CORE POLARIZATION AND THE COULOMB CORRECTION FOR NUCLEON SCATTERING

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Effects leading to differences J_{np} in the mean field felt by neutrons and protons scattering from an $N=Z$ nucleus are examined. The contribution of core polarization effects is shown to be significant (about 30% of the size of the usual Coulomb correction) and it reduces the overall discrepancy between theoretical estimates of J_{np} and recent comparisons of the optical potentials obtained from neutron and proton scattering from ^{12}C, ^{28}Si, ^{32}S and ^{40}Ca.

A number of phenomena affect the difference in the mean field felt by protons and neutrons interacting with a given nucleus. If the nucleus has $N>Z$, then the symmetry potential makes the field for protons deeper than that for neutrons, reflecting the V_τ part of the two-body potential (or alternatively, showing that the interaction between unlike nucleons is more attractive than that between like nucleons). But even for $N=Z$ nuclei, the interaction may differ because of: (i) the change in the effective energy of the interacting proton caused by the repulsion of the charged target, (ii) core polarization, by which we mean the difference in proton and neutron distributions due to the mutual Coulomb repulsion of the protons in a nucleus, and (iii) the possibility of a charge symmetry breaking (CSB) component of the effective interaction [1,2]. It is important to understand these effects both because they are interesting in their own right, as in the case of any CSB potential, and because they enter into phenomenological evaluations of the mean symmetry potential. The symmetry potential in turn affects many aspects of nuclear structure, for example the splitting of the isovector and isoscalar components of giant resonances.

It is usually assumed that the entire difference is due to the first of the causes listed above – the "effective energy" correction. This is normally called the Coulomb correction, but we use a different nomenclature here because it is not the only Coulomb effect one must consider. In this letter we show that consideration of the effective energy correction alone leads to results in disagreement with comparisons with neutron and proton scattering from ^{28}Si and ^{32}S. We then make a simple estimate of the effects of core polarization for scattering states on the potentials obtained from proton and neutron scattering. We find that the difference is significant and that it reduces the discrepancy with the data, but does not entirely eliminate it.

The effective energy correction for the slowing down of the proton in the Coulomb field of the target nucleus is usually made by assuming that the mean energy of the proton is reduced by the average Coulomb energy E_c associated with the charge of the target. If we take the real potential to have an energy dependence given by

$$V_R(E) = V_R(E=0) - \alpha E ,$$

the correction is $V_{ec} = \alpha E_c$. For $\alpha \approx 0.3$ and

$$E_c = \tfrac{6}{5} Ze^2/1.3A^{1/3} \text{ MeV} ,$$

this yields the usual value of the correction $V_{ec} \approx 0.4Z/A^{1/3}$ MeV [3]. Several attempts have been made to check this estimate of V_{ec} by comparing neutron and proton scattering on the various $N=Z$ nuclei. Published results [4], based on spherical OM analyses for ^{40}Ca, ^{32}S, ^{28}Si and ^{16}O, are generally consistent with $V_{ec} = 0.4Z/A^{1/3}$ MeV, although with rather large uncertainties.

However, three criticisms can be made of these

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analyses: (i) the coupling to excited states in the target is ignored; (ii) a somewhat arbitrary choice of the Coulomb radius for the proton OM potential (typically $r_c = 1.2$ fm) is made; and (iii) the actual proton energy is not reduced by the average Coulomb energy because absorption prevents the proton from fully sampling the centre of the nucleus where the Coulomb potential is largest. The inclusion of channel coupling in the OM searches may lead to large changes in the difference of the volume integrals of the proton and neutron potentials (14 MeV fm^3 in the case of ^{28}Si), and the use of Coulomb potentials which reproduce the experimentally-determined charge radii of the targets leads to a smaller but systematic change (about 4 MeV fm^3) [1] [#1]. To deal with item (iii), a method to obtain the effective energy based on adjusting the proton energy to match the diffraction patterns for neutron and proton scattering was developed by DeVito et al. [4]. One then obtains the results of table 1. The potentials for n and p scattering from ^{28}Si and ^{32}S are essentially the same, corresponding to a difference in volume integrals $(J_n - J_p)/A = J_{np} \approx 0$. The uncertainties are not small, but the results appear to be inconsistent with the simple model which implies that $J_{np} = J_{ec}$. Coupled channels analyses for ^{28}Si and ^{32}S have also been performed by Tailor [5] and Howell [6] (although with $r_c = 1.2$ fm) and one again finds $V_p \approx V_n$ or $J_{np} \approx 0$.

Since the results of coupled channels searches should be more reliable than those of spherical OM searches, and since the effects that led to $V_{ec} \approx 0.4Z/A^{1/3}$ are almost certainly present, other important effects must have been ignored. One of possible significance is core polarization. Coulomb polarization of an $N=Z$ nuclear core leads to an effective charge-dependent nuclear potential in two ways. First, nuclear scattering is most sensitive to the surface region, and the effective potential will reflect the excess of protons pushed out there by the Coulomb field. Yet there is an effect even for the volume-integrated nuclear potential. The nuclear interaction is density dependent and the proton excess at the surface is in a lower density environment. The net effect is to enhance the proton contribution to the potential, since the interaction is reduced at high density. In the work described in ref. [1], we corrected for this latter effect by comparing the volume integrals for neutrons and protons of bound-state Hartree–Fock (HF) potentials, calculated with the SGII Skyrme-type interaction of ref. [7]. A description of the methods and approximations used in the Skyrme HF calculations is given in ref. [8]. These calculations (fig. 1) show that the net potential is stronger for neutrons, as expected since the np interaction is stronger than the pp interaction. The volume integrals $J_{cp}^{HF} = (J_n^{HF} - J_p^{HF})/A$ are given in table 1: the combined effective-energy and core-polarization correction, $J_{ec} + J_{cp}^{HF}$, yield differences closer to the empirical results than the effective-energy correction alone, but not in good agreement.

However, the core-polarization correction should be larger for scattering states, since absorption will

[#1] In ref. [1] the Coulomb OM potential was taken to be that of a uniformly charged sphere with the same RMS radius as measured in electron scattering; a better approximation would be to use a diffuse charge distribution where the diffuseness and radius are fixed from the $\langle r^2 \rangle^{1/2}$ and $\langle r^4 \rangle^{1/4}$ moments. We have re-analyzed several cases from ref. [1] with such a diffuse charge distribution, and have found proton scattering potentials about 0.25% deeper than with the sharp sphere distribution, leading to $(J_n - J_p)/A$ values about 1 MeV fm^3 more positive than those of ref. [1]. We ignore this small difference.

Table 1
Results from linear fits to the real potentials found in coupled channels analyses of proton and neutron scattering from various $N=Z$ targets (taken from ref. [1]; the Coulomb optical potential is assumed to be that of a sharp sphere with the RMS radius observed in electron scattering). Column 5 gives $0.4Z/A^{1/3}$ converted into an equivalent volume integral, J_{ec}. Column 6 is $(J_n - J_p)/A$ for HF (bound state) potentials. J_{cp}^{scat} is defined in the text. All values are volume integrals in MeV fm^3.

Target	$-J_p/A$	$-J_n/A$	$J_{np} = (J_n - J_p)/A$	J_{ec}	J_{cp}^{HF}	J_{cp}^{scat}
^{12}C	$583.1 - 4.09E_p$	$570.0 - 4.09E_n$	13.1 ± 11.7	9.2	−2.5	−3.6
^{28}Si	$503.5 - 2.92E_p$	$501.9 - 2.92E_n$	1.6 ± 5.4	17.2	−3.8	−4.3
^{32}S	$490.2 - 2.45E_p$	$489.8 - 2.45E_n$	0.4 ± 8.1	18.1	−4.6	−5.8
^{40}Ca	$483.0 - 2.34E_p$	$462.9 - 2.34E_n$	20.1 ± 7.1	19.8	−4.6	−6.4

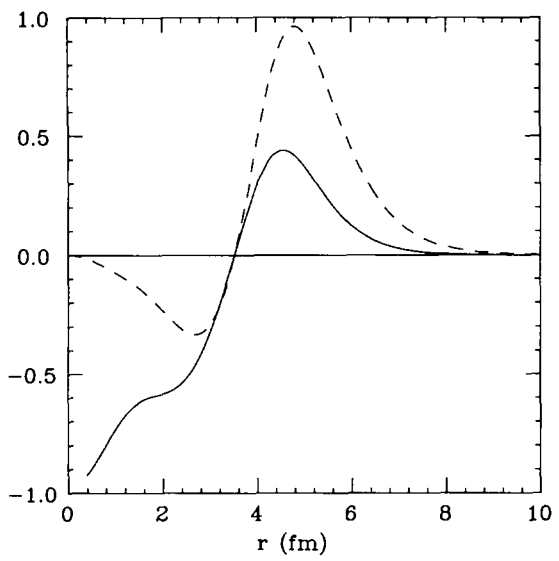

Fig. 1. The difference (in MeV) between neutron and proton Hartree–Fock potentials for ^{40}Ca plotted against radius. The dashed line shows the difference multiplied by r^2 to show the contributions to the volume integral (reduced by a factor of 10). The HF calculations used the SGII interaction and are described in the text.

prevent the projectiles from fully sampling the nuclear interior. To our knowledge, the effect of nuclear absorption on the core-polarization correction has not been evaluated. We estimate the effect as follows. The difference of the bound-state Hartree–Fock potentials, $(V_p^{HF} - V_n^{HF})$ of fig. 1, was added to the real part of a spherical Woods–Saxon potential, U_n, which describes neutron scattering from the target at an incident energy E. The resulting potential was used to generate an angular distribution for proton scattering at energy $E+E_c$, and this is put as data into a standard spherical OM search code (with the depth and radius of the real potential allowed to vary) to obtain the equivalent Woods–Saxon potential, U_p. This procedure is repeated without adjusting U_n by $(V_p^{HF} - V_n^{HF})$. The difference in the volume integrals of U_p with and without the core polarization correction applied is given as J_{cp}^{scat} in table 1. (As a check, the procedure was repeated for "uncharged" protons scattering from ^{32}S without compensating for the Coulomb shift E_c, and J_{cp}^{scat} differed by less than 2% from that for the normal procedure.) For the nuclei considered, J_{cp}^{scat} is 15%–45% larger in magnitude than J_{cp}^{HF} [#2].

In summary, we have shown by a numerical test that the core polarization correction is larger for scattering states than would be implied from a direct subtraction of Hartree–Fock volume integrals, and that it is significant, about 30% of the usual Coulomb correction V_{cc}. This effect must be taken into account when estimating the difference between neutron and proton potentials. It is also possible that charge symmetry breaking of the two nucleon interaction makes the V_{nn} and V_{pp} two-body potentials unequal. If one were to take Negele's estimate [11] of the CSB potential required to explain the ^{41}Ca–^{41}Sc Coulomb energy anomaly, one would need to add a term $J^{CSB}/2 = -9.5$ MeV fm^3 (in the notation of ref. [1]) to $J_{ee}+J_{cp}$.

While inclusion of the core-polarization correction improves the overall agreement of theoretical estimates (taken as $J_{ee}+J_{cp}^{scat}$) with the data (J_{np}), it does not entirely remove the discrepancy. In particular, the empirical result for ^{40}Ca (and ^{12}C, although here the uncertainties are large) is sharply different to those for ^{28}Si and ^{32}S, whereas both J_{ee} and J_{cp} display a smoothly increasing trend with target mass. It is possible that the core polarization correction is larger for deformed nuclei such as ^{28}Si. Deformed Hartree–Fock calculations are presently in progress [12] and should answer this question.

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[#2] The above analysis has also been carried out with the SIII and SVI Skyrme interactions of Beiner et al. [9], and the results for J_{cp}^{HF} and J_{cp}^{scat} were within 5% of the values in table 1 obtained with the SGII interaction. We note that the self-consistency between the densities and interactions which are built into the HF calculations is essential for the evaluation of these isovector quantities [10].

References

[1] J.S. Winfield, S.M. Austin, R.P. DeVito, U.E.P. Berg, Z. Chen and W. Sterrenburg, Phys. Rev. C 33 (1986) 1.

[2] S.M. Austin, in: Proc. Specialists Meeting on the Use of the optical model (OECD, Paris, 1986) p. 53.

[3] F.G. Perey, Phys. Rev. 131 (1963) 745.
[4] J. Rapaport, J.D. Carlson, D. Bainum, T.S. Cheema and R.W. Finlay, Nucl. Phys. A 286 (1977) 232;
J. Rapaport, Phys. Rep. 87 (1982) 25;
R.P. DeVito, S.M. Austin, U.E.P. Berg, R. De Leo and W.A. Sterrenburg, Phys. Rev. C 28 (1983) 2530;
R. Alarcon, J. Rapaport and R.W. Finlay, Nucl. Phys. A 462 (1987) 413.
[5] R. Tailor, Ph.D. thesis, Ohio University (1983).
[6] C.R. Howell, in: Proc. Conf. on Neutron–nucleus collisions – a probe of nuclear structure (Burr Oak, Ohio, 1984) (AIP, New York, 1985) p. 72.
[7] N. van Giai and H. Sagawa, Phys. Lett. B 106 (1981) 379.
[8] B.A. Brown, S.E. Massen, J.I. Escudero, P.E. Hodgson, G. Madurga and J. Vinas, J. Phys. G 9 (1983) 423.
[9] M. Beiner, H. Flocard, N. van Giai and P. Quentin, Nucl. Phys. A 238 (1975) 29.
[10] B.A. Brown, S.E. Massen and P.E. Hodgson, J. Phys. G 5 (1979) 1655.
[11] J.W. Negele, Nucl. Phys. A 165 (1971) 305.
[12] N. Auerbach, private communication.