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Pion Scattering and Nuclear Dynamics

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ABSTRACT

A phenomenological optical-model analysis of pion elastic scattering and single- and double-charge-exchange scattering to isobaric-analog states is reviewed. Interpretation of the optical-model parameters is briefly discussed, and several applications and extensions are considered. The applications include the study of various nuclear properties, including neutron deformation and surface-fluctuation contributions to the density. One promising extension for the near future would be to develop a microscopic approach based on powerful momentum-space methods brought to existence over the last decade. In this, the lowest-order optical potential as well as specific higher-order pieces would be worked out in terms of microscopic pion-nucleon and delta-nucleon interactions that can be determined within modern meson-theoretical frameworks. A second extension, of a more phenomenological nature, would use coupled-channel methods and shell-model wave functions to study dynamical nuclear correlations in pion double charge exchange.

1. Introduction

One of the great challenges to nuclear theory is to obtain a unified microscopic description of the effective interactions that quantitatively describe and link nuclear structure with low-energy-scattering phenomena involving hadronic probes. I will assume that we have an underlying meson-theoretical description of nuclear structure and reactions for this purpose and concentrate on low-energy pion scattering (kinetic energy $T_\pi < 300$ MeV) to discrete states in nuclei with this in mind.

If one is going to make progress in a microscopic understanding of these reactions, it is necessary to pursue phenomenology and microscopic theory simultaneously. I will begin this talk by discussing phenomenology of the optical potential in Sect. 2 and then use this part of the talk as a launch to the discussion of the microscopic theory in Sect. 3 and phenomenological applications. Pion scattering to discrete states has important applications because these reactions are able to probe, through the distinct spin and isospin dependence of the pion-nucleon interaction, specific single-particle and collective properties of nuclei. Furthermore, short-distance correlations in nuclei are probed directly in pion double charge exchange. These will be discussed in Sect. 4. Pion inelastic scattering to the continuum and pion absorption are important sources of information about two- and many-body reaction dynamics. The connection of these to the pion optical potential is rather direct [1], but I will leave discussion of these to other speakers at this conference. In Sect. 5, I will summarize my assessments of open problems and comment on future directions of the field.

Many people have contributed to the understanding that we have in the phenomenological and microscopic approaches to pion scattering. For the most part my lecture will reflect my personal prejudices on the subject and include as examples mostly work in which I have been involved.

2. Phenomenology of Pion Elastic, Single and Double Charge Exchange

I would say that one of the most successful phenomenological descriptions of scattering to discrete states is the optical-potential approach of the Michigan State University (MSU) group [2] in combination with the distorted-wave impulse approximation. The history of the MSU optical potential is a long one, beginning with the pioneering work of Ericson and Ericson [3]. The physical significance of the particular parametrization adopted for the MSU optical potential was generally laid out by the Ericsons, and has been pursued by many other researchers in the meantime.

As you may know, the MSU group put together results of several other groups to show the basic consistency of pionic atom data and pion scattering below T_π of about 50 MeV. A few years ago, Siciliano and I, along with numerous collaborators, developed a Lane type extension of the MSU optical potential to study pion elastic scattering and single- and double charge exchange scattering to isobaric analog states at both resonance [4] and low energy [5].

Next, let me present some of the results that have been obtained with the extended MSU potential. These results will be used to motivate the subsequent discussion.

In order to describe the elastic and charge-exchange reactions to the ground state and isobaric analog states, the optical potential U is expressed in terms of the pion isospin ϕ and the nuclear isospin **T** as

(1) $$U = u_0 + u_1\phi.\mathbf{T} + u_2\,(\phi.\mathbf{T})^2.$$

The optical potential is taken to be expanded as a power series in density. The lowest-order term is determined semi-theoretically. It is proportional to the experimental pion-nucleon-scattering amplitude, evaluated at a shifted (complex) energy ΔE. Theoretical estimates give the real part of ΔE to be approximately 25 MeV for resonance-energy scattering. The pieces of the optical potential second-order in density are closely related to the amplitude for a pion to scatter from two nucleons in the nucleus, and are interesting because of their connection to the poorly known but fundamental short-distance dynamics of hadrons.

We would like to construct the best possible theoretical representation of the lowest-order optical potential so that the phenomenological description of the second-order optical potential will be interpretable based on the underlying theory. For this purpose, it is necessary to use nuclear wave functions with realistic shapes, especially at resonance energy where the reaction is sensitive to the shape of the nuclear surface. In the optical potential model calculations discussed below, wave functions were obtained from Hartree-Fock theory with the Skyrme III interaction.

Near resonance, the p-waves dominate and the second-order optical potential is characterized, for a given partial wave and T_π, by three complex numbers as follows: the isoscalar potential (u_0) is proportional to the coefficient $\lambda^{(2)}{}_0$ and to the square of the total density; the isovector optical potential (u_1) to $\lambda^{(2)}{}_1$ and the product of the total and the transition density to the isobaric analog state; and the isotensor potential (u_2), apart from a correction for double counting, to $\lambda^{(2)}{}_2$ and the square of the transition density to the isobaric analog state. Phenomenological values at T_π = 162 MeV were obtained in Ref. [4] and at two other energies in Ref. [6]. These numbers (and a comparison to calculations of a few specific second-order effects explained below) are given in Table I. Elastic scattering determines ΔE and $\lambda^{(2)}{}_0$, and the resulting fit is shown in Fig. 1. Forward-scattering single-charge-exchange (SCX) (Fig. 2) and double-charge-exchange (DCX) (Fig. 3) cross sections determine $\lambda^{(2)}{}_1$ and $\lambda^{(2)}{}_2$, respectively. The angular distribution for DCX is then predicted as the solid curve in Fig. 4. The fact that the minima of the angular distributions move to smaller angles consistent with the data is an important result that has been difficult to obtain in phenomenological analyses that use alternative representations of the medium modifications.

Although there are a number of parameters in the theory (four complex parameters at each energy in the results that I have shown), they were found to be universal in the sense that they characterize the A-dependence of the cross sections throughout the periodic table. As explained below, the universality is expected, and I believe that it is a non-trivial result that this actually occurs at resonance energy and above. At low energy some of the simplicity is lost because of the long wavelength of the pion and we can no longer argue that the $\lambda^{(2)}$-parameters should be the same for all nuclei.

3. Microscopic Theory

For an elementary introduction to the basic theory underlying the MSU optical potential and its extensions to charge-exchange reactions, see Refs. [13] and [14]. As stressed there, the special form of the optical potential occurs as a result of making the local-density approximation and the static approximation applied to nucleon motion, i.e., the pion is treated relativistically and is assumed to have a much higher velocity than the nucleons, undergoing its multiple scattering before the nucleons have much of a chance to move. This "fixed scatterer" approximation effectively decouples the nucleon motion and the pion dynamics, so that one comes fairly directly to expressions for the pion optical potential in which the pion dynamics and the nuclear structure are factorized in an expansion in nuclear densities. These coefficients are related perturbatively back to the microscopic dynamics using the Dyson expansion, taking advantage of the connection between the optical potential and the proper self-energy of the pion in the medium [15,16] and the assumed isospin invariance of the interactions. By looking at specific examples [16], it was inferred that the λ coefficients would be approximately independent of A for resonance energy scattering. In this fashion, one has, in principle, a connection between the data and the underlying meson theory.

What have we learned from the experience with the MSU optical potential? For one thing, one finds that in charge-exchange reactions there is considerable sensitivity to the medium modifications of the pion-nucleon interaction. So far, we have only hints at what is going on at the microscopic level, and no comprehensive picture has emerged. However, the fact that the data are described as well as they are within the general phenomenological framework of the density expansion might be taken as encouragement to go back to the basic theory, eliminating the static and local density approximations but otherwise following closely the development of the optical potential through the pion self-energy.

Once one eliminates these approximations, the theory becomes considerably more complicated in practice. By using momentum-space techniques developed over the last decade [17], one has the tool needed to make such an extension. I would like to mention in this regard some of the theoretical results obtained by Ernst and myself on the extension of the underlying theory, and some of the numerical results obtained in our study of pion scattering at resonance energy.

We would like to build up the pion-nucleus interaction beginning with a meson theory that has had some successes in other areas. Two candidate approaches come to mind. One is the theory of Quantum Hadrodynamics [18], and the other approach is that of the Bonn group [19]. The latter has been applied to both the nucleon-nucleon interaction and to nuclei using Brueckner-Bethe-Goldstone theory, and it does a reasonably good job here. Pions are well-integrated into this theory, and it may be the more suitable one for immediate application to pion scattering. There have been some attempts to test this theory in pion-nucleon scattering [20], where chiral symmetry constraints are being found important. I would offer the general observation that the task of constructing the pion-nucleon interaction in meson theory has received considerably less attention than it deserves.

In the absence of a satisfactory derivation of the pion-nucleon scattering amplitude from meson theory, numerical studies have proceeded by adopting an empirical, but theoretically motivated, off-shell parametrization of the pion-nucleon interaction. Several exist in the literature, and in our studies we have employed one of our own [21], which is distinguished from some of the others by having a rather high mass cutoff (about 1 GeV) for the pion-nucleon form factor in the important Δ_{33} partial wave.

Next, one needs to perform a systematic expansion of the proper self-energy of the pion sticking as close as possible to the pion-nucleon interaction as a basic expansion element. I will follow in this discussion work that Ernst and I are currently doing to extend our earlier [15] fixed-scatterer approach. In the diagrammatic language that we prefer, the lowest-order optical potential is shown in Fig. 5. In order to completely define it, one needs to specify the dispersive correction [22], which refers to the interaction of the nucleon and the delta resonance in intermediate states. This correction is necessary on physical grounds because it compensates the nucleon-binding corrections, which are included as part of the kinematics.

In our calculations, we have chosen the dispersive correction, E_{MS}, to be the average of the delta-nucleon interaction over the density of the nucleus and the (distorted) wave function of the pion. For reasons explained in Ref. 22, we have taken the delta-nucleon interaction to be the same as the nucleon-nucleon interaction. Presumably, the delta-nucleon interaction could be calculated with some confidence in meson theory, especially that described in Ref. [19]. This is, I believe, an important subject for future activity.

Something quite remarkable happens when we use the momentum-space optical potential with the dispersive correction and full Fermi averaging. One sees in Fig. 6 a comparison of the theoretical and experimental angular distribution on ^{12}C at resonance energy. The angular distribution is fit quite well over the full angular range considering that there are no adjusted parameters. Similar quality (within 30% at back angles) results are found from about 115 to 250 MeV. In these calculations, realistic Hartree-Fock wave functions and single particle energies were used. Our reproduction of the scattering is, however, not perfect and it could be improved by taking the E_{MS} to be a bit less attractive [22]. This presumably reflects the lack of second-order terms and/or the need for adjustments to our dispersive correction. At low energy, elastic scattering seems to be more sensitive to the second-order optical potential than it is at resonance.

In the theoretical description of the second-order optical potential, one can identify many processes that are expected to be important. One of these is the Pauli principle [11], which among other things, narrows the resonance by blocking the nucleon states into which the delta can decay in the nucleus. Another contribution, which has the opposite effect in the isoscalar optical potential, is the broadening of the resonance due to pion true absorption and multiple inelastic scattering. I believe that the competition between the Pauli narrowing and collision broadening is one reason why our phenomenological second-order isoscalar optical potential (Table Ia) tends to be so small, and why the momentum-space optical potential does so well for elastic scattering already in lowest order. Another important correction to the second-order optical potential is the spin-isospin Fermi-liquid parameter $g_{0\Delta}'$ [24]. This and the long-range correlation arising from the Pauli principle give a net repulsive effect, which may explain why our delta-nucleon potential seems a bit too strong in the momentum-space calculations. The amount of repulsion arising from correlations is model dependent, being somewhat sensitive to the off-shell extension of the pion-nucleon scattering amplitude. Perhaps careful systematic studies with the momentum-space optical potential will help narrow the uncertainties in the off-shell extrapolation of the pion-nucleon scattering amplitude and the other related quantities that we have discussed here.

We find that a large part of the isovector second-order potential might be explained by the Pauli principle (see Table Ib). So far we have been unable to give a convincing explanation of the origin of the phenomenological isotensor potential. Table Ib shows a comparison of this to the isotensor part of the delta-nucleon interaction [12], but we see that it does not have the correct phase and variation with energy. It is intriguing that the isotensor coefficient appears to have a resonant shape that agrees well in magnitude and shape with an estimate made by Miller of resonant six-quark cluster effects. Singham and Koltun have recently proposed that the isotensor contribution arising from true absorption should give something that looks like the phenomenological result. Because of the direct connection between the isotensor optical potential and dynamical correlations such as those mentioned here, interest remains high in pion double charge exchange.

4. Applications of pion scattering

In this section I would like to discuss three applications of pion scattering. Can we use our knowledge of the density dependence of the optical potential to determine interesting nuclear properties that have not been previously determined empirically? The first two applications address this question making use of the optical potential discussed in Sect. 2, which was determined from independent measurements on spherical nuclei. The first is a study of the sensitivity of elastic scattering to a dynamical correction to the density that arises from fluctuations of the nuclear surface. The second is a study of the sensitivity of single-charge-exchange scattering to the deformation of the neutrons in oriented, deformed nuclei. The final application is to pion double charge exchange at low energy, where it is likely that one has isolated signatures of the two-body "kinematic," or shell-model correlations, in the data.

The first application was made in collaboration with Geert Wenes [25]. This study was motivated by recent suggestions [26] that the coupling of surface vibrations into the ground-state density are significant, leading to corrections to the root-mean-square radius of up to 5% and the diffuseness of up to 20%. Such corrections would have a large effect on pion scattering. A large effect would be bad because these corrections are difficult to calculate, and because we have assumed in our phenomenological analysis that the uncorrelated Hartree-Fock wave function is a satisfactory description of the nuclear ground state.

For our evaluation of the importance of surface fluctuations, Wenes and I have considered so far only the case of ^{40}Ca. The contribution to the density arising from the surface fluctuation is made up of superpositions of the single particle-hole excitations (phonons) shown in Fig. 7. The phonons were calculated in the random-phase approximation. One must be careful, when embedding the phonons in the scattering theory, to avoid various sources of double counting. We included some of the double-counting corrections in our results, and in the end it came out that the net effect of the surface fluctuations on the neutron and proton densities is quite small. The densities are shown in Fig. 8. The corresponding differential cross section for π^- elastic scattering from ^{40}Ca is shown in Fig. 9. The data agree moderately well with the theory and from this comparison we cannot distinguish between the two calculations. We conclude that the uncorrelated Hartree-Fock description of the density is adequate for the purposes of pion scattering from closed-shell nuclei like ^{40}Ca.

The theoretical results of pion single charge exchange that I will discuss next come from work that has just been completed in collaboration with Johann Bartel and Mano Singham. We consider SCX to the isobaric-analog state in deformed nuclei. Because SCX to the isobaric analog state takes place on the excess neutrons, one can hope to learn something about the wave functions of these neutrons from this type of experiment.

The wrinkle that I want to discuss is that if this experiment is done on an oriented, deformed nucleus, then one can in principle learn about the deformation of the excess neutrons [28]. The study of the deformation by scattering pions from an oriented target represents a new approach to the problem, and the experiment is now being analized.

In order to orient the nucleus, the ground state must have non-zero spin, and it turns out that a good candidate is the rare-earth nucleus ^{165}Ho. The idea of the experiment is to make the measurement for two different orientations of the nucleus, determining the orientation asymmetry $\bar{A}_S$,

$$\overline{A}_S = \frac{d\sigma^{\perp}/d\Omega - d\overline{\sigma}/d\Omega}{d\sigma^{\perp}/d\Omega + d\overline{\sigma}/d\Omega}, \qquad (2)$$

where $\sigma^{\perp}$ refers to the cross section of a nucleus polarized perpendicular to the beam direction and $\overline{\sigma}$ refers to a nucleus with random orientation. (The original idea was to determine the orientation asymmetry A_S corresponding to longitudinally and transversely oriented nuclei, but it turned out that a measurement of the longitudinal orientation is not feasible.) It is easy to convince oneself that the orientation asymmetry is sensitive to the deformation if one makes use of the geometrical character of diffractive scattering of resonance-energy pions.

The case of a deformed nucleus is an interesting application of the optical model because of the existence of a new degree of freedom, namely deformation. To implement the theory, one represents the neutron, proton, and transition densities in the optical potential of Eq. (1) as

$$\rho_i = \rho^{(0)}(r) + 4\pi \Sigma \rho^{(\lambda)}(r)\, Y_\lambda(\Omega)\bullet Y_\lambda^*(\hat{r}) \qquad (3)$$

where Ω is the angle of the intrinsic axis of the nucleus relative to a set of axes fixed in the laboratory. The Klein-Gordon equation now becomes more complicated to solve, and the simplest way to approach the solution is project the scattering wave function onto a complete set of Wigner D-functions $D_{MM'}{}^{I}$, which describe the rotational motion of the nucleus. One then has a set of coupled equations to solve for the scattered wave function when the nucleus is left in a state of rotational motion described by $D_{MM'}{}^{I}$. In the actual calculations it is, of course, necessary to truncate the set of equations.

Let me show some of the results now for simple densities. If we determine the multipole components in Eq. (3) from a Woods-Saxon form whose radial dependence is matched to the result of a Hartree-Fock calculation for deformed nuclei and take $\Delta\rho = \rho_n - \rho_p$, we can calculate the sensitivity to the neutron- and proton-deformation parameters, β_n and β_p, respectively. Results are shown in Fig. 10. One sees in fact that for larger angles, there is a striking sensitivity of the asymmetry to the relative neutron and proton deformation. The experimenters have concluded from such calculations that they should be able to determine β_n/β_p to an accuracy of five percent, which would be the best experimental value so far.

We also solved the theory using densities taken from the constrained Hartree-Fock (CHF) calculations of deformed nuclei. Results for the differential cross section from unoriented ^{165}Ho and for the asymmetry parameter A_S and $\overline{A}_S$ as a function of scattering angle are shown in Fig. 11. One sees that the cross section compares favorably to experiment. We stress that the parameters in the theory have been completely determined from studies of spherical nuclei. For $\overline{A}_S$, our CHF theory gives $\beta_n/\beta_p = 0.95$. The preliminary result of the experiment is a slightly larger value, but the experimenters have requested that I not show the comparison of $\overline{A}_S$ to experiment because the data analysis is not yet complete.

Finally, let me return to pion double charge exchange. One of the main reasons for the long-standing interest in pion double charge exchange is that it requires, in contrast to elastic and single charge exchange, the participation of at least two nucleons. Double charge exchange, therefore, gives a direct measure of the two-body correlations in nuclei.

We have already discussed double charge exchange for pions of resonance energy and higher. There one finds that there is a significant isotensor term, which confirms substantial correlation, i.e., a substantial scattering in addition to sequential single-charge-exchange through the isobaric-analog state. Identifying the origin of the isotensor term remains one of the high priorities of pion physics.

It is useful for interpreting the isotensor potential in terms of the two-body correlations to distinguish two broad classes of correlation effects. One class refers to the "kinematic" correlations that are found in the nucleon sector of the wave function and that are described by the shell model; the other refers to the "dynamic" correlations. The latter arise from non-nucleonic components in the nuclear wave function and those that are induced by the incident pion. These are of great interest because much less is known about them and because they contain fundamental information about the interaction of a pion and two nucleons in close proximity.

Because we have used uncorrelated wave functions to describe the ground state of the target, the phenomenological isotensor potential of Eq. (1) includes both types of correlations, and at the present time we do not know their relative contribution. One important future activity is to differentiate between the kinematic and dynamic correlations in the data. Use of experimental data with an appropriate theoretical analysis will permit the different pieces to be separated. In the next section, I will come back to the question of how one might be able to do this. First, let me try to clarify some of these points by making some remarks about the importance of the kinematical correlations, as determined recently in studies of low-energy pion double charge exchange.

At low energy, it has been shown that the kinematic correlations have a strong influence on the differential cross section for DCX, and analytical formulas of a general character have been derived in the seniority scheme. For example, the differential cross section σ is given in terms of the angular momentum j of the individual orbit and the number of neutrons n = N - Z filling this orbit as [30]

$$\sigma = \frac{n(n-1)}{2}\left| A + \left[\frac{(2j+3-2n)}{(n-1)(2j-1)}\right]B \right|^2, \quad (4)$$

where A and B are two independent amplitudes related to the assumed reaction mechanism and having no dependence on n. Double charge exchange occuring as two single charge exchanges through the isobaric analog state is included entirely in the A term. The optical potential used for the analysis in Sect. 2 would lead to a cross section with similar structure, with the isotensor interaction closely related to B.

An important observation based on the low-energy experimental data is that with $B = 0$ in Eq. (4) double charge exchange cannot be described. In particular, the calculations using the optical model [5] without an isotensor term gave a cross section too small for DCX on ^{14}C even though elastic and single charge exchange were well described. By including an isotensor term [5] or by coupling in the 2^+ state [31,32] in SCX it was shown that the cross section could be raised by about the required amount. The importance of the shell-model correlations was demonstrated explicitly in the numerical work of Ref. [33], where the DCX amplitude was calculated as sequential pion charge exchange in the second Born approximation with closure applied to sum over intermediate states. In this work, the magnitude of these calculations came out rather well at 35 MeV for ^{14}C and the Ca isotopes with just sequential scattering, giving a large B coefficient. Combining all these works, we conclude that the shell-model correlations make a substantial contribution to the isotensor potential at low energy. However, because various phenomenological adjustments were made in all of them, we do not know how much of the isotensor term is also contributed by dynamical correlations.

To summarize the most important point concerning DCX, we can say that the influence of the shell-model correlations is quite significant, at least for low-energy pion double charge exchange. The low-energy DCX calculations have been now made by several different groups from different points of view, but one is still not sure how much of the cross section is due to dynamical isotensor correlations. It is time to combine the understanding gained by the different approaches to try to determine the answer to this question. Some of the necessary ingredients include shell-model wave functions, a proper treatment of single-charge-exchange nonanalog transitions, dynamical isotensor correlations, and distortions of the pion wave function.

5. Future Directions

In terms of development of the microscopic theory, I have indicated that a derivation, from meson theory, of the pion-nucleon interaction and specific higher-order terms in the optical potential, especially the delta-nucleon interaction, are high priorities. Double charge exchange is now an exciting area where much work and understanding is needed. I will spend the remainder of this section discussing the extensions of the theory that could lead to deeper understanding of this process.

In Sect. 2 I discussed the optical model of the ground state and isobaric analog states in closed-shell nuclei, where the pion proper self-energy gives the the optical potential. What is the appropriate extension of the optical model to excited states and to open-shell nuclei? Could all the ingredients that were mentioned above and necessary for understanding dynamical isotensor correlations in pion DCX be combined within an extended optical-model patterned after the approach of Sect. 2-4 in this talk?

The need for a simultaneous study of several reactions at once suggests that coupled channels would constitute the appropriate extension. Furthermore, explicitly summing over the nonanalog as well as analog SCX intermediate states in DCX, as would occur in a coupled channels formulation, would overcome various limitations of the DWIA and closure approximations. Mano Singham and I have proposed a formal scattering theory [34] that provides a microscopic basis for doing this. We have begun to apply some of these ideas to double charge exchange, and we hope that in this fashion we can bring together the shell model, which describes the kinematic correlations, with specific models of the dynamic correlations. Such a procedure is, I believe, the one that is most likely to lead to a clean separation of the two types of correlations, and it is the one to which I alluded in the last section.

So far, our instruments are able to resolve only the isobaric analog state and a few giant resonances in single charge exchange, so an empirical characterization of most of the SCX transitions that contribute to double charge exchange is unavailable. However, the development of a high-resolution neutral pion spectrometer is being considered [35], and this instrument would make possible the required measurements.

A coupled-channel formulation will naturally take us beyond the local-density approximation of Sect. 2 and thereby enable us to deal properly with the kinematic correlations in nearly all cases of interest for pion reactions to discrete final states. The nuclear structure needed for these studies is now available as a result of the extensive development of the shell model that has occured over the last several decades. In an analogous way that the unified approach to pion elastic single and double charge exchange described in Sect. 2 gave insights into the isospin dependence of the second-order pion-nucleus optical potential, we can use what is known about the structure of the excited states of nuclei to study the spin and spin-isospin components of the pion-nucleus interaction and, possibly, their density-dependence as well. This analysis would surely provide further clues about the microscopic origin of the medium modifications to the pion-nucleon interaction.

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TABLE 1(a) Energy dependence of optical potential. T_π and ΔE are given in MeV and $\lambda^{(2)}$ in fm^3. Values of $\lambda^{(2)}_1$ and $\lambda^{(2)}_2$ are shown for several models.

T_π	ΔE	$\lambda^{(2)}_0$ (Fit)	$\lambda^{(2)}_1$ (Fit)	$\lambda^{(2)}_2$ (Fit)
162	35 + 0.3i	0.8 + 3.7i	7.7 + 16i	1.7 + 11i
230	20 + 9.7i	3.1 + 0.8i	-1.0 + 6i	-1.6 + 4.2i
292	19 + 4.9i	1.7 + 2.4i	-2.8 - 0.6i	-2.7 + 0.9i

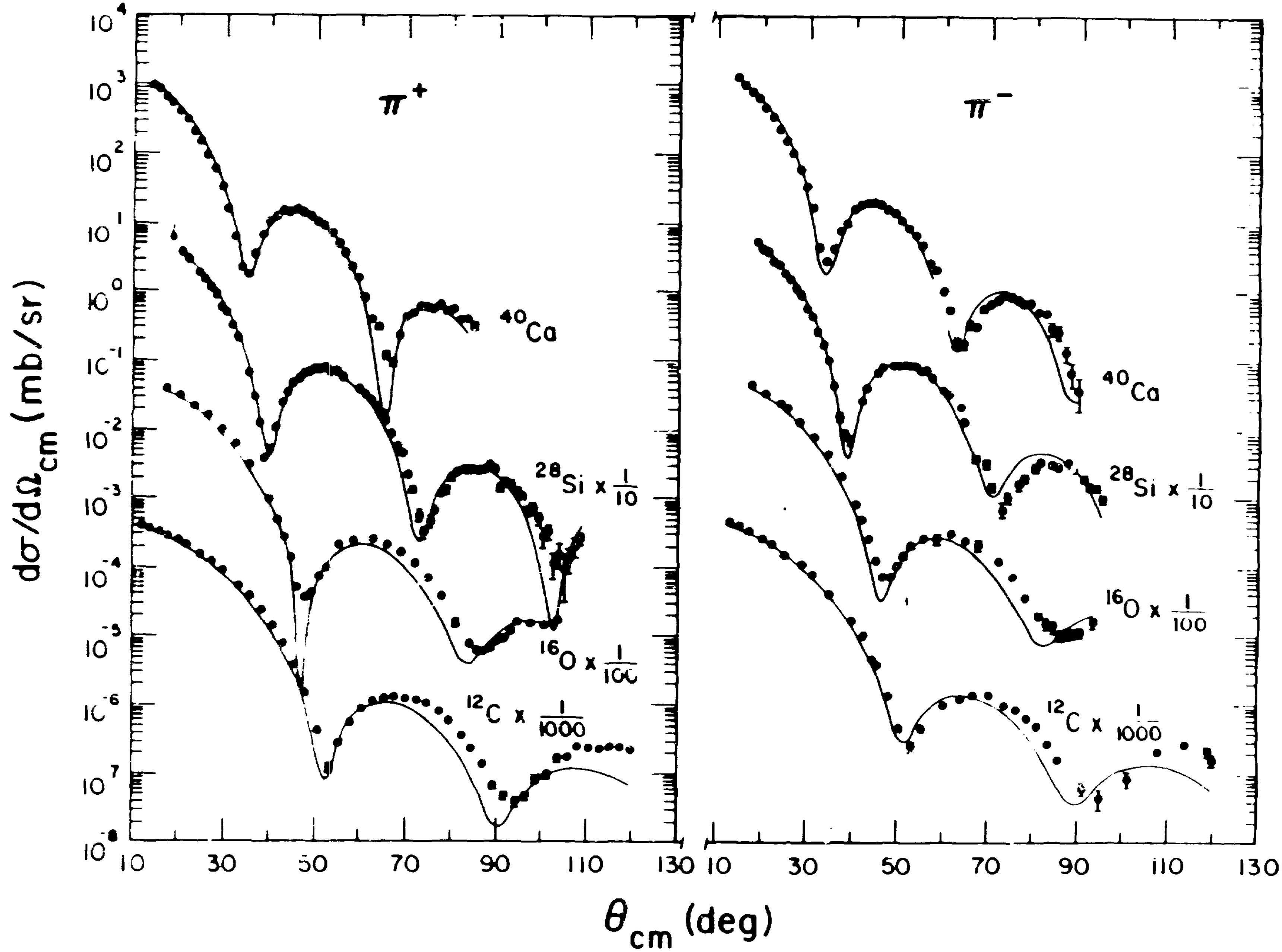
TABLE 1(b)

T_π	$\lambda^{(2)}_1$ (Pauli)[(a)]	$\lambda^{(2)}_2$ ($N\Delta$)[(b)]	$\lambda^{(2)}_2$ (Dibaryons)[(c)]
162	10.4 + 6.8i	-7 + 9.9i	2.4 + 9.8i
230	-2.0 + 4.2i	-2.9 - 2.8i	-1.2 + 3.7i
292	-1.8 + 0.6i	-0.6 - 1.4i	-0.5 + 1.5i

(a) Ref. 11; (b) Ref. 12; (c) G.A. Miller, private communication

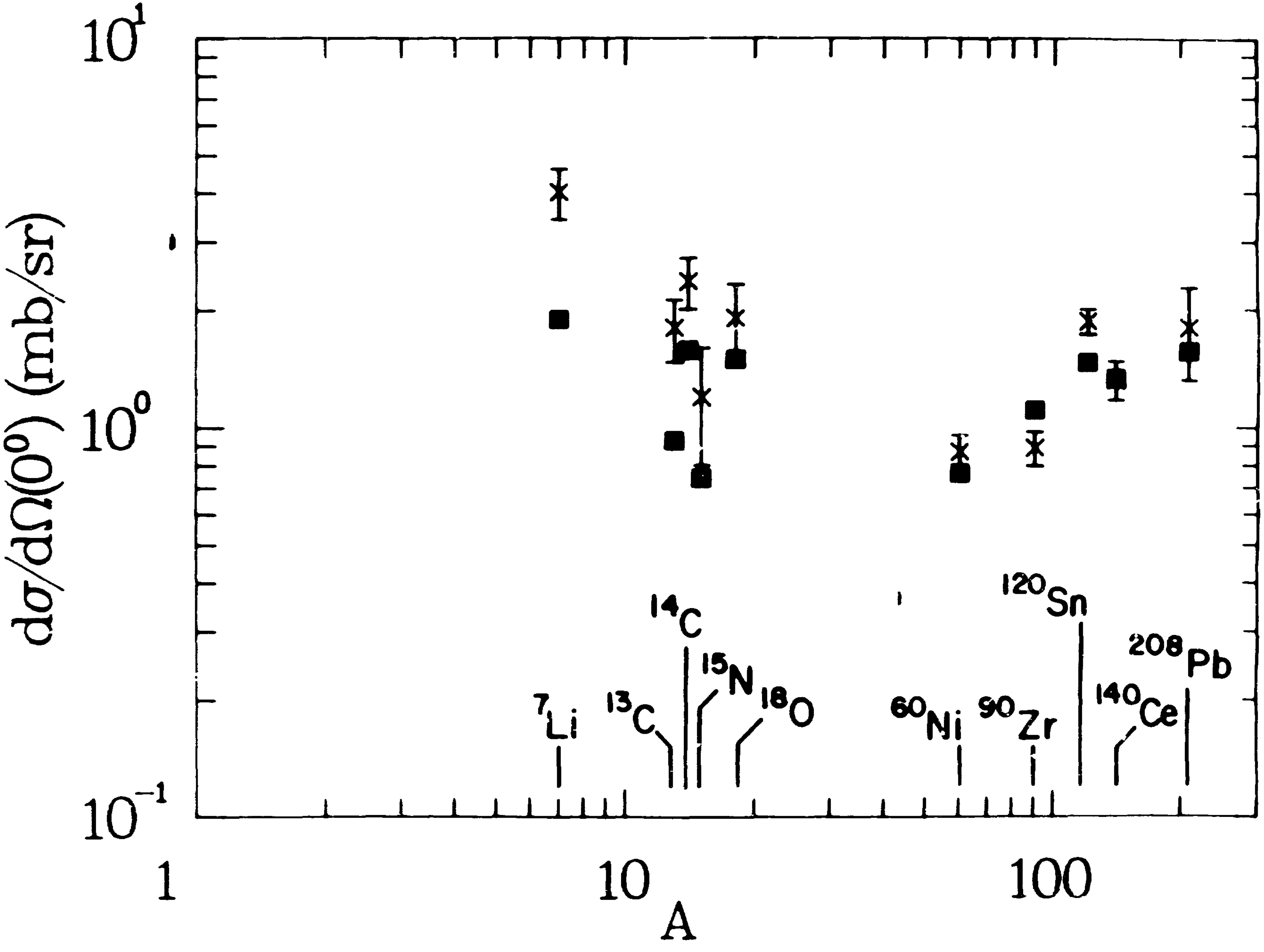
FIGURE CAPTIONS

1. Comparison of optical-model fits to experimental π^+ and π^- elastic-scattering data. The data may be found in Refs. [7] and [8].
2. Comparison of optical-model fits of single charge exchange $d\sigma/d\Omega(0^0)$ to data at T_π = 164 MeV. The x represent data and the solid square represents the theoretical result. The data are from Ref. [9].
3. Comparison of optical-model fits of double charge exchange $d\sigma/d\Omega(5^0)$ to data at T_π = 164 MeV. The x represent data and the solid square represents the theoretical result. For the experimental papers, see Ref. [10].
4. Angular Distribution for DCX to the double-isobaric-analog state. The dashed line corresponds to the simple theory, in which there are no medium modifications. The solid line is a prediction including medium modifications obtained from the optical-model analysis of elastic, SCX and DCX forward-angle cross sections shown in Figs. 1 - 3.
5. Lowest-order optical potential (a) and some of its components (b).
6. Comparison between theoretical-optical-potential calculation and experiment for ^{12}C at T_π = 162 MeV. The data are from Ref. [23]
7. Diagrams evaluated to assess the importance of surface fluctuations in closed-shell nuclei. The spiral is a phonon.
8. Influence of surface fluctuations on neutron and proton densities in ^{40}Ca. The dashed curve is the Hartree-Fock result and the solid curve includes the surface fluctuations corrections.
9. Effect of admixture of surface fluctuations on angular distribution for elastic scattering of π^- on ^{40}Ca. The data are from Ref. [27]. The legend is the same as in Fig. 8.
10. Sensitivity of the orientation symmetry $\bar{A}_S$ to ratio of β_n/β_p.
11. Calculation of pion scattering from unoriented ^{165}Ho. (a) differential cross section; (b) orientation asymmetry. The data are from Ref. [29].



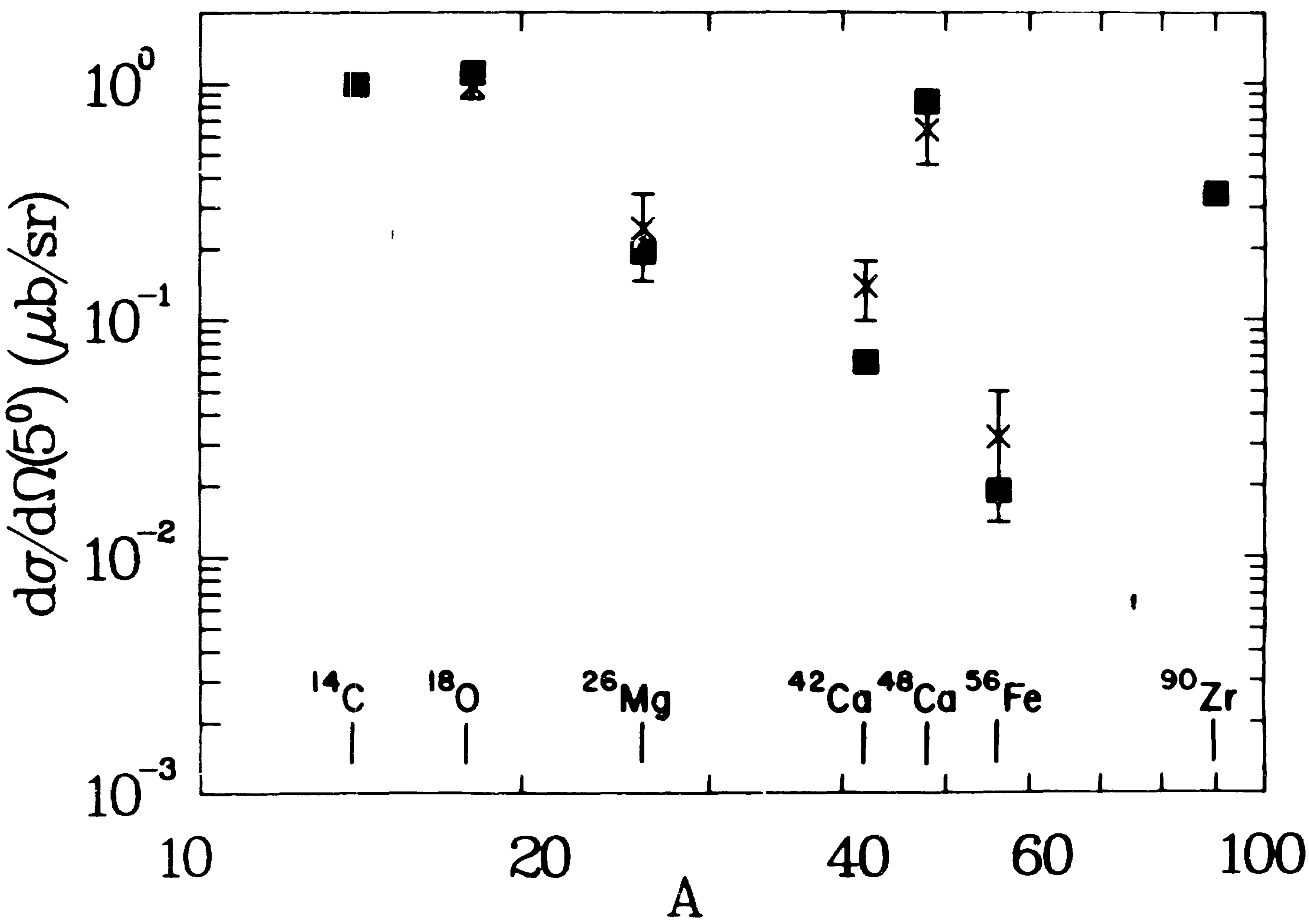
π+
π−
40Ca
28Si x 1/10
16O x 1/100
12C x 1/1000
dσ/dΩcm (mb/sr)
θcm (deg)
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10
30
50
70
90
110
130

1

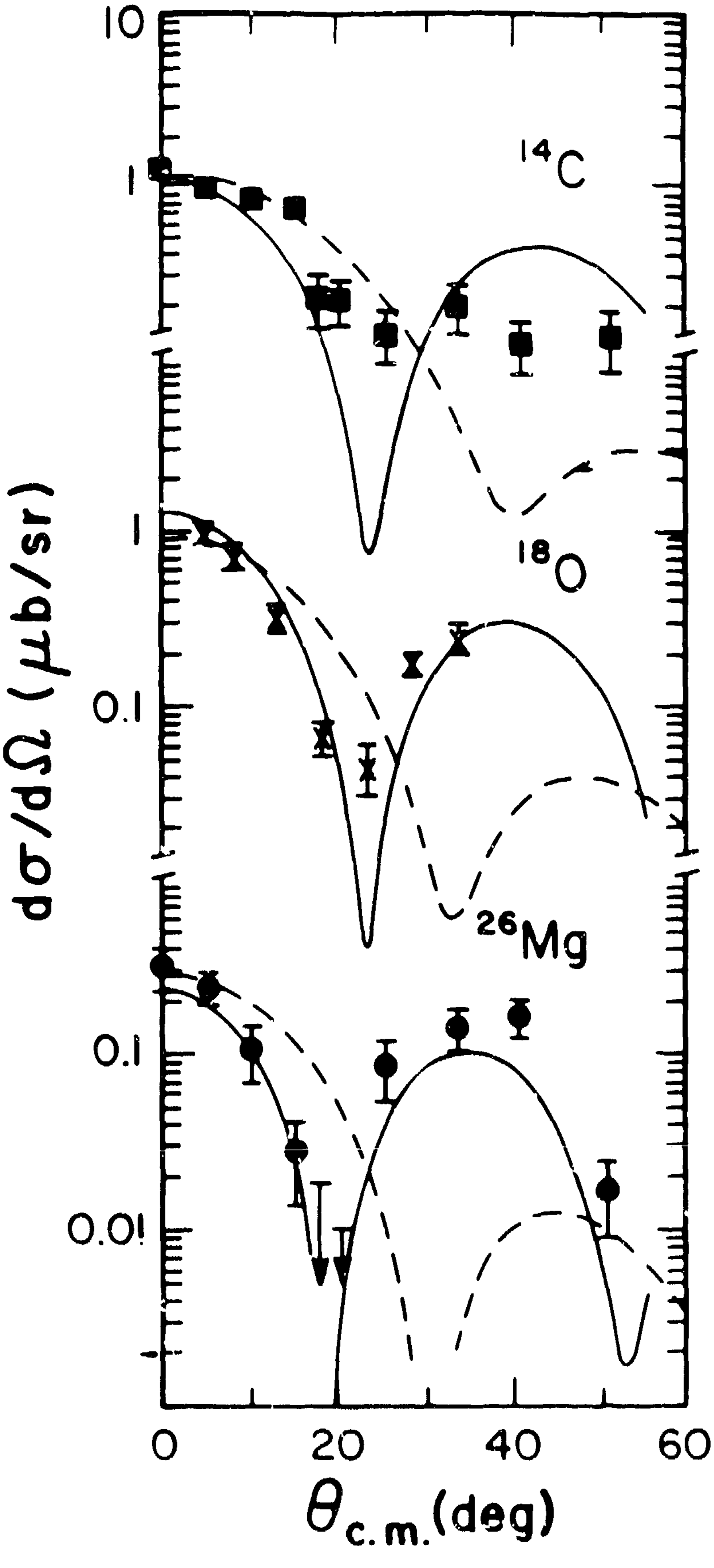


10^1
10^0
10^{-1}
$d\sigma/d\Omega(0^o)$ (mb/sr)
1
10
100
A
^{7}Li
^{13}C
^{14}C
^{15}N
^{18}O
^{60}Ni
^{90}Zr
^{120}Sn
^{140}Ce
^{208}Pb

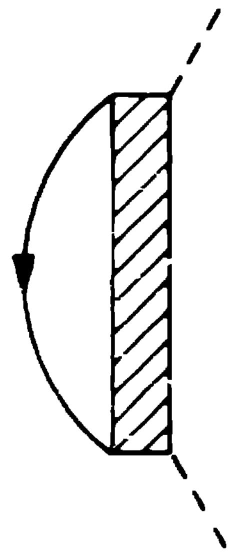
2



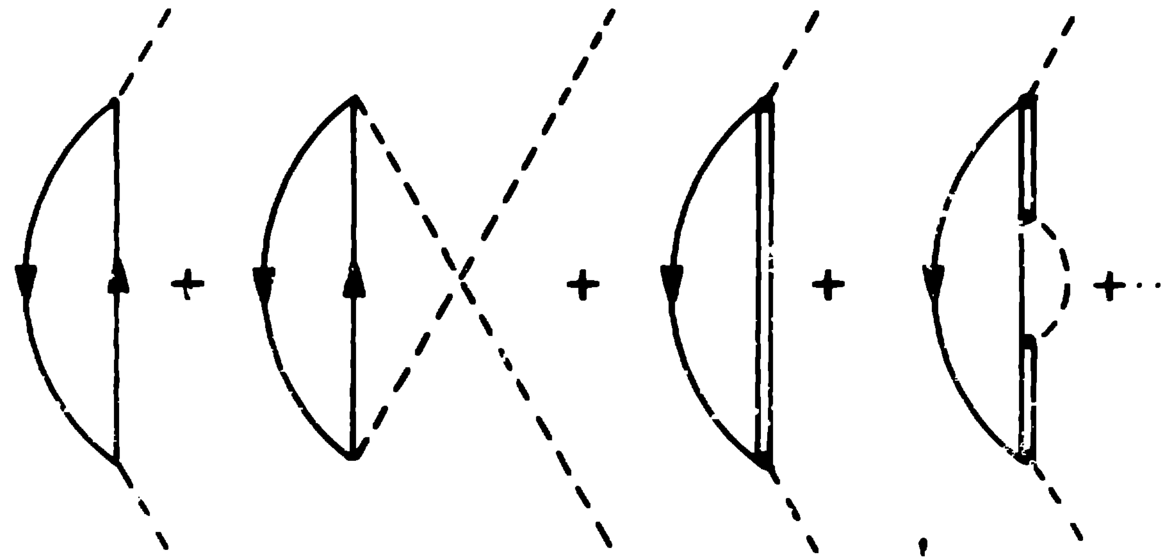
10^{0}
10^{-1}
10^{-2}
10^{-3}
$d\sigma/d\Omega(5^0)$ (μb/sr)
^{14}C
^{18}O
^{26}Mg
^{42}Ca
^{48}Ca
^{56}Fe
^{90}Zr
10
20
40
60
100
A



10
1
0.1
0.01
¹⁴C
¹⁸O
²⁶Mg
dσ/dΩ (μb/sr)
0
20
40
60
θc.m.(deg)

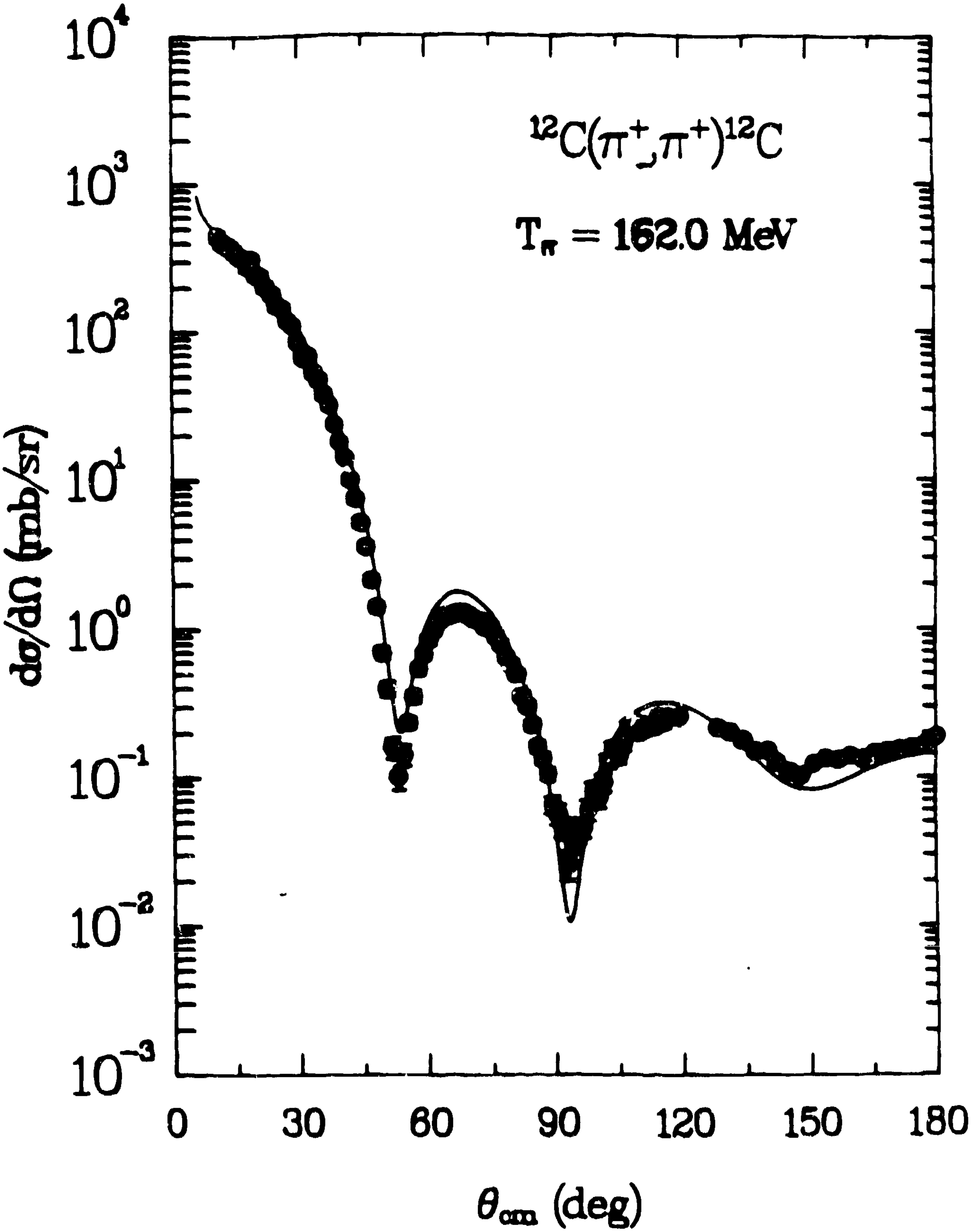


(a)

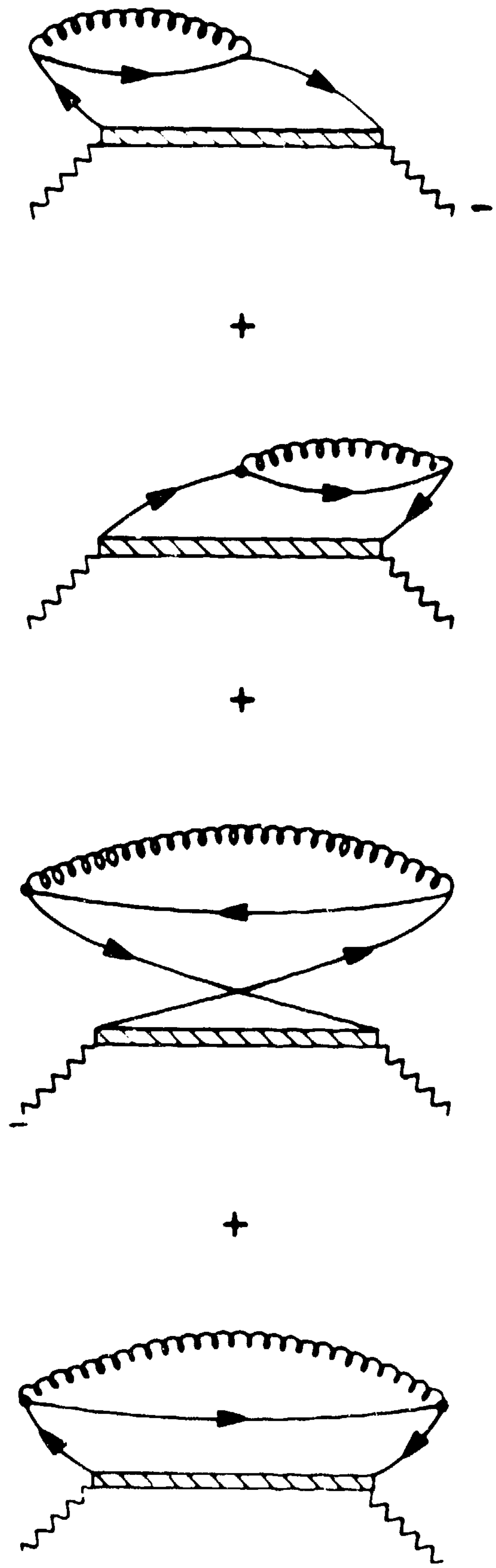


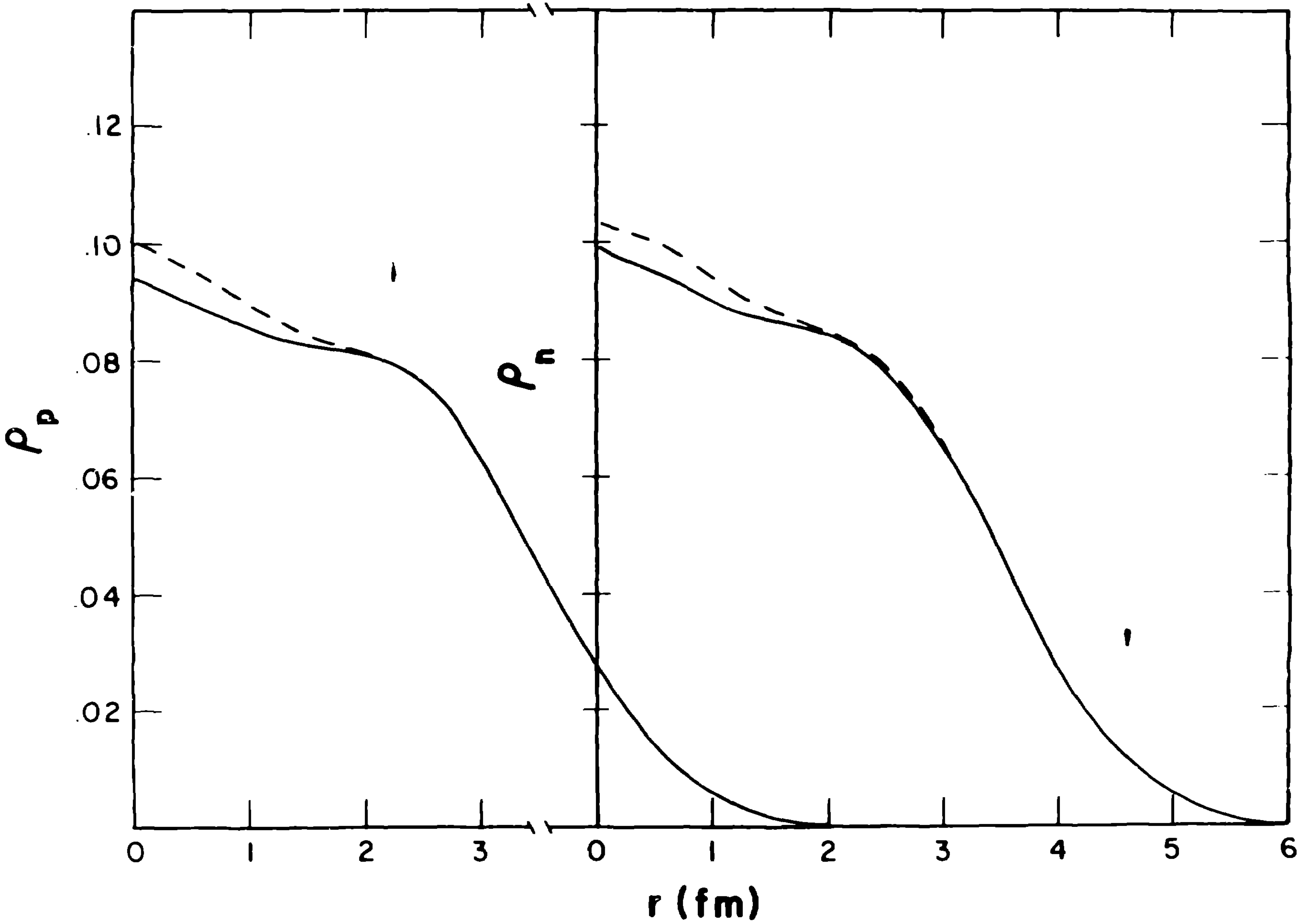
(b)

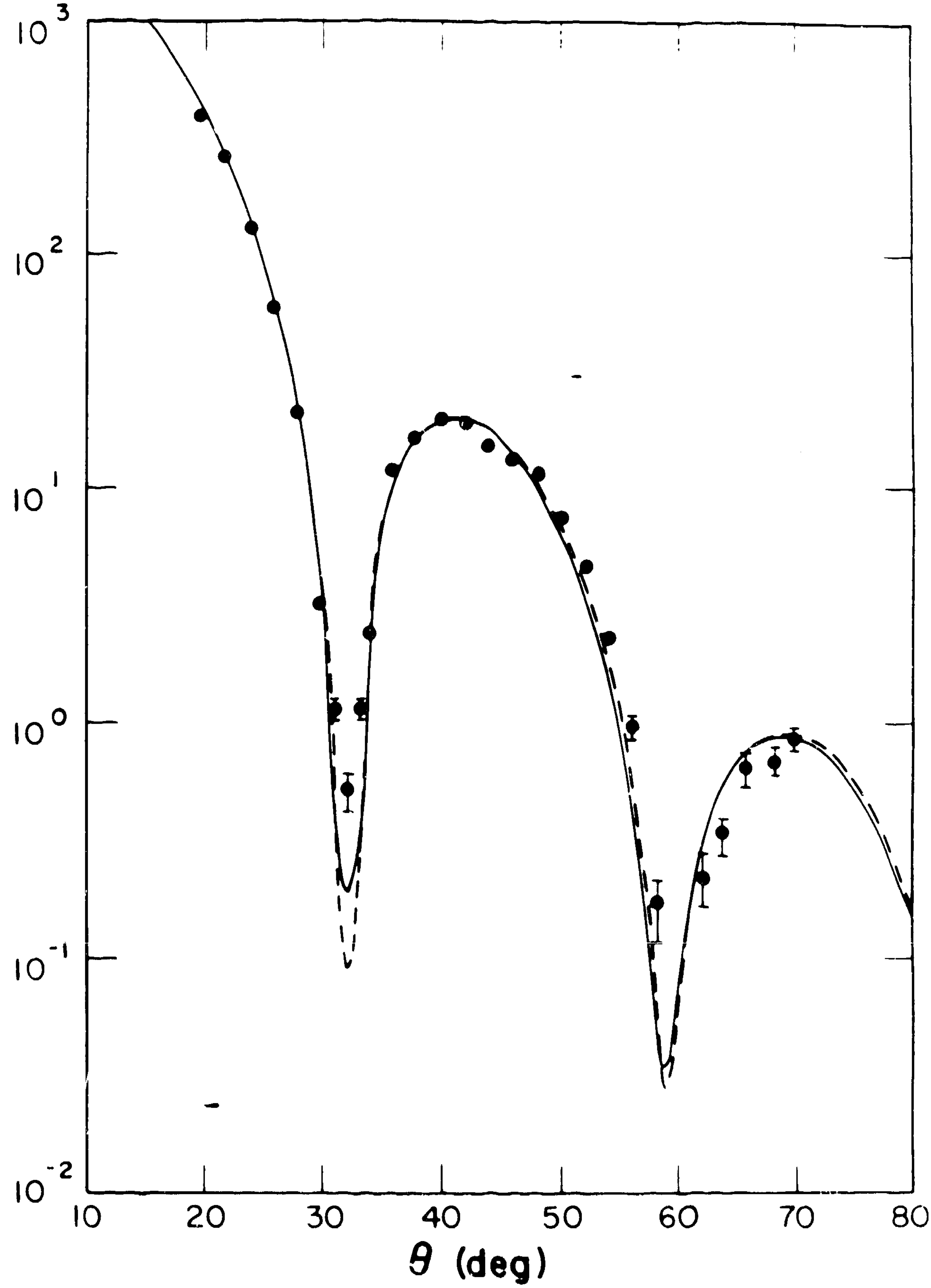
5


$^{12}C(\pi^+,\pi^+)^{12}C$
T_π = 162.0 MeV
$d\sigma/d\Omega$ (mb/sr)
θ_{cm} (deg)
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
30
60
90
120
150
180

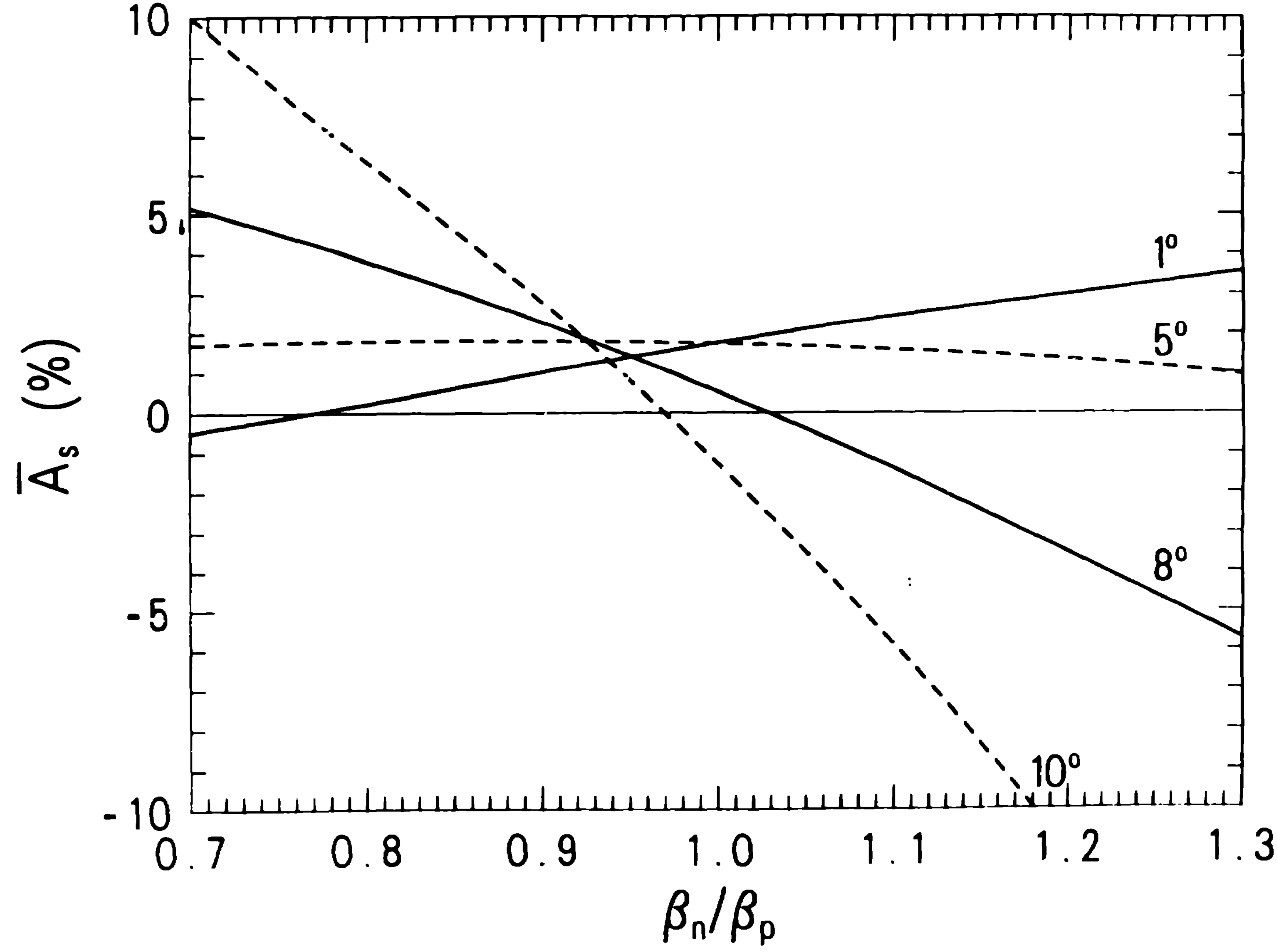
6

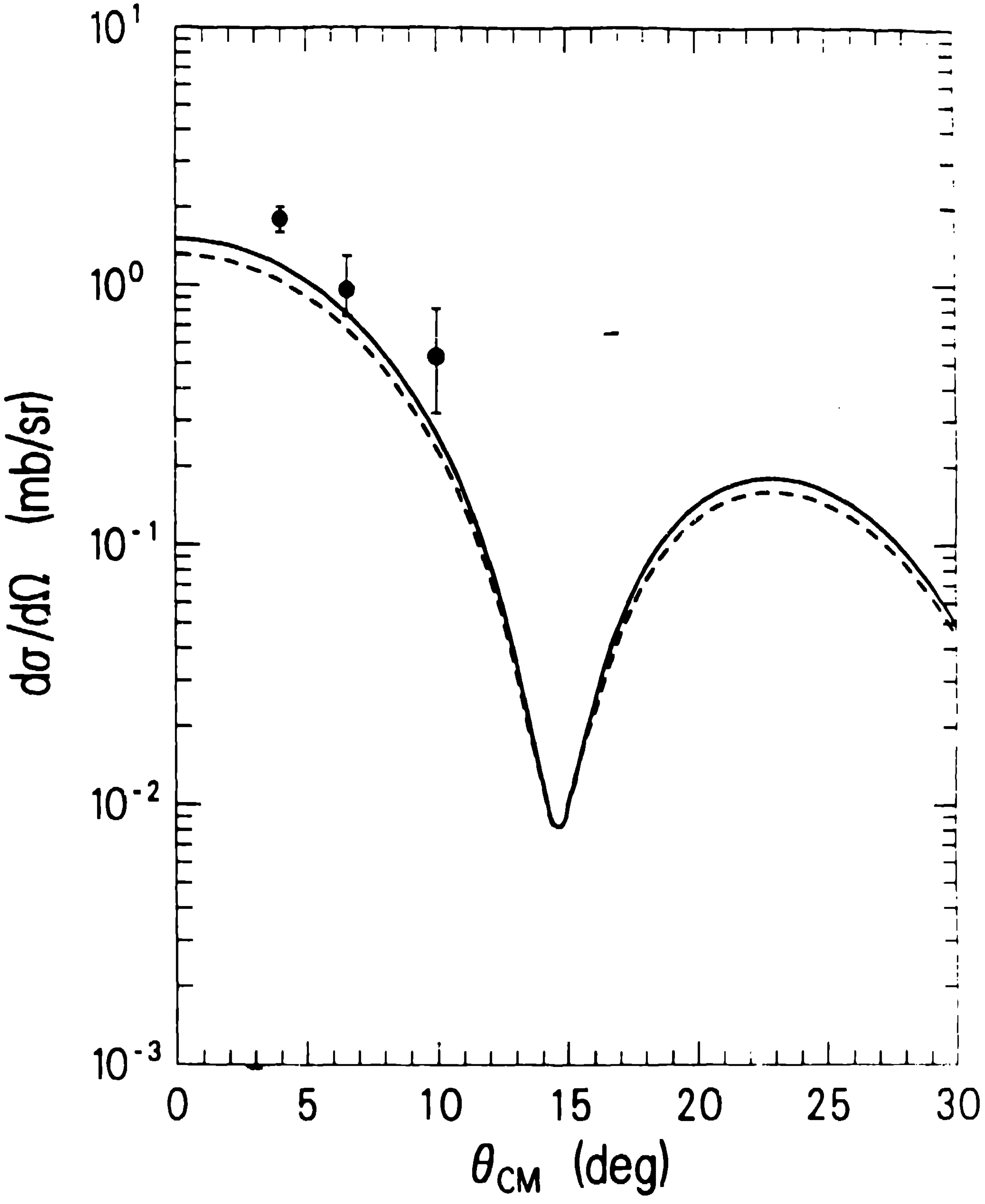



.12
.10
.08
.06
.04
.02
ρp
ρn
0
1
2
3
0
1
2
3
4
5
6
r (fm)

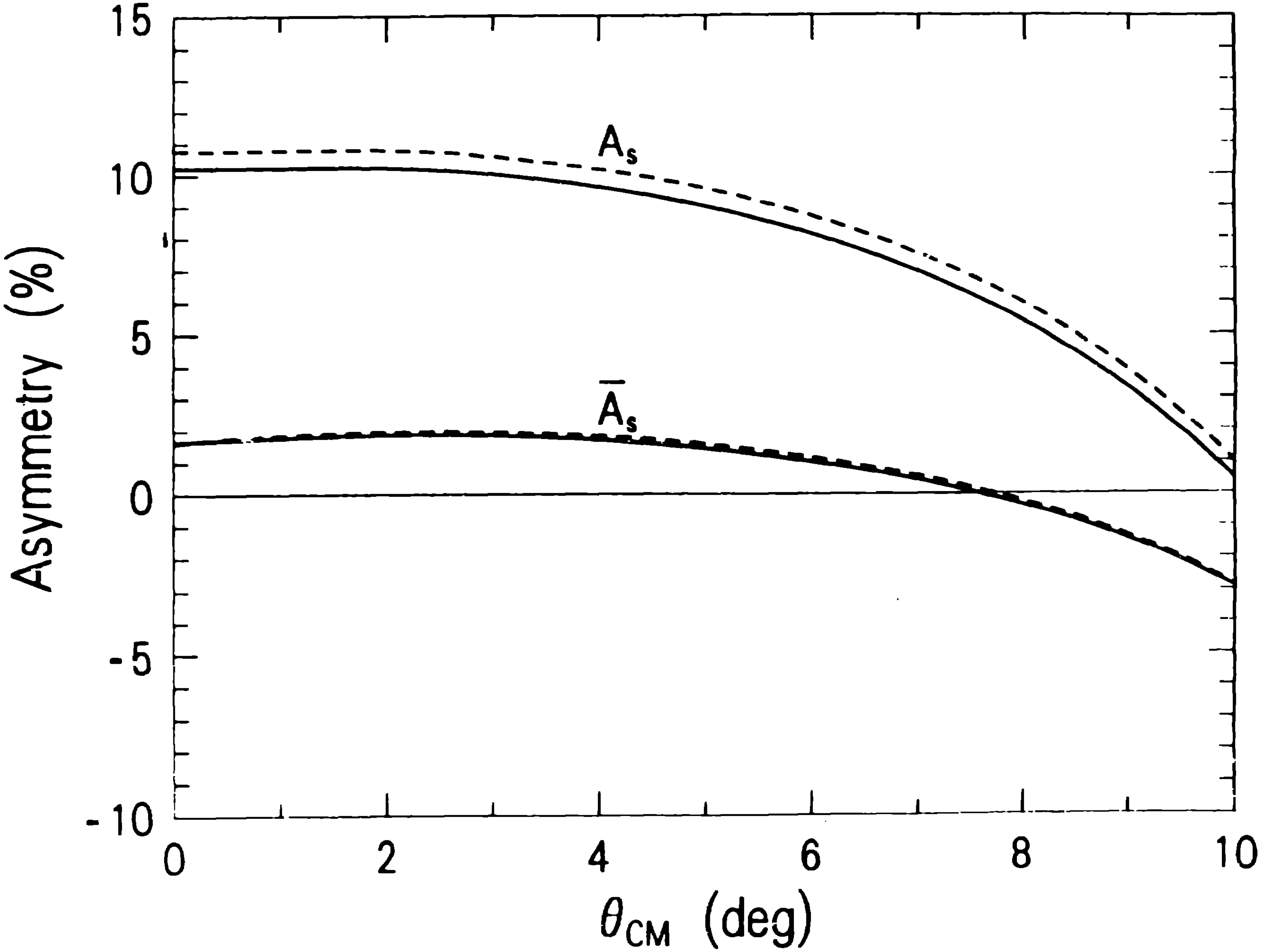


10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
$d\sigma/d\Omega\ (\theta)$
10
20
30
40
50
60
70
80
θ (deg)


10
5
0
-5
-10
$\bar{A}_s$ (%)
1°
5°
8°
10°
0.7
0.8
0.9
1.0
1.1
1.2
1.3
β_n/β_p



11a



11b