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DISCLAIMER

THE INTERFERENCE BETWEEN DIRECT AND INDIRECT MODES IN TWO-NUCLEON TRANSFER REACTIONS WITH HEAVY-IONS*

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Abstract:

Direct and indirect transitions to the lowest 2^+ collective states are shown to interfere constructively in the pick-up reaction $^{122}Sn(^{16}O,^{18}O)^{120}Sn$ at 104 MeV, and destructively in the inverse stripping reaction $^{120}Sn(^{18}O,^{16}O)^{122}Sn$ at 99 MeV.

The presence of indirect transitions in two-neutron transfer reactions to vibrational states in the Sn isotopes has been predicted to have the interesting consequence that the interference between direct and indirect modes is destructive in stripping and constructive in pick-up.[1,2] The effect has not been demonstrated in conventional, light-ion induced reactions owing to the difficulty of performing inverse reactions of the type (p,t), (t,p) at the same center of mass energies, but the flexibility of heavy-ion induced transfer opens up several possibilities. Here we discuss the reactions $^{122}Sn(^{16}O,^{18}O)^{120}Sn$ and $^{120}Sn(^{18}O,^{16}O)^{122}Sn$ to the ground and lowest collective 2^+ excitations. The incident energies of 104 MeV for the ^{16}O beam and 99 MeV for the ^{18}O beam correspond to approximately the same center of mass energy.

Some data for the ^{120}Sn(^{18}O,^{16}O)^{122}Sn reaction at 100 MeV were reported previously.[3] Since this reaction has a positive Q-value of 2.78 MeV, counter telescope techniques were adequate at backward angles to separate the 0^+ and 2^+ states from the intense elastic scattering. For more forward angle data (which is the important region for the indirect effects) and for the corresponding transitions in the inverse pick-up reaction ^{122}Sn(^{16}O,^{18}O)^{120}Sn the reaction products from 104 MeV ^{16}O and 99 MeV ^{18}O ions from the 88-inch cyclotron were detected with the Berkeley QSD magnetic spectrometer. The identification relied on a measurement of (Bρ) using a resistive-wire position sensitive proportional counter,[4] a double (dE/dX) measurement in the transmission proportional counters, combined with the time-of-flight (α M/Q) between a 70 μg/cm^2 scintillator foil of NE111 at the entrance of the spectrometer and a plastic scintillator behind the focal plane detectors.[5] Non-uniformities in the 200 μg/cm^2 self-supporting Sn targets reduced the resolution to 250 keV. The spectrum in Fig. 1 shows that the (^{18}O,^{16}O) reaction populates the superfluid, pairing vibrational ground state strongly and the collective vibrational 2^+ state at 1.14 MeV more weakly, although this state is favored by the reaction dynamics by a factor of approximately eight.

The differential cross sections for the two-neutron transfer reactions are shown in Fig. 2 together with theoretical curves which will be discussed later. The ground state transitions correspond to reversed reactions at almost the same center of mass energy and are similar. Absolute cross sections were measured for both reactions using the spectrometer. Data taken from Ref. 3 were included for the (^{18}O,^{16}O) reaction and normalized to the spectrometer data for the ground state. The distributions for the ground states and for the 2^+ state in the pick-up reaction $^{122}Sn(^{16}O,^{18}O)^{120}Sn$ are all similar in shape, exhibiting a "bell-shaped" maximum at $\Theta_{CM} = 38^\circ$, corresponding to a grazing collision in the combined Coulomb and nuclear fields. This distribution is the well-known characteristic of a single-step, direct transition in heavy-ion induced transfer reactions at moderate energy above the Coulomb barrier. In the stripping reaction $^{120}Sn(^{18}O,^{16}O)^{122}Sn$, the 2^+ transition has a smaller cross section and shows no clear grazing maximum. Instead the cross section at forward angles is rather flat in agreement with the predictions of Refs. 1 and 2. To explain the contrasting behavior observed in the cross sections for stripping and pick-up to the vibrational states, we review the discussion of Refs. 1 and 2, by referring to Fig. 3. In the production of the 2^+ state, transitions 1 and 4 are indirect and are common to both the stripping and pick-up process, while 2 is the direct transition for pick-up and 3 is the direct transition for stripping. The amplitudes for these last two transitions have opposite sign according to the microscopic theory of vibrational states[1,2]. It is this opposite sign which leads to a constructive interference between the direct and indirect modes in the one reaction and destructive in the other. Destructive interference between two amplitudes, both of which are peaked near the grazing angle[6], leads to distortion of the bell-shaped angular distribution, while a constructive interference retains the characteristic peak. The experimental cross sections for the 2^+ vibrational states are clearly in qualitative accord with the theory. That the two ground state cross sections are similar follows from the fact that they are time reversed reactions (the center of mass energies being almost equal in the experiments). That they <u>also</u> retain the characteristic grazing peak, undistorted by interference from higher order processes can also be understood in terms of Fig. 3. In this case, for either ground state transition, both 2 and 3 enter the two lowest order indirect modes. Since they have opposite signs they tend to cancel each other, resulting in negligible higher order contributions to the ground state cross sections. This explains qualitatively why three of the cross sections have bell-shaped angular distributions, while the fourth is distorted.

For the quantitative analysis of this effect with the coupled channels Born approximation (CCBA), we have derived the relevant optical model and deformation parameters from the analysis of elastic and inelastic scattering of ^{16}O on ^{122}Sn, measured during the same experiment. The theoretical fit to this data shown in Fig. 4 used the optical model parameters V = 87.9 MeV, W = 24.24 $r_V = 1.203$, $r_W = 1.19$, $r_C = 1.20$, $a_V = 0.502$, $a_W = 0.67$ (referring to a Woods-Saxon form) together with nuclear and charge deformations for ^{122}Sn of $\beta_N = 0.124$ ($R_N = 1.12(122)^{1/3}$) and $\beta_C = 0.095$ ($R_C = 1.2(122)^{1/3}$) respectively. Here β_N is close to the value obtained in proton inelastic scattering[7] but β_C is slightly reduced from the value of 0.118 derived from the quadrupole moment.[8] For ^{120}Sn we follow the same prescription, viz $\beta_N = 0.13$ and β_C reduced from 0.112 (Ref. 8) to 0.09.

The theoretical predictions using CCBA theory for the stripping and pick-up reactions are shown in Fig. 2. The details of the method are given in Refs. 1 and 2, but briefly, two states of each Sn nucleus were included: the ground state, described as a BCS vacuum state, and the collective two quasiparticle 2^+ state. The single-particle wave functions, in terms of which the 2^+ state is represented, are the $2d_{5/2}$, $2d_{3/2}$, $1g_{7/2}$, $3s_{1/2}$ and $1h_{11/2}$ states bound in a Woods-Saxon potential at one half the 2-neutron separation energy in ^{122}Sn.

The ground state of ^{18}O was treated as an inert ^{16}O core with two neutrons in $s_{1/2}$, $d_{3/2}$ and $d_{5/2}$ orbitals, in a Woods-Saxon potential which binds them at one half the 2-neutron separation energy in ^{18}O. The absolute theoretical cross sections are in remarkably good agreement with experiment since a factor of only 2.5 was required to normalise the ground states. Since the reactions were not studied at precisely the same center of mass energies, the predictions for the ground states differ slightly. The theory successfully reproduces the main features of the data discussed earlier, in particular the characteristic flattening of the 2^+ distribution in stripping due to destructive interference. A calculation ignoring the indirect contributions resulted in a bell-shaped curve like the distributions for the ground states and the 2^+ state in pick-up.[6] The cross section for the 2^+ state is slightly overestimated in the $(^{16}O, ^{18}O)$ reaction and underestimated in the $(^{18}O, ^{16}O)$ reaction, which may be partly due to the incomplete treatment of recoil effects or to the inadequacies in the description of the nuclear wave functions. A more detailed analysis of the data is in progress, to examine the role of the microscopic structure of the Sn isotopes, which influences the relative magnitude of direct and indirect modes. The effect of projectile excitation is also under consideration[9].

Our main concern in this letter is to demonstrate for the first time the existence in nature of cross sections to vibrational states which quantitatively confirm the opposite interference characteristics between direct and indirect modes in the inverse pick-up and stripping reactions. The opposite interference is associated with the underlying microscopic structure of the vibrational states. We point out that previously reported destructive interferences[10,11] in two-neutron transfer reactions occurred in the $(^{12}C, ^{14}C)$ pick-up reactions, and that the reversed reactions are not available for these cases. Heavy-ion reactions are rich in possibilities for studying this phenomenon, not only in neutron transfers, but also in reversed two-proton transfers. These reactions may prove to be a sensitive means of probing inelastic modes which are not directly observable and, ultimately, of deformations and nuclear structure.

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FOOTNOTES AND REFERENCES

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FIGURE CAPTIONS

Fig. 1. Energy spectrum for the reaction $^{120}\mathrm{Sn}(^{18}\mathrm{O},^{16}\mathrm{O})^{122}\mathrm{Sn}$ at $\Theta_L = 30°$ and $E_L = 99$ MeV.

Fig. 2. Differential cross sections for the reactions $^{120}\mathrm{Sn}(^{18}\mathrm{O},^{16}\mathrm{O})^{122}\mathrm{Sn}$ at 99 MeV and $^{122}\mathrm{Sn}(^{16}\mathrm{O},^{18}\mathrm{O})^{120}\mathrm{Sn}$ at 104 MeV. For the $(^{18}\mathrm{O},^{16}\mathrm{O})$ reaction the open symbols represent the counter telescope data of Ref. 3 and the dot-enclosed symbols, spectrometer data. The solid lines are the CCBA predictions for $(^{18}\mathrm{O},^{16}\mathrm{O})$ and the dashed lines for $(^{16}\mathrm{O},^{18}\mathrm{O})$.

Fig. 3. Illustration of the amplitudes relevant to two-neutron transfer reactions involving direct and indirect modes, as discussed in the text.

Fig. 4. The differential cross sections for elastic and inelastic scattering (2^+) of $^{16}\mathrm{O}$ on $^{122}\mathrm{Sn}$ at 104 MeV. The curves are predictions of coupled channels theory. Optical model and deformation constants β_N and β_C are mentioned in the text.

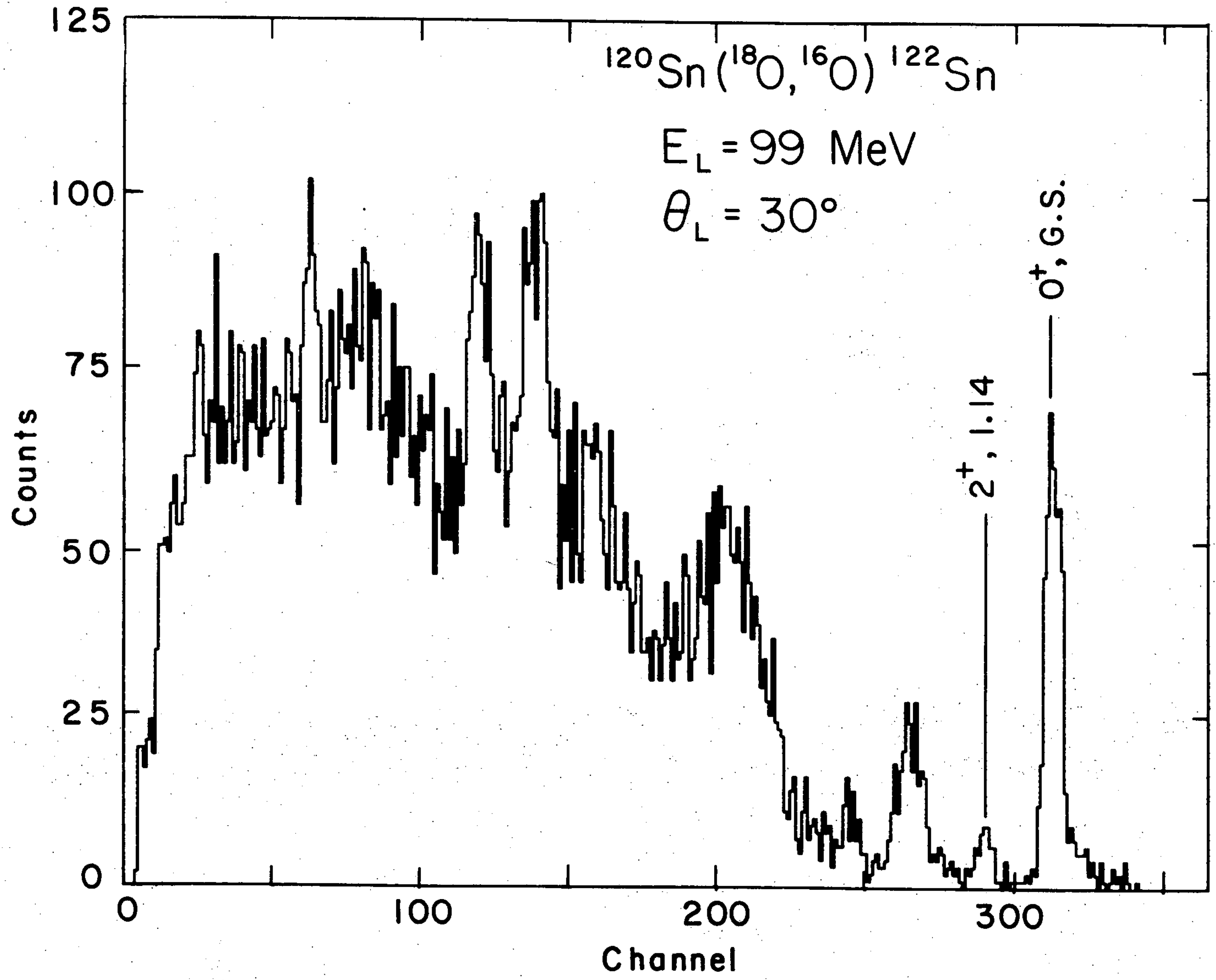

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Fig. 1

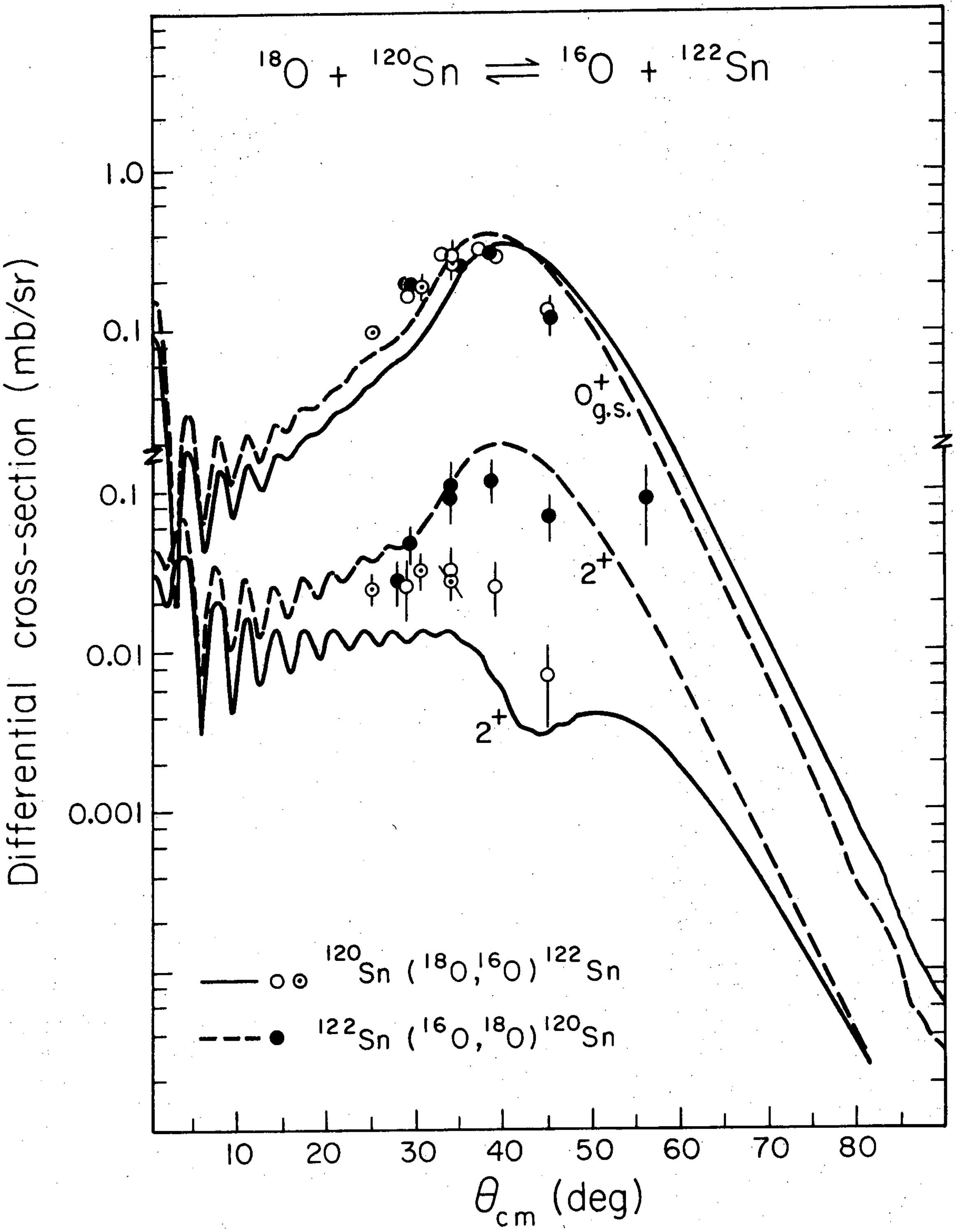

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Fig. 2

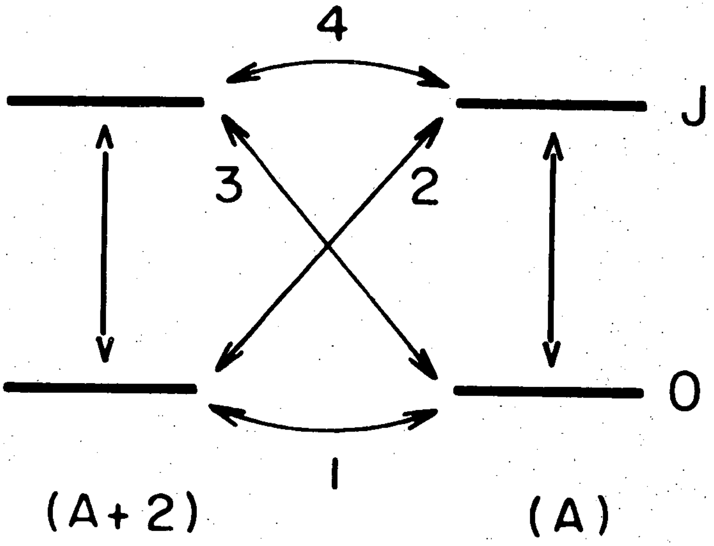

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Fig. 3

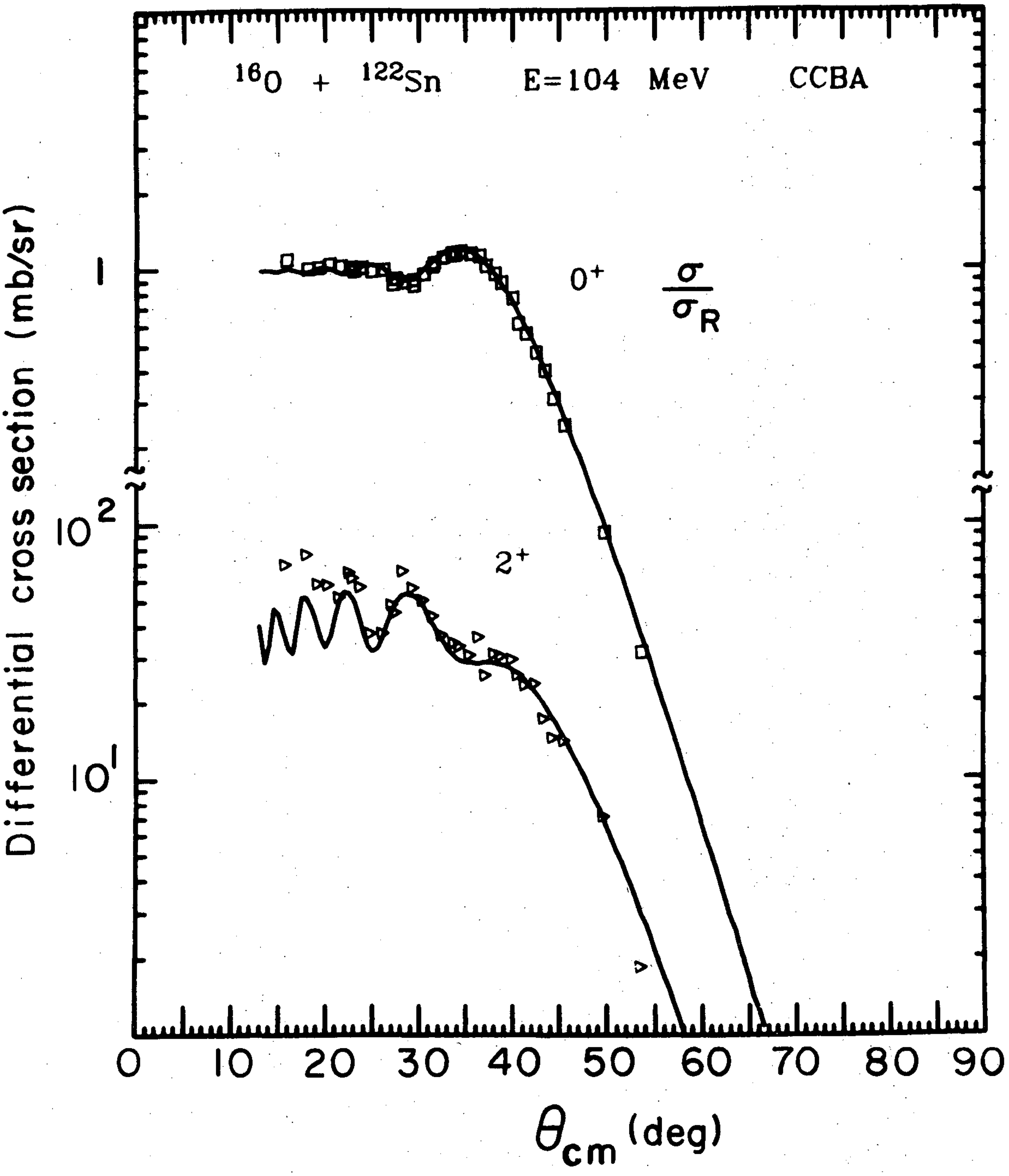

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Fig. 4

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