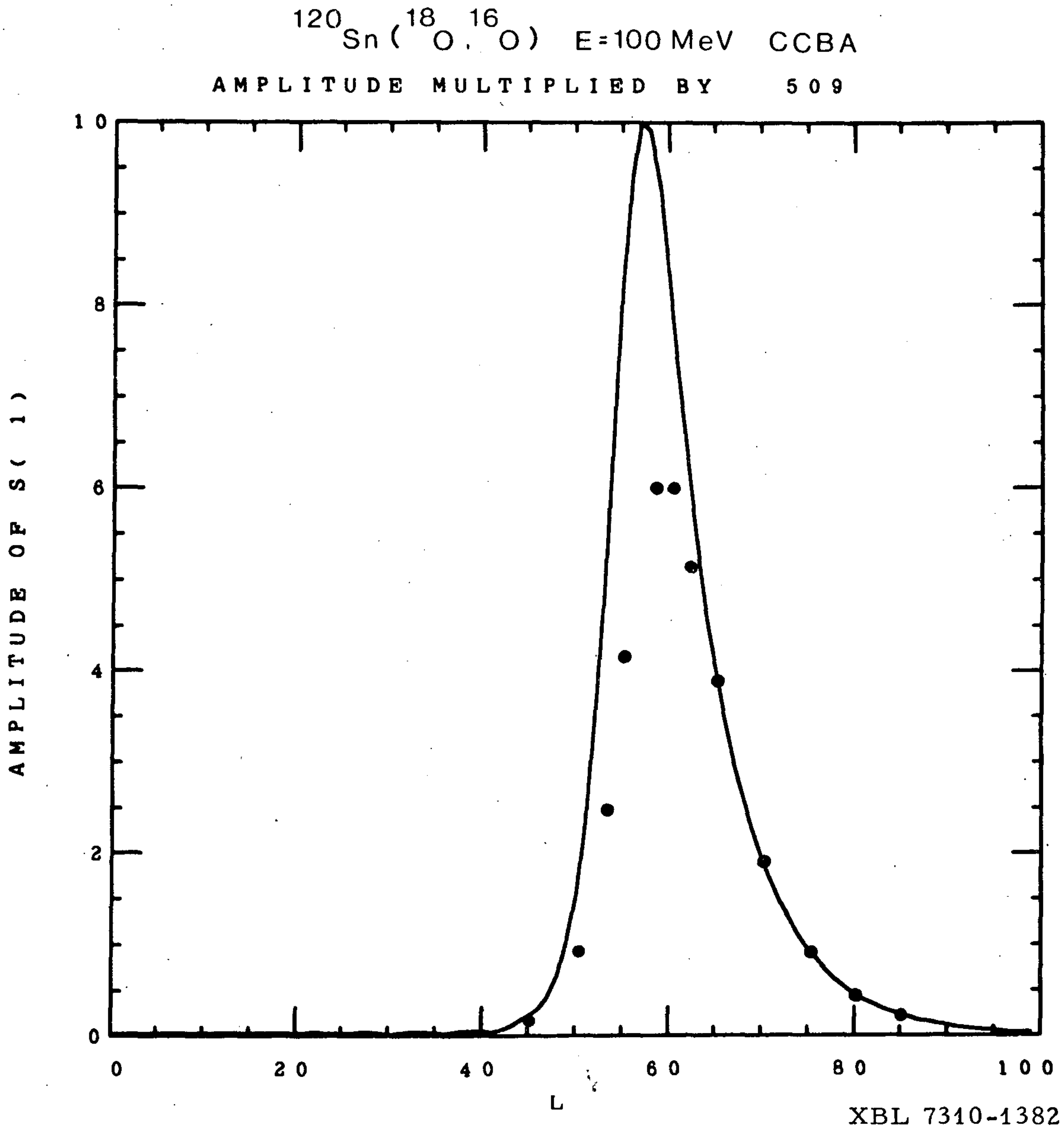

Fig. 4. The absolute value of the S-matrix elements for the 0^+ state are plotted as a function of L and the points (for integer L) joined. The solid lines of this and fig. 2 correspond as do the dots.

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