Title
PHYSICAL BASIS FOR LARGE FORWARD CROSS SECTIONS IN 6oNi(l8o, 160) REACTION

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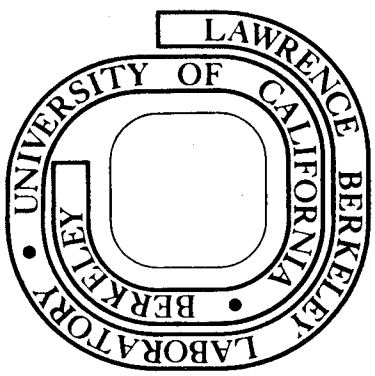

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ABSTRACT

Experiments on the reaction $^{60}Ni(^{18}O,^{16}O)^{62}Ni$ revealed an unexpectedly large forward cross section for production of the ground state, in contrast with an expected grazing peaked distribution. This has most recently been interpreted in terms of a surface transparent optical potential. In the inverse experiment, it is known that ^{18}O is produced in its 2^+ state with larger cross section than the ground state. This suggests that the above ground state reaction can also be produced with appreciable probability through the excitation of ^{18}O in the incident channel, with a subsequent transfer of two neutrons to form the ground state of ^{62}Ni. We find that by including this process together with the direct transfer, we can account for the experimental data. The parameters of the optical potential employed are chosen so as to reproduce both the elastic and inelastic cross sections, and are of the normal strong absorbing type with no surface transparency. We conclude that the projectile excitation is the physical process involved in the large forward cross section. In addition the interference of the direct and indirect processes can give rise to a minimum beyond the grazing peak followed by a secondary maximum, some indication of which can be found in the experiments on neighboring nuclei. The quantal deflection function is employed in a discussion of the S matrix and angular distribution emerging from this calculation and of the surface transparent potential parametrization of the effect.

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PHYSICAL BASIS FOR LARGE FORWARD CROSS SECTIONS IN $^{60}Ni(^{18}O,^{16}O)$ REACTION*

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At moderate energies above the Coulomb barrier, quasi-elastic heavy ion reactions are expected to exhibit a "grazing" peak in the differential cross section arising from the facts that: 1) the opposite sense of the nuclear and Coulomb fields produces an inflection in the scattering angle at what is called the grazing or rainbow angle near which therefore many orbits scatter, 2) penetrating orbits are strongly dispersed in angle and because they are strongly absorbed contribute little cross section, and 3) since the interaction between nuclei falls off rapidly as their separation increases, the distant orbits which scatter forward of the grazing angle, contribute little to the cross section. These three reasons account for the grazing peak in the cross section.[1] Brookhaven experiments[2] produced the surprising result that several reactions of the type

$$^{60}Ni(^{18}O,^{16}O)^{62}Ni, \quad E = 65 \text{ MeV} \tag{1}$$

had a large cross section forward of the grazing angle. Although indirect transfer can produce such effects[3], this was not at first suspected to be the explanation because the experiment did not reveal any likely candidates as intermediate states. A qualitative account was first given[2] in terms of a weakly absorbing optical potential which permitted the survival of penetrating orbits, some of which scatter forward of the grazing angle.

The Brookhaven group proposed a surface transparent optical potential with the property that the edge of the absorptive part is very sharp and lies inside the real part.[4] These authors employed a scaling factor in the relationship between the coordinates in their DWBA calculation, which is different from the one prescribed by the geometrical relationship between the coordinates.[5] This factor turns out to be an essential ingredient in their fit to the data. More precisely the DWBA amplitude can be written, with the neglect of recoil, as

$$T \propto \int \Psi_f^{(-)*}(\alpha R) \quad F(R) \; \Psi_i^{(+)}(R) \; dR \, , \quad \alpha = \frac{M}{M+X} \tag{2}$$

with M and $M + X$ being the masses of the target and residual heavy nuclei, X being the mass of the transferred nucleon(s). While the factor α is less than unity, it is sometimes varied by a few percent in an attempt to simulate recoil effects.[6] The Brookhaven group used a value of 1.05. Fig. 1 shows the effect on the differential cross section of three choices for α, in each case employing the Brookhaven surface transparent potential. It can be seen that, for this kind of potential, the cross-section near the grazing angle depends very sensitively on the scaling factor. Therefore we need to consult a full recoil calculation. Delic[7] has calculated for us the cross section including recoil using the Brookhaven potential. His results coincide in shape so closely with the curve labeled $\alpha = 1.02$ that they cannot be easily distinguished on the graph. We conclude therefore that with

the proper inclusion of recoil effects, the surface transparent potential of Ref. 4 does not produce a sufficiently large forward cross section, compared to that at the grazing angle.

We now turn to what we consider to be the physical basis for the large forward cross section seen in the experiment. The clue was provided in a previous paper which took into account the fact that for the Sn(^{16}O,^{18}O) reactions, the ejectile, ^{18}O is produced in its excited 2^+ state more frequently than its ground state.[8] Its subsequent deexcitation through an inelastic interaction with the residual nucleus has the effect on the ground state cross section of: 1) shifting the grazing peak forward by a few degrees and 2) producing a forward angle yield that is ten times larger than calculated from the direct process alone. The analogous process in the entrance channel of the reaction (1) above can explain the observed forward distribution when all relevant cross sections are determined to the extent possible by the available experiments.

The relevant experimental data needed to determine the important indirect processes and to assess their effect on the ground state cross section of the reactions (1) are:

i) The cross sections for producing the low excited states of ^{16}O and ^{62}Ni in the reaction (1). The lowest lying collective state is the 2^+ in Ni. To affect the ground state it would have to be not only strongly coupled, but have a significantly larger cross section than the ground state itself. Since it does not,[2] it is unimportant as an intermediate state.

ii) The cross sections for excited states of ^{18}O and ^{60}Ni in the reaction inverse to (1). These data are not available. However, the cross section for a similar reaction were measured in Berkeley,[9] namely ^{60}Ni(^{16}O,^{18}O)^{58}Ni. It was found that ^{18}O is produced in its excited state with a cross section 3.4 times larger than the ground state at $\theta_{CM} = 32.6^\circ$. Therefore the ^{18}O(2^+) state is a possibly important intermediate state in the reaction (1).

iii) The elastic and inelastic cross sections for producing ^{18}O(2^+) by scattering from nickel determines the optical model parameters and the deformation parameter β which characterizes the strength of the inelastic transition.

As for the elastic and inelastic data,[10] these are shown for the neighboring target in Fig. 2 together with our calculation. The optical potential parameters are listed in Table I. The inelastic scattering is calculated on the assumption of a macroscopic vibrational form factor for the 2^+ transition in ^{18}O. The parameter ϕ referred to in the figure corresponds to the phase of the nuclear form factor,

$$F(r) = e^{i\phi}\,(-\beta R)\sqrt{V^2 + W^2}\,\frac{\partial f}{\partial r}\,, \qquad f = \left[1 + \exp\left(\frac{r-R}{a}\right)\right]^{-1} \tag{3}$$

which according to frequent practice is the phase prescribed by the monopole part of the potential $V + iW$, namely

$$\phi = \tan^{-1}\,(W/V) \tag{4}$$

It is recognized that this need not be the case.[11] The value of ϕ prescribed by a strict interpretation of the vibrational model (Eq. 4) is $\phi = 33^\circ$, while $\phi = 90^\circ$ corresponding to a purely imaginary nuclear form factor,

TABLE I. Woods-Saxon potentials employed in the CCBA calculations. The potential for the ^{16}O channel was obtained in Ref. 12 from an optical model fit of the $^{16}O + ^{58}Ni$, E_L = 63, 71.5, 81 MeV elastic scattering data; the potentials for the ^{18}O channel from our coupled channels fit of the $^{18}O + ^{58}Ni$, E_L = 60 MeV elastic and $^{18}O(2^+)$ inelastic data (Ref. 10). See Fig. 2 for deformation constants and phase of inelastic formfactor. Note $R = r(A_1^{1/3} + A_2^{1/3})$.

Channel	V	W	r	a
$^{16}O + ^{58}Ni$	-70.	-18.5	1.19	0.54
$^{18}O \quad ^{58}Ni$	-70.	-45.	1.19	0.56

reproduces the data best of those shown, and is used in the subsequent calculations of transfer reactions. Actually it is probably relevant to observe that rather than rotating the nuclear form factor by the difference $90^\circ - 33^\circ = 57^\circ$, a rotation of the Coulomb form factor by this amount produces the same result since the relative phase is the same in either case. Such a complex Coulomb form factor can arise because of virtual Coulomb excitations, just as the imaginary part of the nuclear optical potential arises, in part, from virtual inelastic excitations. Another possible explanation for the departure from the phase of the macroscopic model may be that the 2^+ state in oxygen is not accurately described as either a vibration or rotation. While these would be interesting points to pursue, for our purposes here it is sufficient to regard the above phase as a convenient means, together with the deformation constant β, and the optical potential, of parameterizing the inelastic amplitude which enters as an intermediate step in the calculation of the reaction (1). We stress that the optical potential of Table I which fits the data as shown in Fig. 2 is of a normal strong absorbing type, unlike the Brookhaven surface transparent potential.

In Fig. 3 our complete calculation is shown for the inverse reaction to (1) which includes the direct transition to the ground state of both final nuclei and the coherent indirect transition corresponding to particle transfer to the 2^+ state of ^{18}O followed by inelastic deexcitation to the ground state. We neglect the explicit calculation of recoil effects but employ the scaling factor $\alpha = 1.02$ which as far as the direct transition is concerned reproduces the angular distribution of the full recoil calculation, as discussed in connection with Fig. 1. This point is not crucial however, since with "normal" optical potentials the sensitivity to α is much less than indicated in Fig. 1. Also shown in Fig. 3 is the cross section for direct transfer alone, which by comparison allows us to see the large effect of the indirect transition on the ground state cross section. In an earlier publication we gave a simple classical explanation of why the two-step process is forward biased compared to a single-step process.[8] In addition it is broader because each scattering process introduces its own dispersion on the previous one. (Thus a delta function angular distribution centered at θ_0 scatters to θ_0 for a single scattering, and all angles between 0 and $2\theta_0$ for a double scattering.) Both effects are apparent in the figure. The ratio at the nuclear surface of the two transfer form factors involving respectively the ground and excited state of ^{18}O is consistent with the data

of the neighboring reaction, in accordance with point ii) above, as concerns the relative cross sections although the forward peaking of the 2^+ cross section is not reproduced.[9] It is quite possible that its angular distribution would be modified by higher states just as transitions through it modify the ground state cross section. Since, however, neither the experimental data for the 2^+ nor any higher state is available for the reaction inverse to (1), we leave this matter as it stands.

It is very interesting to compare the S-matrix corresponding to our coupled calculation for the cross section which is shown in Fig. 3, with the one that corresponds to the surface transparent potential and the large scaling factor, $\alpha = 1.05$ corresponding to the cross section shown in Fig. 1. The amplitudes of these two S-matrices are shown in Fig. 4 together with the quantal deflection function which is shown for our coupled calculation, but which is very similar to the one arising from the surface transparent potential. The two S-matrices are similar in the region of the peak which accounts for the fact that the two models lead to similar cross sections in the angular region where the cross section is large, $\theta = 0$ to 60°. However, the surface transparent potential gives rise to a large secondary peak which we believe corresponds to a reflection of the low partial waves off of the sharp imaginary potential. The deflection function indicates that these low partial waves are scattered to large angles beyond the grazing angle of 40°. This is in contrast to our coupled calculation for which these low partial waves have vanishing amplitude. Figure 5 confirms this difference in the large angle behavior of the cross section of the two models. It is fascinating that for heavy ion reactions different regions of the S-matrix can be related, through the quantal deflection function to specific angular regions of the differential cross section.

In conclusion, we have exhibited a physical process that is capable of accounting for the large forward cross section in the Brookhaven experiment $^{60}Ni(^{18}O,^{16}O)^{62}Ni$ at an energy where one would normally expect a grazing peak with sharply falling cross section on either side. This process consists of the inelastic excitation of the projectile ^{18}O followed by the transfer of two nucleons to form the ground states of ^{16}O and ^{62}Ni. The destructive interference of this process with the direct transfer causes a decrease of cross section in the region of the grazing angle where the two have comparable amplitudes. At angles forward of the grazing angle, the cross section is dominated by the second order process, since, as discussed above its distribution is more forward biased and broader.

We note here two additional features that can be introduced by indirect transitions which may be observable in experiment. i) The destructive interference between the peaked direct amplitude and the broad indirect one can lead to a minimum somewhere in the grazing region or beyond followed by a second peak. Some indication of such a phenomenon exists in the $^{62}Ni(^{18}O,^{16}O)^{64}Ni$ data.[2] ii) In a series of isotopes the relative contribution of direct and indirect processes can change both because the structure of the nuclear wave functions change and because the Q of the reactions change. It is worth noting that the reaction under investigation is a badly Q-matched one. Based on a semiclassical argument[3] one can understand that direct processes are not attenuated as strongly by Q-mismatch as direct ones. Thus the second order processes may be less important relative to the direct

in other nickel isotopes where the Q-matching is better, unless the nuclear structure strongly favors the indirect. Assuming that it does not, then there ought to be an evolution in cross sections from one end to the other of the nickel isotopes from forward distributions at the large-Q end to more grazing peaked at the small-Q end. The data suggest this trend.[2]

FOOTNOTES AND REFERENCES

*Work supported by U. S. Energy Research and Development Administration.
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FIGURE CAPTIONS

Fig. 1. Transfer cross sections in the no-recoil DWBA are shown for which the Brookhaven transparent potential is used. The three cases correspond to different scaling factors (Eq. 2). The first is prescribed by the geometry; the last was employed by the Brookhaven group, who intended that it should simulate recoil effects. The middle value reproduces with great accuracy a full recoil calculation.[7] Data are from Ref. 4.

Fig. 2. Elastic and inelastic cross sections are compared with the data (Ref. 10) for several values of the phase of the inelastic form factor (Eq. 3) with deformation lengths, $\beta_N R$ = 1.01 Fm, $\beta_C R$ = 0.94 Fm. The middle one corresponds to the normal collective model prescription specified by the optical potential. Much better agreement with the data is obtained with a pure imaginary form factor. Optic potential parameters

are listed in Table I.

Fig. 3. The solid lines are cross sections based on a coupled calculation in which both states of oxygen, the 0^+ and 2^+ are fed both by direct transfer, and by indirect transfer through the other state. Dashed lines show cross sections computed for each state when only the direct transfer contributes (but the inelastic coupling is still included). Normal optical potentials (Table I) were employed. All cross sections are normalized by the same factor. The ground state data[2] are for the time reversed reaction at the corresponding energy of E = 65 MeV (in the lab).

Fig. 4. The amplitude of the S-matrix for the 0^+ cross-section corresponding to the coupled calculation of the reaction (Fig. 3) and the surface transparent potential model (Fig. 1) are compared. Also shown is the quantal deflection function.

Fig. 5. The cross sections arising from the two models of the reaction, the coupled and the surface transparent potential model are compared. The large angle differences can be traced to the different behavior of the S-matrices of Fig. 4 for small ℓ through the deflection function.

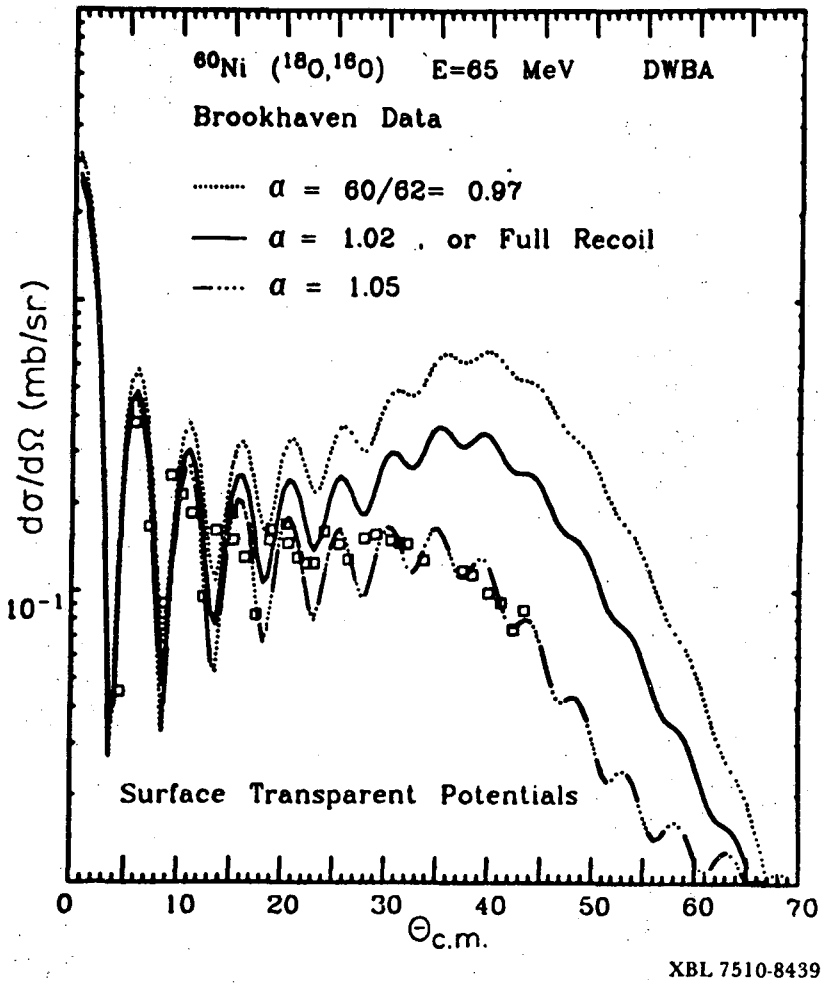

Fig. 1

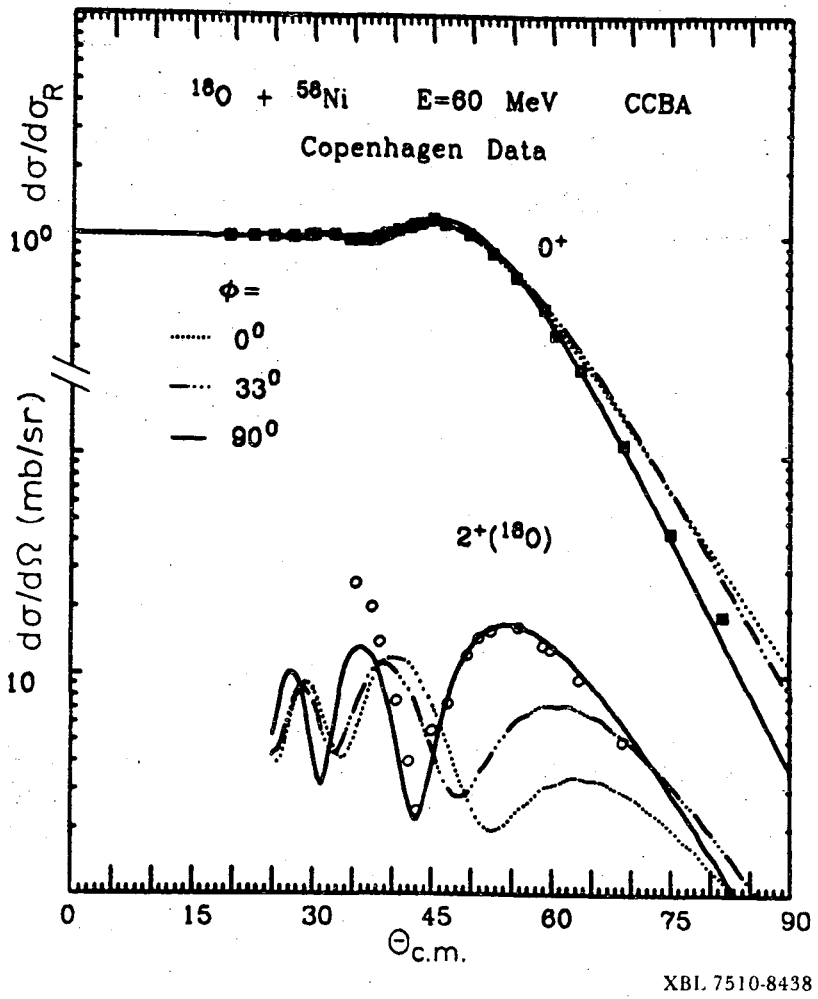

Fig. 2

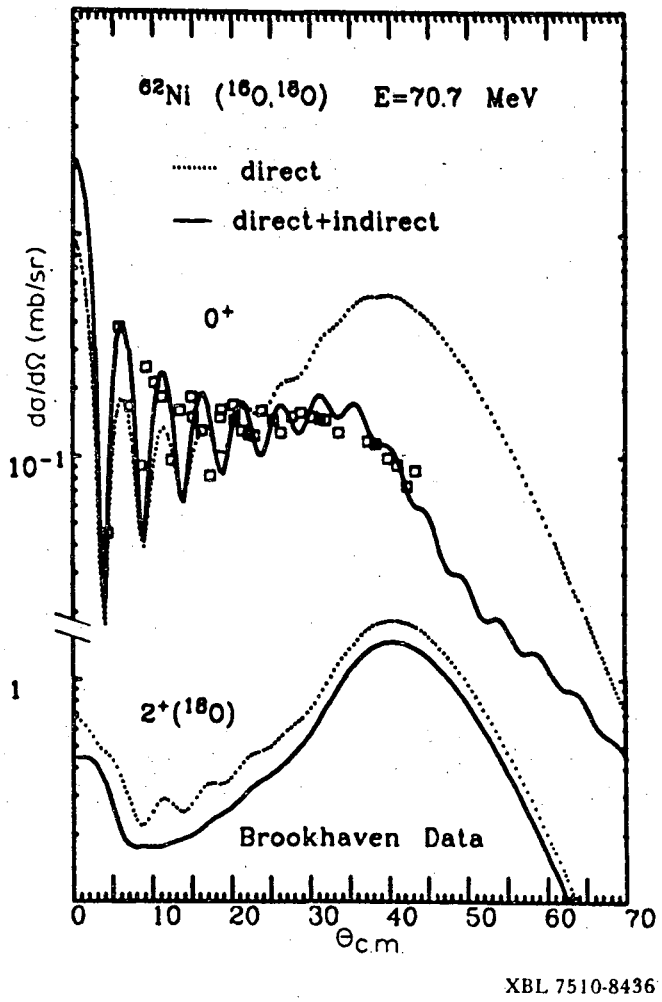

Fig. 3

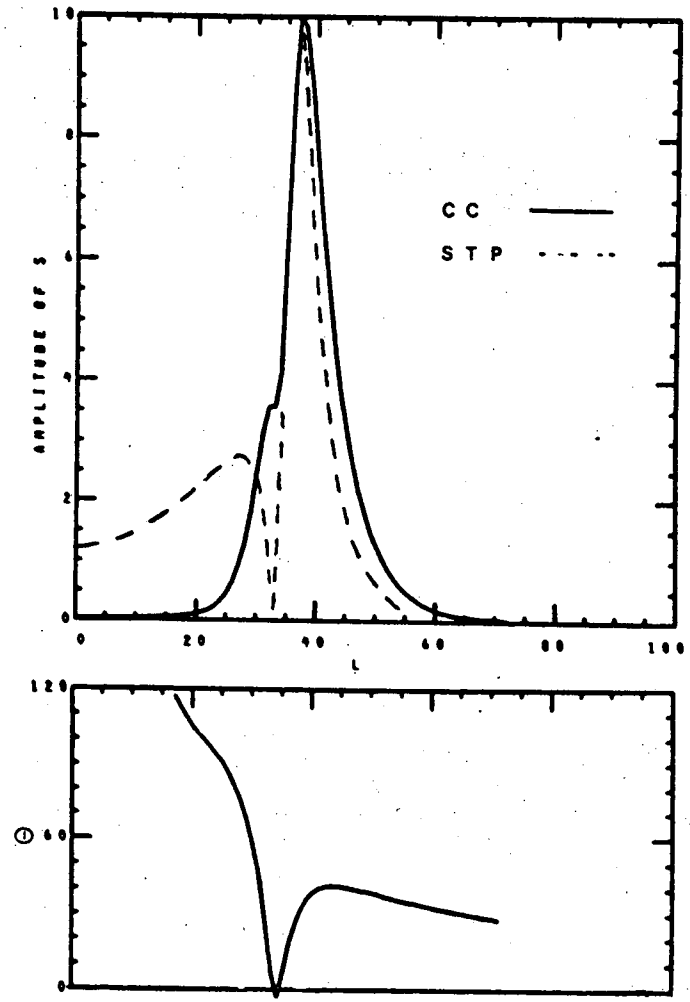
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Fig. 4

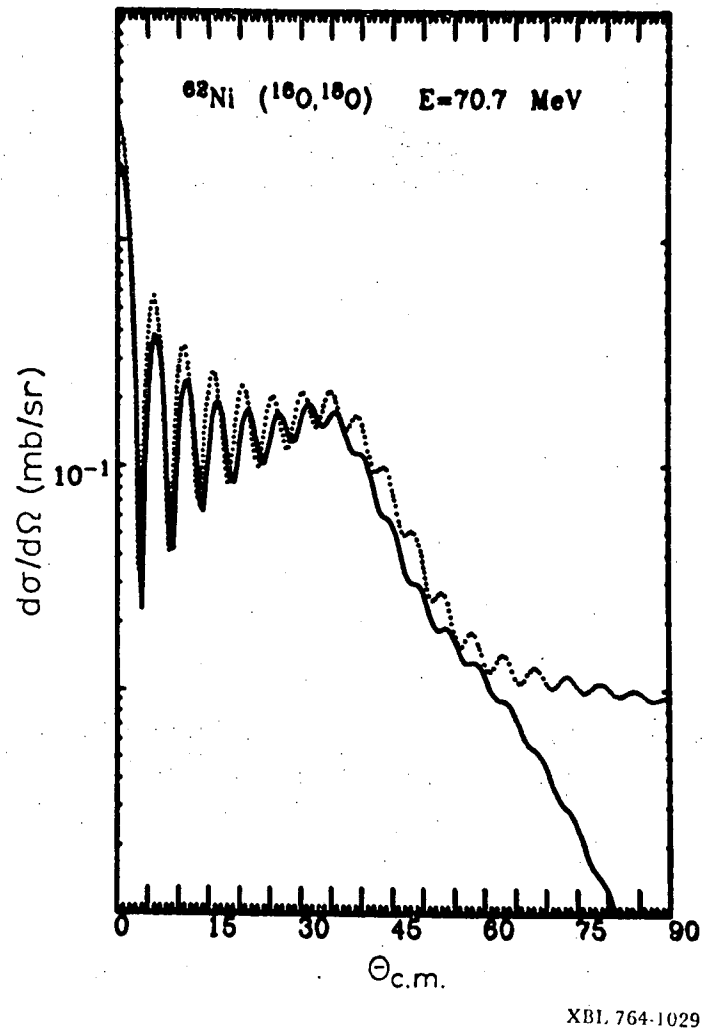
62Ni (16O,18O) E=70.7 MeV
dσ/dΩ (mb/sr)
10-1
0
15
30
45
60
75
90
Θc.m.
XBL 764-1029

Fig. 5

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