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ENHANCEMENT OF FORWARD-ANGLE CROSS SECTIONS IN HEAVY-ION
REACTIONS BECAUSE OF PROJECTILE EXCITATION[*]

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Abstract:

It is shown that the forward-angle cross section in

heavy-ion reactions can be strongly enhanced by indirect

processes in the projectile or outgoing nucleus. This is

demonstrated specifically for the $^{122}Sn(^{16}O,^{18}O)^{120}Sn$ reaction

at 100 MeV, where data for the relevant transitions exist.

At the lower energy of 60 MeV, which is just above the

barrier, the effect on the forward cross section vanishes

but at large angles beyond the peak the cross section is

reduced in agreement with experiment.

A remarkable feature in the spectrum of outgoing oxygen nuclei from the reaction

$$^{122}Sn(^{16}O, ^{18}O)^{120}Sn \quad , \quad E = 104 \text{ MeV}$$
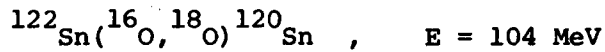
is that they are produced in the excited 2^+ state with a cross section which is about five times larger than the ground state cross section.[1] A typical spectrum taken at the Berkeley 88 inch Cyclotron is shown in Fig. 1. Such a preference for excited states of the light outgoing nucleus has been observed for some other targets as well.

For typical vibrational nuclei, of which tin is an example, it had been predicted that second-order processes going through intermediate states in these nuclei would affect the 2^+ vibrational states in a characteristic way but not the more strongly populated ground states.[2] If the direct and indirect modes of producing the vibrational state interfere destructively for the stripping reaction, they interfere constructively for the pickup (and vice versa). In the constructive case the usual bell-shaped angular distribution is expected at moderate energies above the Coulomb barrier, whereas in the destructive case, the angular distribution is predicted to be flat or may even have a dip at the grazing angle. This has now been confirmed experimentally at the Berkeley Cyclotron for the above reaction and its inverse.[3]

In drawing our attention to the spectrum of Fig. 1, the experimenters expressed concern whether producing the light nucleus in excited states, and their subsequent deexcitation would ruin or modify the agreement between theory and experiment reported in Ref. 3, which took account only of the ground states of the light nuclei ^{16}O and ^{18}O. We, therefore, investigated this question. It turned out that the oxygen and tin wave

functions that we used in our analysis, underestimated the cross

section for $^{18}O(2^+)$. Because ^{18}O is produced in its excited state in

preference to its ground state, we may infer that the $^{18}O(2^+)$ cross section

is dominated by the direct transfer. Therefore, we amplified the form

factor for this transfer over what was computed from the wave functions,

by the factor 1.3 necessary to produce the observed ratio of the cross

sections for $^{18}O(2^+)$ and $^{18}O(0^+)$ (with tin produced in its ground state in

both cases). These computed cross sections are compared with the data in

Fig. 2 (solid lines). Also we show the cross sections for the direct

transitions. In the region of the grazing peak, the effect of indirect

feeding of the ground state is not dramatic. The cross section for producing

the ground state of both nuclei is reduced by a factor of 2, and the grazing

peak is shifted to a somewhat smaller angle. Given all the uncertainties

and complexities of reactions between complex nuclei, we would have considered

either calculation to be in satisfactory agreement with experiment.

As concerns the 2^+ cross sections of tin, we were not able,

because of restrictions in our computer programs, to evaluate this effect.

For reasons that we cannot go into here, we expect that the pickup cross

section will be unaffected, while the stripping reaction will be moderately

enhanced, yielding an improved agreement with experiment.[3]

However, the real interest in this calculation turns out to be the

unexpected change in the forward-angle cross section. Here we see a

dramatic increase, by a factor of 10, in the ratio of forward to grazing-angle

cross section for the ground state, when the effect of excitation of ^{18}O

to its 2^+ state is included. Since the cross section to the $^{18}O(2^+)$ state

is adjusted to agree with experiment, and the strength of the inelastic transition in the ^{18}O nucleus is prescribed by the measured[4] β_2 of this nucleus, this result is quite firm. We note that the sign of the interference changes between grazing angle and forward angles.

The significance of this result must be viewed in connection with the interpretations of large forward-angle cross sections by the Brookhaven group. We recall that in the ^{A}Ni(^{18}O,^{16}O) reactions on a series of isotopes, the cross sections have normal grazing peaks for the heavier isotopes, while at the light end they have anomalously large forward cross sections.[5] In an early work they varied the parameters of a weakly absorbing potential to reproduce this trend.[5] Recently, they have treated only one of these cases using a surface transparent potential to obtain a large forward cross section.[6] It appears however that these potentials may actually be simulating the physical process of indirect feeding of the ground state through excited states of the light nucleus.

In Fig. 3 we show the cross sections arising from the direct and indirect transitions alone. The indirect transitions have larger forward distributions compared to the direct. This can be understood as characteristic at energies for which the classical deflection function has a rainbow angle.

First we recall a general principle.[7] The angular momentum region that dominates a given process is determined by the competition of several factors. Two competing factors are the absorption, which reduces the cross section for small angular momenta, and the preference for close collisions when particles are transferred. Naturally a two-step process requires a

closer collision than a direct one. The balance of these two factors leads to a preference of two-step processes for orbits with angular momenta somewhat smaller than the rainbow or grazing angular momenta associated with the peak in the cross section of the direct process. Therefore, forward-angle scattering is enhanced for two-step processes compared to direct ones when the energy is such that the deflection function possesses the rainbow or grazing angle.

A different behavior is observed when the energy is lower and closer to the Coulomb barrier. In this case there is no rainbow angle, and the closer orbits preferred by the two-step process scatter to larger angles than the slightly more distant orbits preferred by the direct process. This is the case for the same reaction of Figs. 2 and 3, when the energy is just above the Coulomb barrier, as in Fig. 4. The forward-angle cross section at this energy is unaffected by the excitation of $^{18}O(2^+)$ but the back-angle cross section is reduced by the destructive interference between direct and indirect transitions. The improvement in the agreement is marked. The data are for the reaction inverse to the one for which we did the computation. They are equal by time reversal invariance. We only chose to do the calculation for the pickup reaction because this is the one for which the important intermediate state, $^{18}O(2^+)$, is a direct observable.

To summarize our results, we have found that transitions through excited states in the projectile or outgoing particle involved in a transfer reaction can produce a large enhancement at forward angles in the ground-state cross section, when the energy is sufficiently high above the barrier so that the grazing angle is truly a rainbow effect. Such an enhancement may occur

when an excited state of one of the light nuclei is produced in the transfer reaction with larger cross section than its ground state, and the two are strongly coupled.
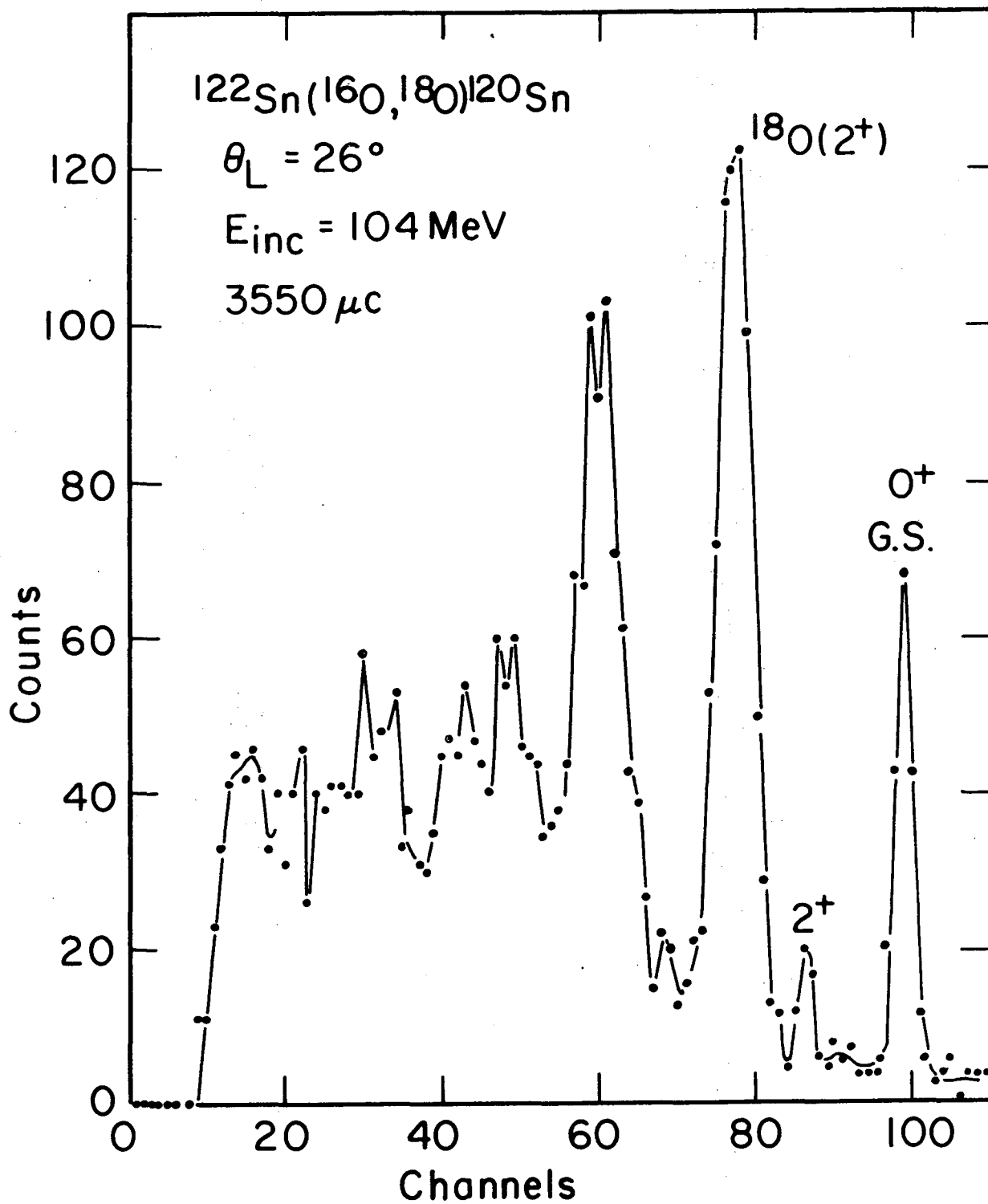
Clearly it is of interest to perform the $(^{16}O, ^{18}O)$ reactions on the nickel isotopes so as to measure the relative cross sections of $^{18}O(2^+)$ and $^{18}O(gs)$. If the ratio is large, then it is very likely that a substantial part of the forward-peaked cross sections in the $(^{18}O, ^{16}O)$ reactions measured by the Brookhaven group is due to the second order effect of the light-nucleus excitation.

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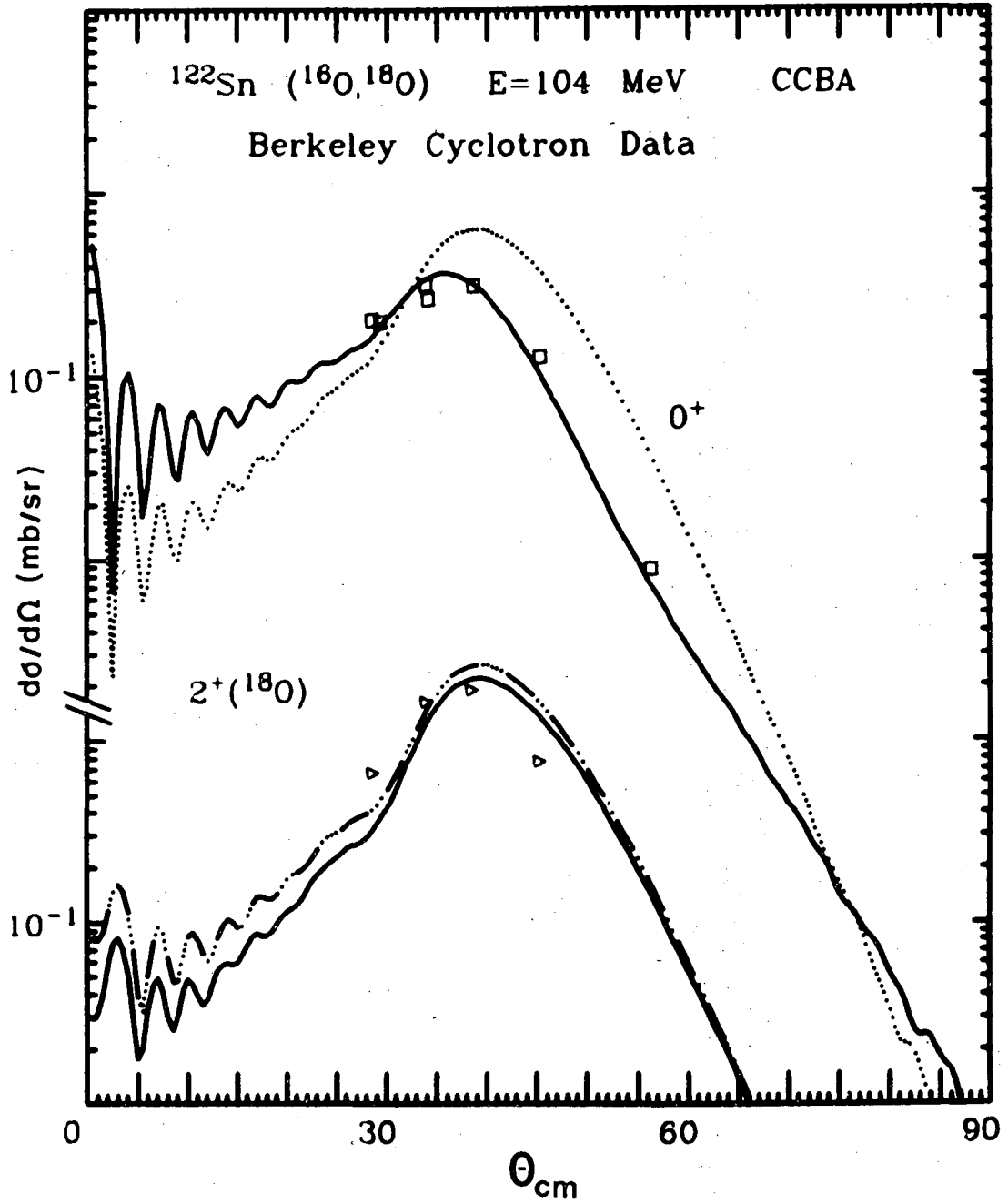
Figure Captions

Fig. 1. Energy spectrum for the reaction indicated. Note large cross section for producing ^{18}O in its 2^+ state (with ^{120}Sn in its ground state).

Fig. 2. Broken lines show direct cross sections for producing the ground state of ^{120}Sn with outgoing nucleus ^{18}O in its ground and excited state. Solid lines show effect of coupling these two levels. A common normalizing factor 2.7 is used for all curves. The optical model parameters which reproduce elastic and inelastic data are given in Ref. 3.

Fig. 3. Shows separately direct and indirect cross sections for producing the ground and excited state of the outgoing ^{18}O nucleus (^{120}Sn in its ground state in both cases).

Fig. 4. Computed ground state cross section for pickup reaction is compared with data on the time reversed reaction (Ref. 8). The effect of indirect feeding of the ground state through the intermediate 2^+ state in ^{18}O is seen by comparing the dotted and solid curve. Cross section computed for the 2^+ state in ^{18}O is also shown, but no data are available. A common normalization factor 6.2 is used for all curves. The calculation is as described for Fig. 2. Optical parameters were derived from the ^{18}O + ^{120}Sn elastic scattering data at 60 MeV.

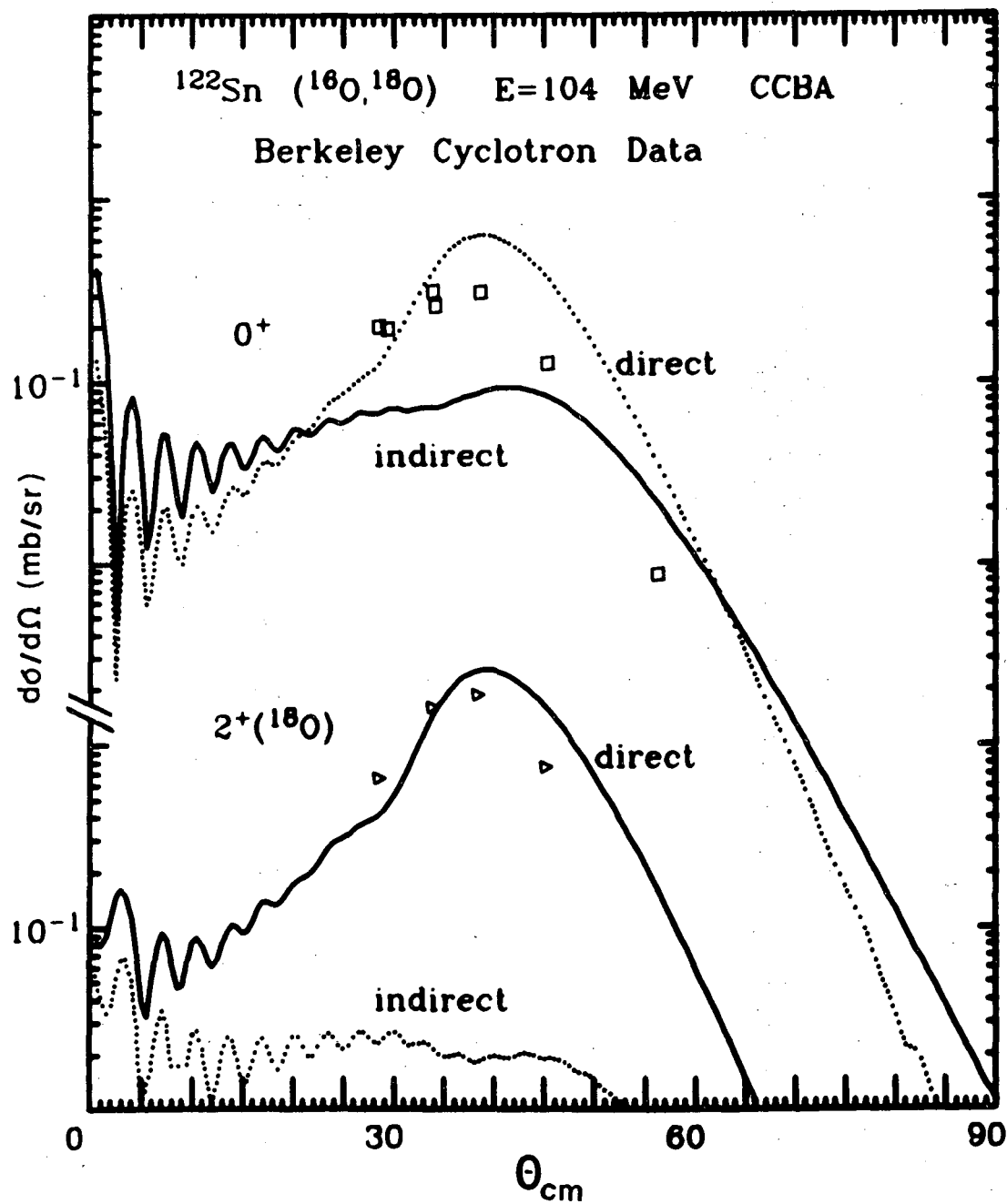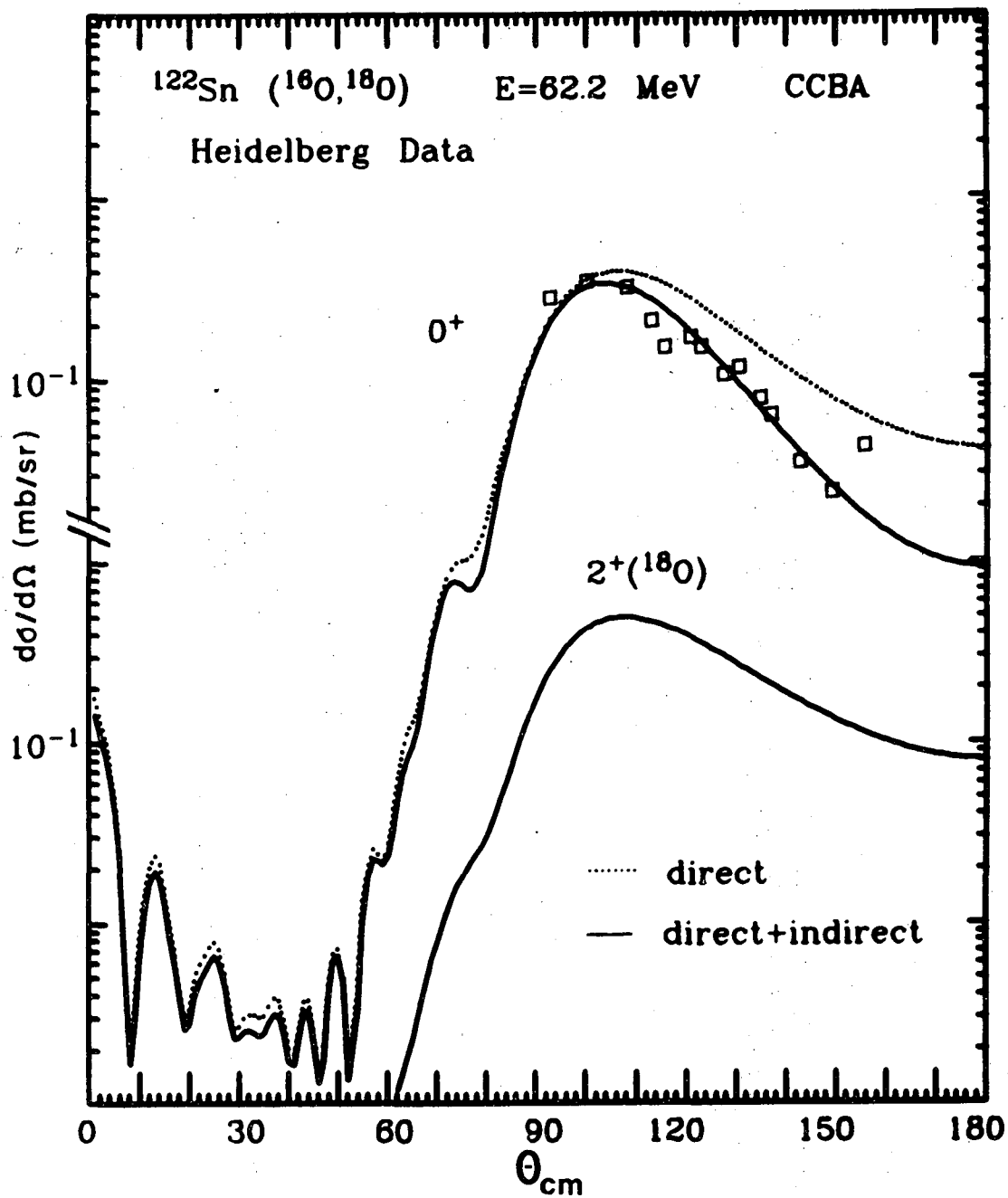$^{122}Sn(^{16}O,^{18}O)^{120}Sn$

$\theta_L = 26°$

$E_{inc} = 104\,MeV$

$3550\,\mu c$

$^{18}O(2^+)$

0^+ G.S.

2^+

Fig. 1

Fig. 2

XBL 753-755

^{122}Sn $(^{16}O,^{18}O)$ E=104 MeV CCBA
Berkeley Cyclotron Data

XBL 753-756

Fig. 3

$$^{122}Sn \ (^{16}O, ^{18}O) \quad E=62.2 \ MeV \quad CCBA$$

Heidelberg Data

0^+

$2^+(^{18}O)$

.... direct

——— direct+indirect

$d\sigma/d\Omega$ (mb/sr)

Θ_{cm}

XBL 753-757

Fig. 4