Title
THE EFFECT OF INDIRECT TRANSITIONS ON TWO NUCLEON TRANSFER BETWEEN HEAVY IONS AND THEIR Q-DEPENDENCE

Authors
Ascuitto, R.J.
Glendenning, Norman K.

Publication Date
1973-03-01

Submitted to Physics Letters

LBL-1645
Preprint c.1

THE EFFECT OF INDIRECT TRANSITIONS ON TWO NUCLEON TRANSFER BETWEEN HEAVY IONS AND THEIR Q-DEPENDENCE

R. J. Ascuitto and Norman K. Glendenning

March 1973

Prepared for the U. S. Atomic Energy Commission under Contract W-7405-ENG-48

THE EFFECT OF INDIRECT TRANSITIONS ON TWO NUCLEON TRANSFER BETWEEN HEAVY IONS AND THEIR Q-DEPENDENCE†

R. J. Ascuitto

Niels Bohr Institute
Copenhagen, Denmark

and

Norman K. Glendenning

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

March 1973

Strong contributions from indirect transitions are predicted which lead to rather broad flat angular distributions up to the grazing angle in contrast to the strong peak at the grazing angle usually expected in heavy ion reactions. The ratio of indirect to direct amplitudes increases as the Q of the reaction departs from the optimum value.

- - -

In this paper we report our calculation of the effect of indirect transitions on two-neutron transfer cross sections between heavy ions. These processes involve an inelastic transition in the target or final nucleus as an intermediate step compared to the direct particle transfer from initial to final state. This work is a natural outgrowth of our earlier investigations on such effects on light nuclide induced reactions, where our calculations indicated strong higher order contributions [1]. This prediction was most dramatically confirmed in the case of (p,t) reactions on deformed nuclei [2]. It would be surprising if they did not play an important role in heavy ion reactions and the present

†Work performed under the auspices of the U. S. Atomic Energy Commission.

note suggests they do, and proposes a very interesting Q-dependence of the ratio of indirect to direct amplitudes, and of the shape of the angular distribution.

We have performed our calculation for the following reaction at 100 MeV.

$^{18}O + ^{120}Sn \rightarrow ^{16}O + ^{122}Sn$

First we describe briefly the nature of the structure of the nuclei which is relevant to this reaction. The ground state of ^{18}O is treated as an inert core of ^{16}O plus two neutrons which may occupy the $s_{1/2}$, $d_{3/2}$ and $d_{5/2}$ orbitals in a Woods-Saxon potential which binds them at approximately the energies observed in ^{17}O. The interaction matrix elements between pairs of neutrons in each of these configurations is assumed to be of the pairing force type of such a strength that the binding energy of the last two neutrons is correct. Two states of each tin nucleus are included, the ground and the collective 2^+ state. The former is described as a BCS vacuum state, and the latter as a collective two-quasiparticle state. The neutron orbitals of Sn are generated from a Woods-Saxon potential corresponding to the average parameters of Myers [3]. The form factor for the transfer of two nucleons based on these nuclear descriptions is shown in fig. 1. The projected wave function, or form factor, is more complicated to obtain than in (t,p) reactions, because of the necessity to retain the finite range of the interactions. It is defined by the following identity for transfer from the pure configuration $(j^2)0$ in the projectile to the configuration $(j_1j_2)J$ in the residual nucleus:

$$\iint d\underset{\sim}{r}_1 \, d\underset{\sim}{r}_2 \, \psi_{(j_1j_2)J}^{M\,*}(\underset{\sim}{r}_1', \underset{\sim}{r}_2') \, \{V(r_1) + V(r_2)\} \, \psi_{(j^2)0}(\underset{\sim}{r}_1, \underset{\sim}{r}_2)$$

$$\equiv U_J(R) \, Y_J^{M\,*}(\hat{R}) \qquad (1)$$

Here V is the Woods-Saxon potential which binds the neutrons in ^{18}O, $\mathbf{R}$ is the vector joining the core of the projectile (^{16}O) to the target nucleus (^{120}Sn), $\mathbf{r}_1$ and $\mathbf{r}_2$ are the coordinates of the two neutrons with respect to the projectile core, while $\mathbf{r}_1'$ and $\mathbf{r}_2'$ and their coordinates with respect to the target nucleus.

$$\mathbf{r}_1' = \mathbf{r}_1 + \mathbf{R} \tag{2}$$

For mixed configurations such as we use the form factor is obtained by weighting such form factors by the product of parentage amplitudes for the light and heavy nuclei involved. We note from fig. 1 that the J = 0 form factor is considerably bigger than the J = 2. For this reason, we include only the monopole transition connecting the 2^+ states, although in principle they can be connected by J = 2 and 4 as well. The reduction of the left side of eq. (1) to a form suitable for numerical computation of the form factor $U_J(R)$ is complicated and we do not discuss it here.

The inelastic transitions are computed on the basis of the macroscopic vibrational model. The nuclear deformation parameter β_2 for the tin isotopes are taken from an analysis of proton scattering [4]. We use the same optical model parameters as Becchetti et al. [5] in their analysis of ^{16}O + ^{208}Pb scattering. These authors find the deformation parameter obtained in proton experiments consistent with their determination in the heavy ion experiment. For this reason we can have considerable confidence in our estimate of the strength of the inelastic processes. We determine the strength of the Coulomb quadrupole term in the interaction by using the experimentally determined [6] value of B(E2). The nuclear and charge deformation are shown in table 1. The nuclear field is deformed according to

$$V[r - R(\theta)] = V(r - R) - \beta_2 R_T \frac{\partial V}{\partial r} Y_2(\theta) \tag{3}$$

where

$$R(\theta) = R_P + R_T[1 + \beta_2 Y_{20}(\theta)] \tag{4}$$

corresponding to a spherical projectile of "radius" R_P and a vibrational target of radius R_T. Of course it is $R_P + R_T$ which is to be identified with the optical model radius which is typically parameterized as $r_o(A_P{}^{1/3} + A_T{}^{1/3})$. It is the product $\beta_2 R_T$ which is determined for us by the proton scattering experiment while the sum $R_P + R_T$ is determined by the analysis of heavy ion elastic scattering. We have relied upon an extrapolation of the optical potential from Pb to Sn. We checked this by using an alternative potential determined by Morrison [7] for $^{16}O + {}^{48}Ca$. These two rather different parameterizations are shown in table 2. They yield elastic, inelastic and transfer cross sections which are virtually the same for tin and this gives us confidence that the results presented below do not contain any uncertainty attributable to optical model parameters or deformation.

Of course in a calculation such as this, the relative phase between inelastic and particle transfer form factors must be preserved when the inelastic scattering is computed from a macroscopic parameterization.

In our calculations we include the inelastic coupling between the ground and collective 2^+ state in both tin nuclei, to all orders, and the first order particle transfer from the ground state of the target to both states of the final nucleus and the monopole transition from the 2^+ state of the target to the 2^+ state of the final nucleus. We do not consider those transitions in which either oxygen nucleus is excited. Neither do we include recoil effects. We do not believe that this neglect can effect our estimates of the importance of the indirect compared to the direct transitions, although in a detailed comparison with experiment it may well be important to include such effects [8]. The method by which we include the indirect transitions is the so-called source term method [9].

The result of a coupled channel calculation for 100 MeV oxygen ions which includes the effects of inelastic excitation of the tin nuclei is shown in fig. 2. The ground state is barely altered so we show no comparison, but the 2^+ state is strongly effected by the additional modes of excitation. In particular, the direct transition, shown by a dashed line, interferes destructively with the indirect modes of excitation and produces an angular distribution in which the expected peak at the grazing angle is absent. Instead a poor angular resolution experiment would observe a monotonically decreasing distribution, fairly flat at first, and then falling rapidly after the grazing angle, or peak in the ground state cross section. This is in marked contrast with the DWBA prediction. Of course there is a continuous evolution from the dashed curve to the solid as a function of deformation constants β, or collectivity of the intermediate states. As remarked earlier, we determined the appropriate values from other experiments, and such values, listed in table 1, were used in the calculation shown in fig. 2.

The Q value of this reaction is 2.8 MeV. It is interesting to know how the balance between direct and indirect amplitudes depends on Q, since as is well known, the magnitude of the cross sections depend strongly on the Q. In fig. 3 we show what would result if the Q had the less favorable value of -6 MeV. Comparing with fig. 2 we see that the ground state cross section and the direct cross section to the 2^+ state have fallen by a factor of about 50, while the complete 2^+ cross section has fallen only by about a factor of 30. This indicates that the indirect ampltidues are not attenuated as strongly as the direct in unfavorable Q situations [10]. Also we note that the shape of the 2^+ cross section has changed considerably in comparison with fig. 2 owing to a change in angular distribution of the indirect amplitudes.

From this comparison we learn that, other things being similar, an unfavorable Q value emphasizes the contribution of multiple step transitions to particle transfer.

In the present calculation the excited 2^+ state is strongly effected by the indirect transitions while the ground state is not. This can be understood in terms of the stronger J = 0 form factor shown in fig. 1 which favors the $0(A) \to 2(A) \to 2(A + 2)$ transition over the direct $0(A) \to 2(A + 2)$. However, in other nuclei, the J = 2 form factor may be larger than the J = 0 which could then cause the indirect transition $0(A) \to 2(A + 2) \to 0(A + 2)$ transition to be more important than the direct ground state transition. This would lead to a reversal of the situation in tin.

On the basis of these calculations we suggest that, under appropriate circumstances, higher order processes will be very strong in heavy ion particle transfer reactions. The simple angular distribution which consists of a strong peak at a grazing angle is characteristic of single-step transition. The contribution of indirect transitions changes this, leading to a fairly flat distribution to the grazing angle, and then falling off. We found that the ratio of indirect to direct transitions increases as the Q value departs from the optimum value, suggesting that such effects will be seen in experiments on a series of isotopes for which the Q value changes over a few MeV.

We remark, parenthetically, on the high frequency oscillations at small angles seen in our cross sections. We believe that they would be present in the cross section of any process which is governed by a modest number of partial waves, say $\Delta\ell$, centered at a large value of ℓ so that $\Delta\ell/\ell$ is small. Then the maxima occur at intervals of $\sim 180/\ell$ degrees and they are damped with increasing angle more rapidly as $\Delta\ell$ becomes larger. Such a localization occurs in heavy ion transfer reactions because of the localization of the reaction in r-space to an annulus bounded on the inner side by absorption and on the outer side by the decay of the bound state wave functions.

References

1. R. J. Ascuitto and N. K. Glendenning, Phys. Rev. C2 (1970) 1260; N. K. Glendenning and R. S. Macintosh, Nucl. Phys. A168 (1971) 575.

2. R. J. Ascuitto, N. K. Glendenning, and B. Sorensen, Phys. Rev. Letters 34B (1971) 17 and Nucl. Phys. A183 (1972) 60; T. Tamura, D. R. Bès, R. A. Broglia, and S. Lansdowne, Phys. Rev. Letters 25 (1970) 1507 and errata 26 (1971) 156.

3. W. D. Myers, Nucl. Phys. A145 (1970) 387; table 1.

4. O. Beer <u>et al</u>., Nucl. Phys. A147 (1970) 326; table 2 and 9.

5. F. D. Becchetti <u>et al</u>., Phys. Rev. C6 (1972) 2215.

6. P. H. Stelson and L. Grodzins, Nuclear Data A1 (1965) 21.

7. G. C. Morrison, Journal de Physique 32 (1971) No. 11-12.

8. M. A. Nagarajan, Nucl. Phys. A196 (1972) 34.

9. R. J. Ascuitto and N. K. Glendenning, Phys. Rev. 181 (1969) 1396, Phys. Rev. C2 (1970) 415, and Nucl. Phys. A188 (1972) 185.

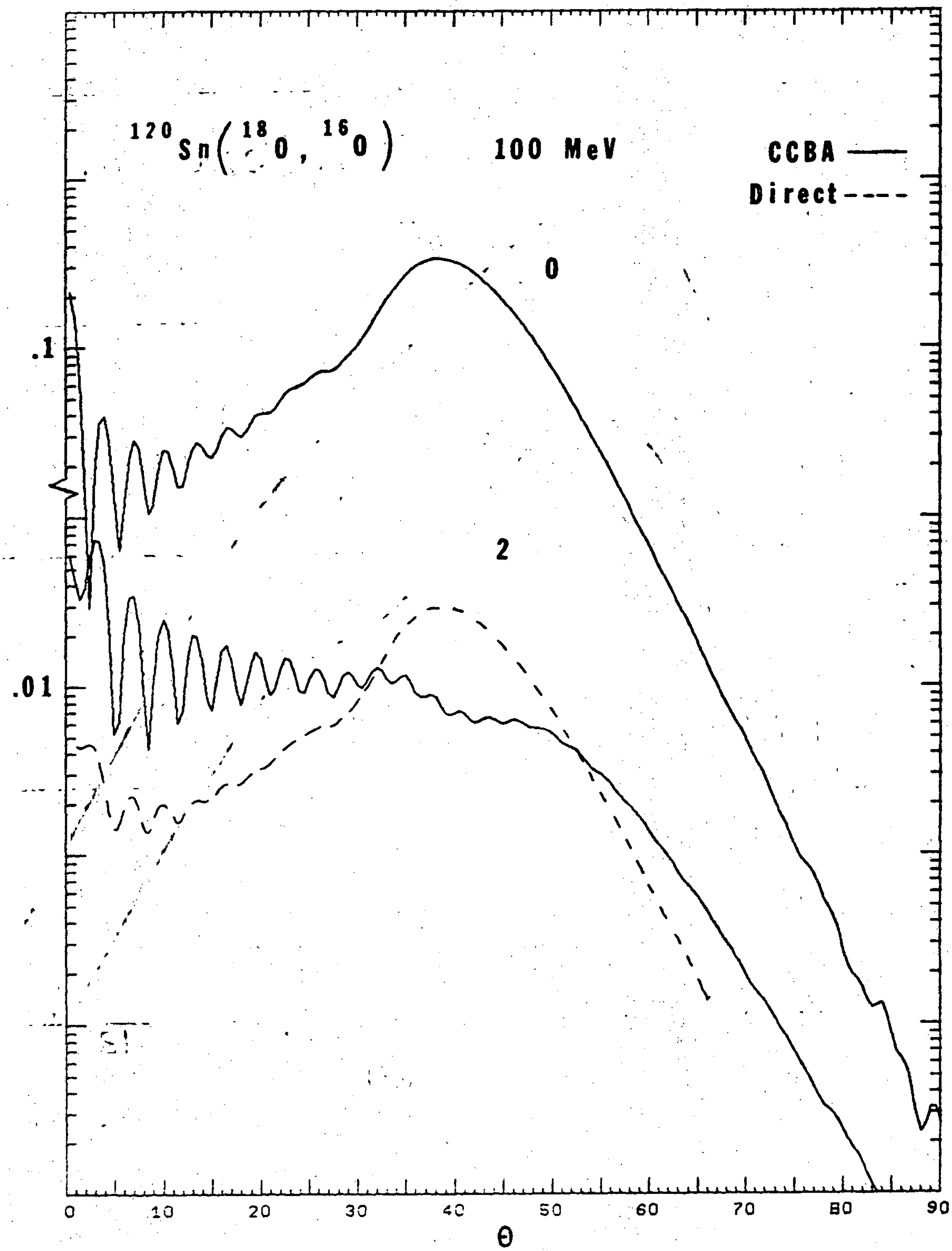
10. From consideration of classical coulomb trajectories one expects a Q-dependence of the form $\exp(-\alpha|Q - Q_{opt}|^2)$; D. M. Brink, Phys. Letters 40B (1972) 37. If the reaction goes in two steps with associated values Q_1 and Q_2 so that $Q = Q_1 + Q_2$, then the same considerations leads to a Q-dependence which is like $\exp(-\alpha|Q_1 - Q_{opt}|^2 - \alpha|Q_2 - Q_{opt}|^2)$. The latter is much more favorable than the former especially if $Q_1 \sim Q_2$.

Table 1. Nuclear and charge quadrupole deformation constants which are to be associated with radii of $r_o = 1.12$ and $r_c = 1.2$, respectively.

	β_N	β_C
^{120}Sn	.13	.112
^{122}Sn	.124	.118

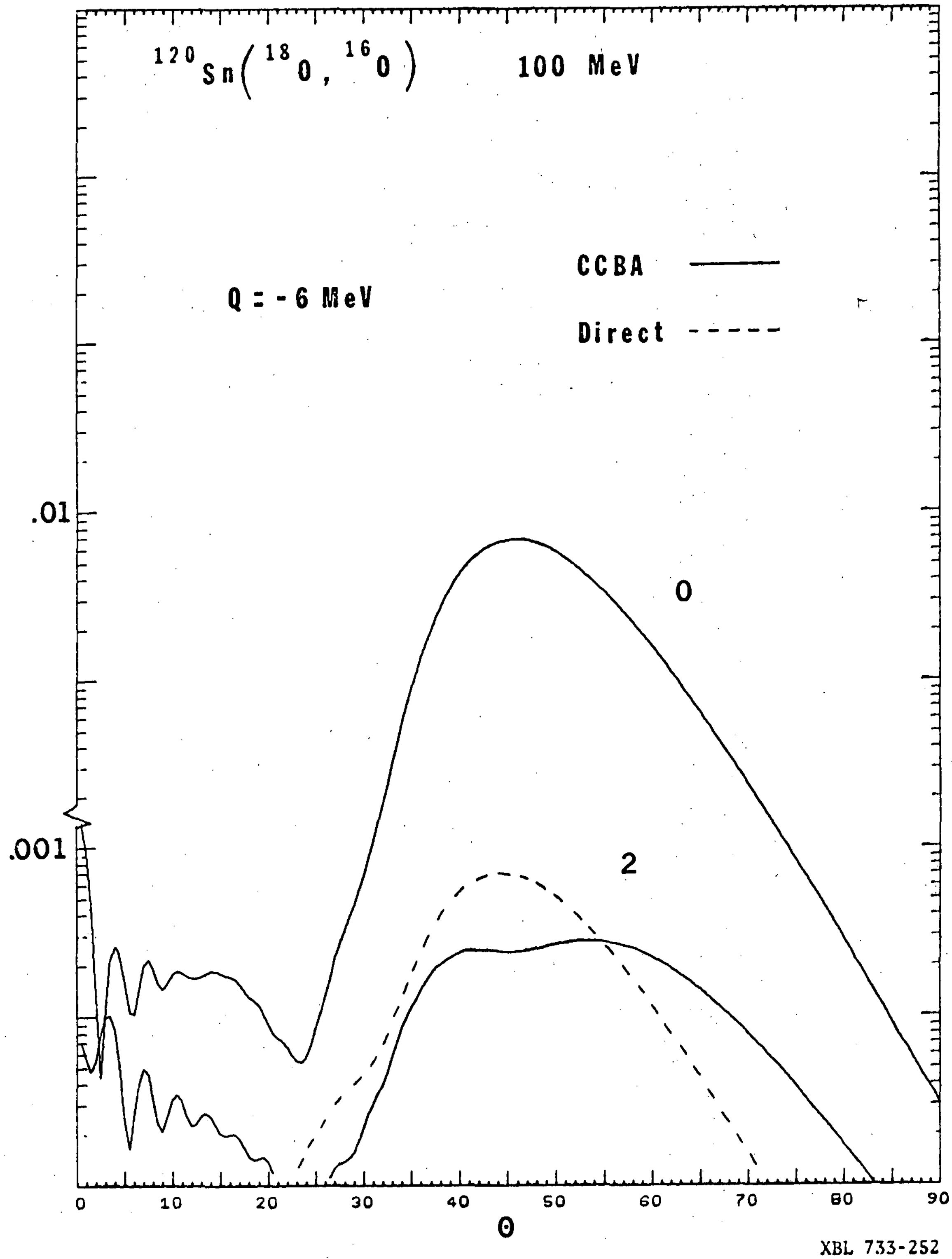
Table 2. Two sets of optical model parameters which yield virtually the same elastic and reaction cross sections for O + Sn at E = 100 MeV. The optical model radius is $r_o(A_p^{1/3} + A_T^{1/3})$ and the charge radius is $r_c\ A_T^{1/3}$.

	V	W	r_o	a	r_c
Becchetti (ref. 5)	-40	-15	1.31	0.45	1.2
Morrison (ref. 7)	-100	-40	1.22	0.5	1.2



XBL 733-249

Fig. 2



$^{120}Sn(^{18}O, ^{16}O)$ 100 MeV
Q = -6 MeV
CCBA
Direct
.01
.001
0
2
0
10
20
30
40
50
60
70
80
90
θ
XBL 733-252

Fig. 3

TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720