Total reaction cross sections for neutron-nucleus scattering

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(Dated: November 1, 2018)

Abstract

Neutron total reaction cross sections at 45, 50, 55, 60, 65, and 75 MeV from nuclei $^{12}$C, $^{28}$Si, $^{56}$Fe, $^{90}$Zr, and $^{208}$Pb have been measured and are compared with (microscopic) optical model predictions. The optical potentials were obtained in coordinate space by full folding effective nucleon-nucleon interactions with realistic nuclear ground state density matrices. Good to excellent agreement is found.

PACS numbers: 25.40.-h,24.10.Ht,21.60.Cs,24.10.Eq

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The usual vehicle for specifying \( NA \) total reaction cross sections, required as inputs in diverse applications ranging from transmutation of waste to nuclear astrophysics, has been the \( NA \) optical potential; a potential most commonly taken as a local parametrized function, usually of Woods-Saxon type. However, it has long been known that the optical potential must be nonlocal and markedly so, although it has been assumed also that the energy dependence of the customary (phenomenological) model accounts for that. Of more concern is that the phenomenological approach is not truly predictive. The parameter values chosen, while they may be set from a global survey of data analyses, are subject to uncertainties and ambiguities, stemming in part from the lack of any density dependences of the specific scattering systems. While differential cross sections may be described by such local potentials, different parameter sets, describing the same elastic scattering data, may lead to different predictions for the total reaction cross section.

In this letter we compare predictions with new experimental data on total reaction cross sections for neutron scattering at a number of intermediate energies and from five nuclei ranging in mass from \(^{12}\)C to \(^{208}\)Pb [1]; the results were compared with the LA-150 data [2]. Unlike those analyses using phenomenological local form interactions, the predictions we report were found using, without approximation, complex, nonlocal, coordinate-space optical potentials formed by full folding realistic, effective, nucleon-nucleon (\( NN \)) interactions with density matrices (hereafter simply termed densities) specified from credible models of the structure of the targets. All details of this approach have been given in a recent review [3].

With this coordinate space approach, all analyses have been made using the DWBA98 programs [4] which allow the projectile-target nucleon interactions not only to be complex but also energy and density dependent, the latter specific to the target in question. The properties of (nonlocal) optical potentials arise from mapping effective interactions to \( NN \) matrices that are solutions of the Bruckner-Bethe-Goldstone (BBG) equations for nuclear matter. We use the Bonn-B \( NN \) potentials as input to solving those BBG equations. As the BBG equations include allowance for Pauli blocking and of medium influence in the propagators, the ensuing effective \( NN \) interactions that will be folded with the nuclear structure are nuclear density dependent. Such density dependence has been shown to be critical in making good predictions of angular and integral observables, including all spin observables, for intermediate energy nucleon scattering from all nuclei [3, 5].

Formally, the nonlocal optical potentials can be written

\[
U(r_1, r_2; E) = \sum_n \zeta_n \left\{ \delta(r_1 - r_2) \int \varphi_n^*(s) v_D(r_{1s}) \varphi_n(s) \, ds + \varphi_n^*(r_1) v_{Ex}(r_{12}) \varphi_n(r_2) \right\}
\]

\[
\Rightarrow U_D(r_1; E)\delta(r_1 - r_2) + U_{Ex}(r_1, r_2; E),
\]

(1)

where \( v_D \) , \( v_{Ex} \) are combinations of the components of the effective \( NN \) interactions, \( \zeta_n \) are ground state one body density matrices (which often reduce to bound state shell occupancies), and \( \varphi_n(r) \) are single nucleon bound states. All details and the prescription of solution of the associated nonlocal Schrödinger equations are given in the recent review [3].

The specification of the nuclear ground state density is taken from a given nucleon-based model of structure. For \(^{12}\)C we have used a complete \((0+2)\hbar\omega \) shell model [3] using the WBT interaction of Warburton and Brown [6]. For \(^{28}\)Si, we have used a complete \(0\hbar\omega \) shell model wave function as formed by Brown and Warburton [7]. With \(^{56}\)Fe a packed shell model was chosen with allowance of 2\( p \) - 2\( h \) excitations into the \( f - p \) shell. Potentials used in the structure calculation were those of Richter et al. [8]. The NIS model of Ji and Wildenthal [3] was used to describe \(^{90}\)Zr. With that the protons are in the packed shells
TABLE I: Neutron total reaction cross sections in barn.

| Energy (MeV) | $^{12}$C | $^{28}$Si | $^{56}$Fe | $^{90}$Zr | $^{208}$Pb | type |
|--------------|---------|---------|---------|---------|---------|------|
| 45           | 0.435 (39) | 0.738 (72) | 1.156 (71) | 1.407 (122) | 2.425 (181) | expt. |
|              | 0.408    | 0.786   | 1.122   | 1.487   | 2.443   | SHF  |
|              |          |         |         |         |         | 2439 | SKX |
| 50           | 0.388 (55) | 0.675 (72) | 1.131 (67) | 1.449 (117) | 2.287 (179) | expt. |
|              | 0.378    | 0.742   | 1.075   | 1.432   | 2.376   | SHF  |
|              |          |         |         |         |         | 2370 | SKX |
| 55           | 0.312 (40) | 0.493 (80) | 0.946 (76) | 1.313 (134) | 2.027 (205) | expt. |
|              | 0.362    | 0.713   | 1.033   | 1.382   | 2.315   | SHF  |
|              |          |         |         |         |         | 2306 | SKX |
| 60           | 0.257 (40) | 0.542 (80) | 0.921 (75) | 1.222 (132) | 2.032 (204) | expt. |
|              | 0.346    | 0.684   | 0.996   | 1.338   | 2.277   | SHF  |
|              |          |         |         |         |         | 2247 | SKX |
| 65           | 0.325 (46) | 0.451 (89) | 0.896 (91) | 1.133 (159) | 2.112 (245) | expt. |
|              | 0.338    | 0.658   | 0.964   | 1.299   | 2.226   | SHF  |
|              |          |         |         |         |         | 2195 | SKX |
| 75           | 0.244 (27) | 0.412 (52) | 0.820 (47) | 1.091 (84) | 1.922 (131) | expt. |
|              | 0.319    | 0.617   | 0.913   | 1.236   | 2.075   | SHF  |
|              |          |         |         |         |         | 2108 | SKX |

while neutrons were allowed to spread in the $f_{\frac{5}{2}}, p_{\frac{3}{2}}, p_{\frac{1}{2}},$ and $g_{\frac{9}{2}}$ orbits. With $^{208}$Pb we have used two recent Skyrme-Hartree-Fock wave functions [10, 11] for which the neutron skin is 0.17 fm.

With $E \propto k^2$, the total reaction cross sections are

$$\sigma_R(E) = \frac{\pi}{k^2} \sum_{l=0}^{\infty} \left\{(l + 1) \left[1 - \left(\eta^+\right)^2\right] + l \left[1 - \left(\eta^-\right)^2\right]\right\},$$

(2)

where $\eta^\pm$ are the moduli of $S$ matrices that are determined from solutions of the radial Schrödinger equations with the specified optical potentials. They are

$$\eta^\pm \equiv \eta^\pm(k) = \left|S^\pm_l(k)\right| = e^{-2\delta^\pm_l(k)},$$

(3)

where $\delta^\pm_l(k)$ are the scattering phase shifts.

The results are given in Table I and also in Fig. I. The units are in barn. From the table it is clear that our predictions compare well with most of the data with the exception of the 55 MeV values and of those from $^{28}$Si in particular. Also there is a tendency for our predictions to be higher than the data for all five nuclei at 75 MeV. Those effects are revealed also in the figure. However, inspection of the plotted results stresses that the statistical error bars encompass most of our predicted values. While in general the energy trends are well reproduced, we note that there appears to be a discrepancy in the case of $^{28}$Si, where our results tend to overpredict the data.

We have used a microscopic, nonlocal, optical model to predict total reaction cross sections for the scattering of intermediate energy neutrons from various nuclei. The agreement
between the set of results found for neutron reaction cross sections and the new data is now comparable with that obtained for proton scattering [5]. We note that in that earlier work the available neutron reaction cross sections were consistently overpredicted by ~10%. The data used in that paper were far older and relied on the subtraction of the large elastic scattering cross sections from the total cross sections. The level of agreement found with the present data are much better and give confidence in the predicted results. Thus the nonlocal optical potentials generated by full folding $NN_g$ matrices with microscopic (nucleon) structures for targets can be used to predict both neutron and proton reaction cross sections.
Acknowledgments

This work was supported by a grant from the Australian Research Council and also by DOE Contract no. W-7405-ENG-36.

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