Low-energy neutron-$^{12}\text{C}$ analyzing powers: results from a multichannel algebraic scattering theory.

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Abstract

Analyzing powers in low-energy neutron scattering from $^{12}\text{C}$ are calculated in an algebraic momentum-space coupled-channel formalism (MCAS). The results are compared with recently obtained experimental data. The channel-coupling potentials have been defined previously to reproduce the total cross section and sub-threshold bound states of the compound system. Without further adjustment, good agreement with data for the analyzing powers is obtained.

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A multi-channel algebraic scattering theory (MCAS) has been formulated for scattering of nucleons from nuclei, and tested on the well-studied $^{12}$C nucleus [1]. This formulation of the coupled-channel scattering theory has the following desirable features: (i) the Pauli principle is satisfied even in the context of collective nuclear models [2]; (ii) all resonances, no matter how narrow, as well as sub-threshold bound states of the compound system are found, without the need of calculations on an excessively fine energy mesh; and (iii) nuclear structure information can be extracted from the results of the MCAS calculations, providing the Pauli principle is satisfied [3].

Our first work with this formulation focused on calculating cross sections for neutron [1] and proton [3] scattering from $^{12}$C, though some sample polarization results have also been shown [3]. Work is in progress on other light nuclear systems, in particular mass seven [4] and mass fifteen [5]. In this paper, we return to $^{12}$C to obtain analyzing powers which have been recently measured in a detailed study by Roper et al. [6]. The data range in neutron laboratory (lab.) energy from 2.2 MeV to 8.5 MeV. In our MCAS results we limit the energy range to a maximum of 4 MeV. Beyond that it may be necessary to take account of higher-energy states of the target nucleus $^{12}$C besides the three we have used so far.

The MCAS formulation yields the complete $S$-matrix for the selected scattering system. So, from all entries with the elastic channel, and by using standard formulas, we extract differential cross sections and polarizations as functions of the scattering angle and energy. For neutron scattering, the total cross section as a function of energy can also be found. The total cross section for neutron scattering from $^{12}$C was published in Refs. [1] and [3]. The calculations reported here use the same channel-coupling potentials as were used in Refs. [1] and [3]; namely, three states of the target nucleus $^{12}$C, the ground ($0^+$) and two excited states ($2^+, E = 4.389$ MeV, $0^+_2, E = 7.6542$ MeV). The coupling to the incoming neutron is via a rotational model potential, with quadrupole deformation, $\beta_2 = -0.52$. Coupling is taken to second order, and spin-orbit, orbit-orbit and spin-spin interactions as well as a central potential are included. Closed-shell Pauli blocking effects have been included using orthogonalizing pseudo-potentials, with very large couplings (1000 MeV). The potential parameters are those given in Ref. [3]; namely, we have not adjusted any parameters in our calculation to compare with the recent data.

In Figs. 1 and 2, we show the differential cross section and analyzing power as a function of neutron lab. energy ($E_n$) in the range from 2 to 4 MeV for two center-of-mass (c.m.) scattering angles, 43.36° and 147.15°. In both cases, the calculations quite satisfactorily match the data. It should be noted that no adjustment of parameters in the theory was done to achieve these results. None of the data points lie on the narrow resonances at 2.1 and $\sim$ 3.0 MeV, but there is a data point close to the first of these. In Fig. 1, we show also some older data from Bucher et al. [7], taken at 45° (square points), which do have measurements in the region of the $\sim$ 3.0 MeV resonance. But the error bars on these data are large.

The MCAS results for differential cross section, solid line in the lower panel of Figs. 1 and 2, have never been published before. These theoretical curves compare well with the experimental data from Fasoli et al. [8]. The error bars in these data are less than the size of the triangles indicating the data points. Note that the data [8] are at slightly different angles than the MCAS calculations, since those were done at the angles of the $A_y$ measurements in Ref. [6].

Next, we show a number of graphs of the analyzing power $A_y$ as a function of c.m. angle at various energies in the range 2 to 4 MeV. In these graphs, Figs. 3 and 4 more than one theoretical curve is shown. This is because the shape of the analyzing power as a function
of angle is very sensitive to energy near a resonance. Compounding this is the fact that, in
the data, there is an experimental spread in the neutron lab. energy ranging from 0.2 to 0.4
MeV, as shown in Fig. 5 of Ref. [6]. Very near a narrow resonance, the sensitivity of shape
to energy can be extreme. That is most readily seen in our Fig. 5 which we discuss later.

In Figs. 3 and 4, the thick solid line always represents the theoretical result closest to
the data points. The long-dashed and dot-dashed lines are for ±0.1 MeV different from the
energy for the solid line, except for the highest energy considered, in panel (d) in Fig. 4.
At all but two of the data sets, the theoretical curve agrees with data within the ±0.2 MeV
experimental spread in the neutron energy. For energy $E_n = 2.79$ MeV (panel (c) of Fig. 3)
and $E_n = 3.78$ MeV (panel (c) of Fig. 4), there is a fourth, short-dashed, curve at an energy
with the result closest to that of the data. In these two cases the shape of the MCAS result
at the quoted experimental neutron lab. energy is significantly different from that of the
data. However, it should be noted that, even in these two cases, the difference between the
energy of the closest theoretical representation of the data and the energy at which the data
was taken is just at the limit of the experimental uncertainty in the neutron lab. energy.
Overall, the agreement between the analyzing powers predicted by MCAS and the data of
Ref. [6] is very good.

In Fig. 5 the rapid change with energy of the shape of the analyzing power close to the
sharp $\left(\frac{5}{2}\right)^+$ resonance at 2.1 MeV is shown. The curves marked 2.1, 2.12 and 2.14 differ by
20 keV from each other, but they are very different in shape, and from the shape of the data
taken at 2.2 MeV.

Determination of the potential parameters (central, spin-spin, orbit-orbit, and spin-orbit)
was made in 2003 by fitting the overall features of the experimental spectrum (resonances
and bound states) [1]. The very good agreement between theoretical and experimental
total cross section (in $n^{+12}$C scattering) demonstrates that the model correctly describes
the process. The present analysis on new analyzing power data, Ref. [6], gives even more
confidence in the reliability of the model, since spin observables are more sensitive quantities
to test the interaction mechanism. We believe, therefore, that our model can represent a
good starting point for a phase shift analysis. Important to this is the inclusion of spin-spin
and orbit-orbit terms, as well as a spin-orbit term in the interaction potential. Similarly
important is the expansion to second order in the deformation parameter. Most critically
needed is the inclusion of the Pauli principle. With the MCAS approach, that is done by
the use of orthogonalizing pseudo-potentials, as detailed in Ref. [2]. We conclude that the
MCAS theory has predictive power as we reproduce data which were not available when the
theory was first used to fit the total cross section in Ref. [1].

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FIG. 1: (Color online) The results from MCAS for differential cross section and analyzing power ($A_y$) at $\theta_{cm} = 43.36^\circ$ for the $n + ^{12}$C system. Data (circles) are from Ref. [6]. The last data point is at $41.86^\circ$. The squares with large error bars represent the $45^\circ$ data from Ref. [7]. The data for the differential cross section (triangles, lower panel) at $43.03^\circ$ are from Ref. [8].
FIG. 2: (Color online) The results from MCAS for differential cross section and analyzing power ($A_y$) at $\theta_{cm} = 147.15^\circ$ for the $n + ^{12}C$ system. Data (circles) are from Ref. [6]. The last data point is at 146.51°. The data for the differential cross section (triangles, lower panel) at 143.03° are from Ref. [8].
FIG. 3: (Color online) The $n + ^{12}C$ analyzing power results from using MCAS theory compared to experimental data from Ref. [6]. Panel (a) represents a prediction of our calculation at 1.9 MeV (solid line). Dashed line is for 1.8 MeV and dashed-dotted line for 2.0 MeV. Panel (b): data taken at 2.20 MeV. The solid line is the MCAS result for $E_n = 2.3$ MeV, the dashed/dot-dashed lines are for 0.1 MeV below/above that value. Panel (c): data taken at 2.79 MeV. The solid line is the MCAS result for $E_n = 2.6$ MeV, the dashed/dot-dashed lines are for 0.1 MeV below/above that value. The dotted line is for 2.8 MeV. Panel (d): data taken at 3.21 MeV. The solid line is the MCAS result for $E_n = 3.1$ MeV, the dashed/dot-dashed lines are for 0.1 MeV below/above that value.
FIG. 4: (Color online) The $n + ^{12}$C analyzing power results from using MCAS theory compared to experimental data from Ref. [6]. Panel (a): data taken at 3.41 MeV. The solid line is the MCAS result for $E_n = 3.4$ MeV, the dashed/dot-dashed lines are for 0.1 MeV below/above that value. Panel (b): data taken at 3.62 MeV. The solid line is the MCAS result for $E_n = 3.6$ MeV, the dashed/dot-dashed lines are for 0.1 MeV below/above that value. Panel (c): data taken at 3.78 MeV. The solid line is the MCAS result for $E_n = 3.6$ MeV, the dashed/dot-dashed lines are for 0.1 MeV below/above that value. The dotted line is for 3.8 MeV. Panel (d): data taken at 3.92 MeV. Calculations at 3.6 MeV (solid line), at 3.8 MeV (dashed line), and 4.0 MeV (dashed/dot line).
FIG. 5: (Color online) The $n + ^{12}\text{C}$ analyzing power results from using MCAS theory, evaluated at energies between 2.1 and 2.3 MeV compared to experimental data at 2.20 MeV from Ref. [6]. The solid line closest to the data is for $E = 2.3$ MeV; the dot-dashed line is for $E = 2.2$ MeV. The other three lines have their energies, in MeV, marked next to the line.