Toward a Global Dispersive Optical Model for the Driplines

C. Barbieri[a], R. J. Charity[b], W. H. Dickhoff[c] and L. G. Sobotka[b c]

[a]Theoretical Nuclear Physics Laboratory,
RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

[b]Department of Chemistry, Washington University, St. Louis, Missouri 63130, USA

[c]Department of Physics, Washington University, St. Louis, Missouri 63130, USA

A dispersive-optical-model analysis has been performed for both protons and neutrons on ^{40,42,44,48}Ca isotopes. The fitted potentials describe accurately both scattering and bound quantities and extrapolate well to other stable nuclei. Further experimental information will be gathered to constrain extrapolations toward the driplines.

1. Introduction

Experiments with radioactive beams are unraveling the properties of nuclei at the limits of stability [1]. Studies of low-energy processes and transfer reactions require optical potentials (OP) suitable for dripline isotopes. This is also important for astrophysics applications, where capture and decay processes require a consistent determination of both scattering and bound states. Dispersive optical models (DOM) provide a useful tool that allows one to describe the mean field consistently over a broad energy range.

The DOM is grounded in the theory of many-body Green's functions (or propagators) [2] and in the proven equivalence between the many-body self-energy (of propagator theory) and the Feshbach theory of the microscopic optical model [3]. In practice the DOM can be thought as a parametrization of the self-energy. This has several advantages. It allows us to develop an OP that describes consistently both elastic scattering and bound-state properties. The theory directly imposes important analytic constraints, such as the dispersion relation between the real and imaginary components (see below). Also microscopic calculations [4] can be employed to determine the physical ingredients of the potentials.

The DOM was developed by Mahaux and collaborators for a number of individual magic or near magic nuclei [5]. Recently, the authors of Refs. [6, 7] have performed a DOM study for the chain of Ca isotopes. This employed the world data on $^{40-48}$Ca, including *both* elastic scattering (up to 200 MeV) and bound-state information from $(e,e'p)$ experiments. This analysis also discussed possible extrapolations toward the driplines and suggested new experiments to constrain the predictions for exotic nuclei [8]. A global parametrization of the coupled-channel DOM was also reported in Ref. [9] for stable nuclei.
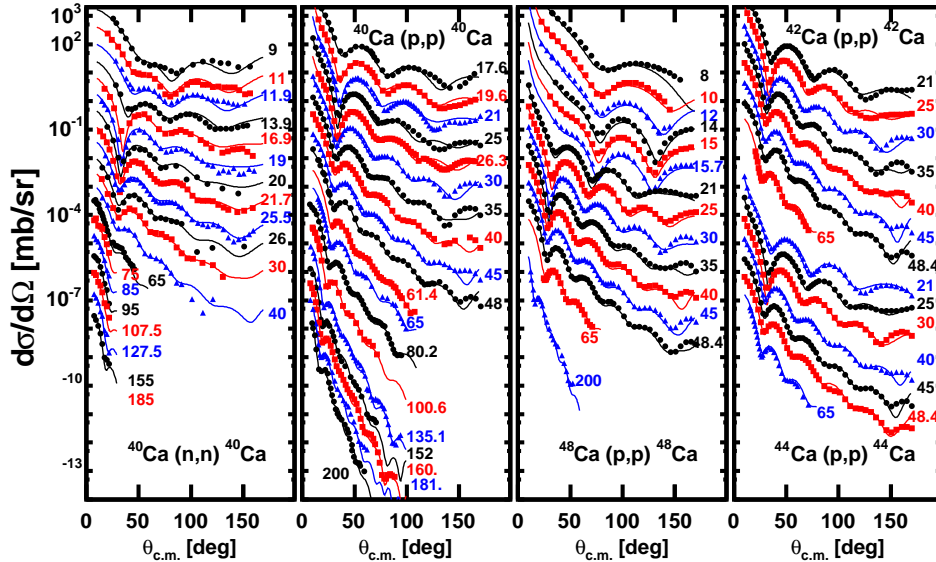
Figure 1. (Color online) Comparison of experimental (data) and fitted (curves) differential elastic scattering cross sections. Successively larger energies are scaled down by a factor of 4. For p+^{42}Ca, the data and curves are scaled down by an additional factor of 100.

The present talk discusses briefly the analysis of Refs. [6, 7] and points to open issues that are being addressed to refine the predictions for unstable isotopes.

2. The DOM for Ca Isotopes

While the nucleon self-energy is an *energy dependent* and *non-local* potential, the vast majority of DOM applications employ a local approximation of it. The same approach is followed here, although this approximation may be removed in future works. Mahaux and Sartor [5] start by separating the real part of the optical potential at the Fermi surface ($\mathcal{V}_{HF}$) and write the DOM as

$$\mathcal{U}(r, E) = \mathcal{V}_{HF}(r, E) + \Delta\mathcal{V}(r, E) + i\mathcal{W}(r, E) \ , \tag{1}$$

where $\mathcal{V}_{HF}(r, E)$ is the local equivalent of the self-energy, $\mathrm{Re}\Sigma(r, r'; E_F)$, at the Fermi energy (E_F)[1]. Normally, this would be a static potential but it acquires an energy-dependence to account for the non-locality of $\Sigma(r, r'; E_F)$. The real and imaginary parts of the dynamic components of the DOM are linked by the subtracted *dispersion relation*,

$$\Delta\mathcal{V}(r, E) = \frac{1}{\pi}P\int \mathcal{W}(r, \omega)\left(\frac{1}{\omega - E} - \frac{1}{\omega - E_F}\right)d\omega \ . \tag{2}$$

---

[1]Strictly speaking, $\mathcal{V}_{HF}$ is not an Hartree-Fock potential but it does describe the effects of the nuclear mean-field. We maintain this notation for consistency with the rest of the literature.
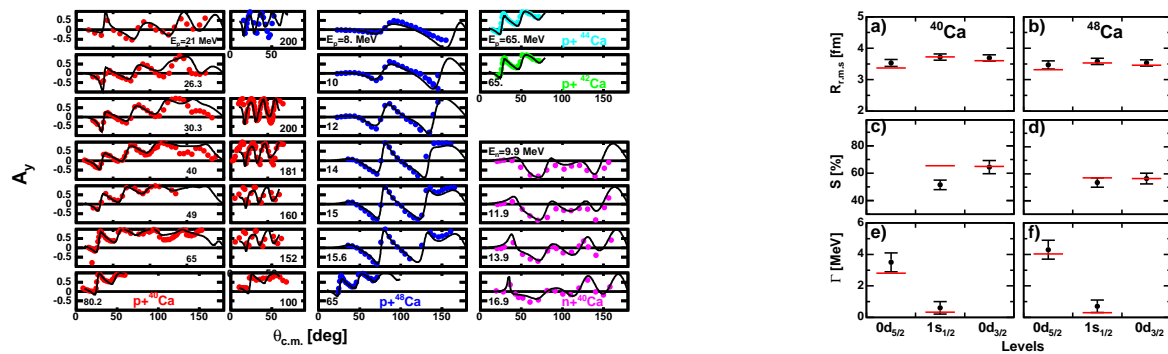
Figure 2. (Color online) *Left.* Comparison of experimental and fitted analyzing powers. *Right.* Fitted (horizontal lines) and experimental (data points) level properties for the $0d_{5/2}$, $1s_{1/2}$, and $0d_{3/2}$ proton hole states for ^{40}Ca (left panels) and ^{48}Ca (right panels). The fitted quantities include the root-mean-squared radius R_{rms}, the spectroscopic factors S and the widths Γ of these states.

This relation is a direct consequence of the causality principle, which is therefore embedded in the model. Thus, the DOM is fully determined by parametrizing only the $\mathcal{V}_{HF}(r, E)$ and $\mathcal{W}(r, E)$ components. The explicit form employed in this work is reported in detail in Ref. [7].

The potential (1) was fitted to published data sets at both positive and negative energies. These included elastic scattering data for $p+^{40,42,44,48}$Ca and $n+^{40}$Ca, with energies up to 200 MeV, total reaction cross sections, experimental single-particle levels and spectroscopic factors and radii of proton bound states measured in $(e,e'p)$ reactions. The quality of the fit to the differential cross sections and analysing powers is shown in Figs. 1 and 2 (left). For proton bound states, only one data point could not be reproduced, i.e., the $s_{1/2}$ orbit in ^{40}Ca as shown in Fig. 1 (right). An independent re-analysis of $(e,e'p)$ data has later corrected this value and resolved this discrepancy [10].

For such a large body of data (81 data sets comprising 3569 data points), the excellent agreement of the fit with just 25 free parameters provides confidence in the predictive power of the DOM calculations.

3. Extrapolation to Other Isotopes

Figure 3 shows a *preliminary* comparison between the elastic proton scattering on stable Ni sotopes and the prediction of the above DOM, which was fitted to Ca data only. The overall agreement is quite satisfying and shows the potentiality for global fits with this approach. However, proper extrapolations to unstable isotopes (and in particular close to the driplines) require particular care for the N/Z asymmetry dependence of the surface part of the imaginary potential. This is usually assumed to behave as

$$W_s(E) = W_s^0(E) + \varepsilon \frac{N - Z}{A} W_s^1(E) . \tag{3}$$
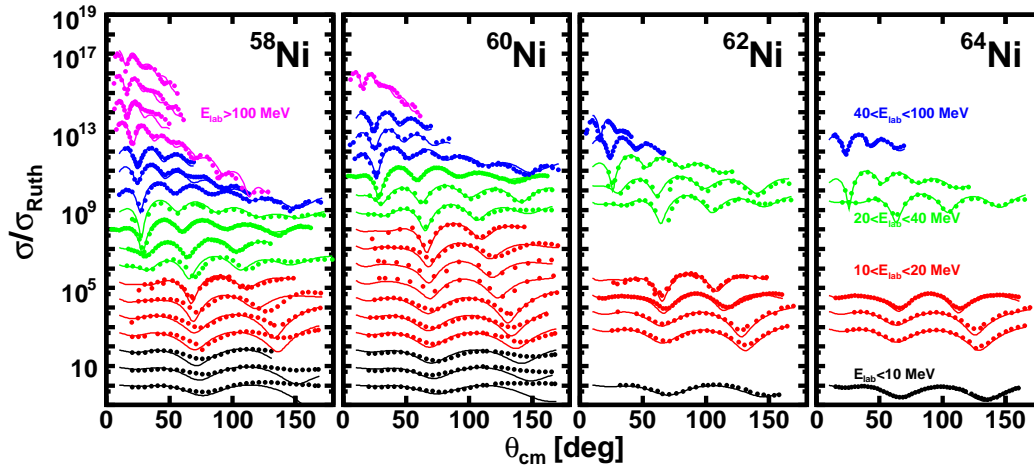
Figure 3. (Color online) *Preliminary* comparison between the proton scattering data on Ni isotopes and the prediction from the DOM of Ref. [7] (fitted solely to Ca isotopes). The plot shows the ratio with respect to the Rutherford differential cross sections.

The choice for protons is ε_p=+1, which works quite well for $p+^{40-48}$Ca scattering. For neutrons, the standard assumption in the literature (ε_n=-1) leads to inconsistencies for neutron-rich isotopes. Similar difficulties have also been reported in a recent global OP fit [11].

Unfortunately, the n+^{40}Ca scattering data solely available to Ref. [7] are not sufficient to constrain ε_n. Choosing ε_n=0 was found to be consistent with spectroscopic factors from (d,p) reactions but does not rule out other possibilities. New data for the n+^{48}Ca have recently been taken to verify this assumption [8]. It is expected that this will allow new fits that improve the description of dripline isotopes.

REFERENCES

1. A. Gade and T. Glasmacher, Prog. Part. Nucl. Phys. **60**, 161 (2008).
2. W. H. Dickhoff and D. Van Neck, *Many-Body Theory Exposed!* (2nd edition, World Scientific, Singapore, 2008).
3. F. Capuzzi and C. Mahaux, Ann. Phys. **245**, 147 (1996).
4. C. Barbieri and and B. K. Jennings, Phys. Rev. C **72**, 014613 (2005).
5. C. Mahaux and R. Sartor, Adv. Nucl. Phys. **20**, 1 (1991).
6. R. J. Charity, L. G. Sobotka, W. H. Dickhoff, Phys. Rev. Lett. **97**, 162503 (2006).
7. R. J. Charity, J. M. Mueller, L. G. Sobotka, W. H. Dickhoff, Phys. Rev. C **76**, 044314 (2007).

8. R. J. Charity, L. G. Sobotka *et al.*, in preparation.
9. L. Hao, W. Sun, E. Sh. Soukhovitskii, J. Phys. G **35** 095103 (2008).
10. L. Lapikás, priv. comm. and to be published.
11. S. P. Weppner, Phys. Rev. C **80**, 034608 (2009).