Measurement of the Electric Polarizability of the Deuteron

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The electric polarizability of the deuteron has been determined by measuring deviations from the Rutherford scattering formula for deuteron elastic scattering from ^{208}Pb at energies from 3.0 to 7.0 MeV. The measured value of the electric polarizability, $\alpha = 0.70 \pm 0.05$ fm^3, is in fair agreement with theoretical predictions.

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The scattering of projectiles from nuclei at energies far below the Coulomb barrier is described only approximately by the Rutherford expression. At sufficiently low energies residual nuclear effects resulting from the tail of the nuclear potential or from barrier penetration can be neglected, but in spite of this there can still be significant deviations from the Rutherford scattering law. From the point of view of nuclear physics, the most interesting effects are those which result from the internal degrees of freedom of the target or projectile—i.e., from real or virtual excitation of nuclear states.

The problem which we shall address here is that of deuteron scattering from heavy nuclei at very low energies. If the target nucleus has no low-lying collective states, it is essentially inert and may be thought of as a point charge.[1] In this case the deviations from Rutherford scattering result primarily from the electric polarization (i.e., stretching) of the deuterons in the Coulomb field of the nucleus.

If a deuteron is located at some position $\vec{r}$ relative to the target nucleus, the electric field of the target ($\vec{E}$) will polarize the deuteron, and consequently the electrostatic potential energy will be slightly smaller than Ze^2/r. If we keep only the dipole term, the change in the potential energy is simply $-\vec{P}\cdot\vec{E}$, where $\vec{P}$ is the induced electric dipole moment. Assuming that $\vec{P}$ is proportional to $\vec{E}$ one finds that the dipole correction to the potential energy can be written as $-\frac{1}{2}\alpha Z^2e^2/r^4$, where the constant α is the electric polarizability of the deuteron. For deuteron scattering at very low energies the dipole stretching potential is weak enough to be treated as a perturbation, and it follows that the deviations from Rutherford scattering are essentially proportional to α. This suggests[1] that it might be possible to determine α by obtaining accurate measurements of the cross section for deuteron elastic scattering at low energies.

The primary reason for our interest in measuring α is simply that the deuteron electric polarizability is a fundamental property of the n-p bound state which, up until now, has not been measured. A measurement of the electric polarization is also of importance because Coulomb stretching of the deuteron is closely related to the more general issue of the role of deuteron stretching and breakup in nuclear reactions. This is a topic of considerable interest for sub-Coulomb energies and for higher energies as well.

Calculations of the electric polarizability of the deuteron have been reported by a number of authors,[2-7] and a variety of calculational methods have been employed. While values of α ranging from 0.21 to 0.64 fm^3 have been reported, it appears that the best calculations give values close to 0.60 fm^3.

In the present Letter we report the first empirical determination of α. Measurements of the cross section have been obtained for deuteron elastic scattering from ^{208}Pb at energies from 3 to 7 MeV. (The Coulomb barrier for ^{208}Pb is approximately 11 MeV.) Since the expected deviations from Rutherford scattering are typically only a few tenths of one percent, the experiment must be done with great care. Rather than attempting to obtain absolute cross-section measurements we have measured only ratios of cross sections. The quantity which we determine is

$$R = \frac{\sigma(E_1,\theta_1)/\sigma(E_1,\theta_2)}{\sigma(E_2,\theta_1)/\sigma(E_2,\theta_2)}, \quad (1)$$

where E_1 and E_2 are two bombarding energies and θ_1 and θ_2 are two scattering angles. (In our experiment θ_1 is a forward angle, θ_2 is a back angle, and $E_1 < E_2$.) To determine R we measure the number of elastically scattered deuterons simultaneously at the two angles θ_1 and θ_2. Then R is obtained from the expression

$$R = \frac{C(E_1,\theta_1)/C(E_1,\theta_2)}{C(E_2,\theta_1)/C(E_2,\theta_2)}, \qquad (2)$$

where $C(E,\theta)$ is the number of counts recorded at energy E and angle θ. For pure Rutherford scattering $\sigma(E,\theta_1)/\sigma(E,\theta_2)$ is independent of energy and therefore $R=1$ in this case. Because the main effect of deuteron stretching is to reduce the cross section at back angles, and since this effect increases with increasing energy, deuteron stretching will give rise to values of R which are less than 1.

The measurements were carried out with the deuteron beam from the University of Wisconsin tandem Van de Graaff accelerator. The beam was defined by rectangular slits 0.7 mm wide by 1.5 mm high located 16.5 cm upstream of the target. A fast feedback system was used to keep the beam centered on the slits. The target consisted of 40 $\mu g/cm^2$ of ^{208}Pb (enriched to 99.1%) evaporated onto a 5-$\mu g/cm^2$ carbon backing. Solid-state detectors were placed symmetrically to the left and right of the incident beam at scattering angles of 60°, 140°, 150°, and 160°. The use of symmetric detectors allows one to compensate, to first order, for possible counting-rate variations caused by changes in the position and direction of the beam. The entire experiment was carried out without moving the detectors or altering the experimental setup in any way. This is important because even a slight change in the scattering angle from one energy to another could lead to a significant error in the determination of R. To reduce background each detector was equipped with a slit system which limited the field of view to a small region surrounding the target. Magnets were used to prevent electrons from reaching the detectors. All beam-defining and detector slits were constructed of thin (0.13-mm) tantalum foil to reduce slit-edge scattering.

Measurements were taken at deuteron energies of 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, and 7.0 MeV. To provide a consistency check, the measurement at 3 MeV was repeated four times while the measurement at each of the higher energies was repeated either two or three times.

A typical pulse-height spectrum, obtained at $E_d=5$ MeV, $\theta=160°$, is shown in Fig. 1. In addition to the ^{208}Pb elastic scattering peak the spectrum contains a number of peaks from reactions on target contaminants. While the larger contaminant peaks (i.e., those from ^{12}C) remained well resolved from the ^{208}Pb peak at all energies except 7 MeV, the presence of smaller peaks from ^{16}O, ^{14}N, and ^{13}C made corrections necessary at several energies. To correct for the contaminants, two additional targets were prepared. The first was a carbon foil which contained a significant amount of oxygen, while the second consisted of melamine ($C_3H_6N_6$) evaporated onto a carbon backing. Spectra were obtained at each energy and angle for both targets. With these spectra it was a straightforward matter to subtract out the contaminant peaks. The corrections to the peak sums were typically a few tenths of one percent, except at 7 MeV where the correction amounted to 10% at two of the three angles. Counting rates were adjusted to keep electronic dead times small (typically 0.4%). Beam currents and detector solid angles were chosen to make the dead times nearly equal for all energies and angles, and consequently the dead-time corrections produced only slight changes in R. Calculations indicate that the effects of multiple scattering in the target are negligible.

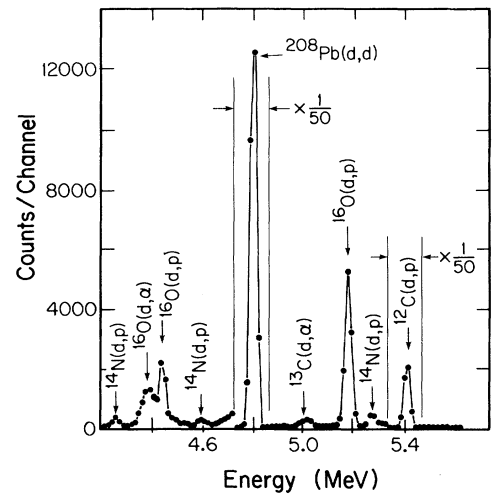

FIG. 1. A typical pulse-height spectrum obtained with $E_d=5$ MeV and $\theta=160°$.

The measurements are presented in Fig. 2. The quantities shown are values of R corresponding to energies $E_2=3.5$–7.0 MeV and angles $\theta_2=140°$, 150°, and 160°. In each case we have used $E_1=3.0$ MeV and $\theta_1=60°$. The displayed error bars include statistical errors as well as an estimate of the uncertainty associated with the subtraction of contaminant peaks.

Our results show clearly that there are significant deviations from Rutherford scattering even

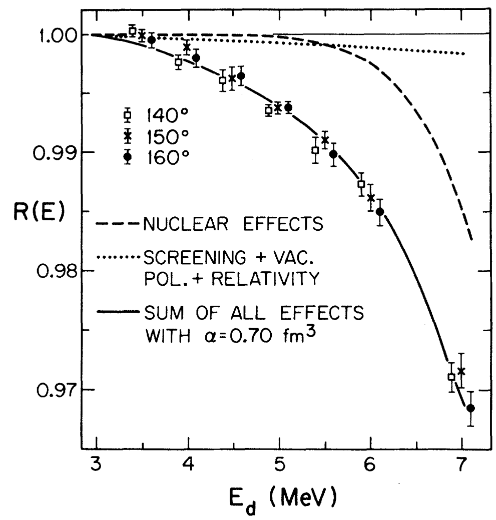

FIG. 2. Measurements of $R(E_2)$ [see Eq. (1)] for E_1 $=3$ MeV, $\theta_1=60°$ and $\theta_2=140°$, 150°, and 160°. The dotted curve shows the sum of the contributions to R from atomic screening, relativistic corrections, and vacuum polarization, while the dashed curve is an estimate of the effects of nuclear processes. The solid curve includes these effects as well as the calculated effect of the electric polarizability of the deuteron, with $\alpha=0.70$ fm^3. The curves are for $\theta_2=150°$.

for energies as low as 4 MeV. The question which we must now address is whether these deviations result from the electric polarization of the deuteron or from some other effect.

First let us consider the possibility that nuclear effects may be of some importance. For deuteron scattering at low energies the dominant nuclear effect is the loss of flux into reaction channels. As one would expect from a classical picture of the scattering process, this loss of flux leads to a reduction in the elastic scattering cross section at back angles. The most direct approach to determining the magnitude of the deviations from Rutherford scattering would be to use the optical model. However, the difficulty with this approach is that the calculations are quite sensitive to the choice of parameters for the absorptive potential.[8] To get around this problem we note that if one varies the imaginary-potential parameters, there is a close correlation between the predicted total reaction cross section and the back-angle elastic scattering cross section. Since one knows that the only reactions which have an appreciable cross section at these low energies are (d,p) reactions and (to a lesser extent) deuteron breakup, and since one can calculate the cross sections for these reactions with reasonable accuracy,[9] it is possible to make a fairly accurate prediction of the total reaction cross section. This in turn places the required constraint on the optical-model parameters and allows us to predict the effect of nuclear interactions on the elastic scattering cross sections. The dashed curve in Fig. 2 shows the result of such a calculation. We note that for $E_d \leq 5.5$ MeV the predicted nuclear effect is small (i.e., less than 10% of the measured deviation from $R=1$).

One should also consider the possibility that the elastic scattering cross section might be affected by electromagnetic processes which involve excitation of the target nucleus. Since ^{208}Pb is a spherical nucleus with no low-lying excited states we can safely neglect conventional Coulomb excitation effects.[1] The most important electromagnetic effect is the electric polarization of the ^{208}Pb nucleus (i.e., virtual excitation of the ^{208}Pb giant dipole resonance) by the deuteron. However, this effect is expected to be 2 orders of magnitude smaller than the deuteron stretching effect,[1] and thus it can be neglected as well.

Vacuum polarization, atomic screening, and relativistic corrections all produce small but nonnegligible changes in the cross section for elastic scattering at low energies. In each of these cases the effect is well understood and accurate calculations are possible.[10] We have performed the necessary calculations and find that these effects lead to cross-section changes of as much as 0.5%; however, the changes in R are considerably smaller. The combined effect of the three processes is indicated by the dotted curve in Fig. 2.

On the basis of the calculations outlined above we conclude that the observed deviations result primarily from the electric polarization of the deuteron. For $E_d \leq 5.5$ MeV one can safely use the measurements of R to determine α, since nuclear effects are small for these energies. The solid curve in Fig. 2 shows the result of a calculation in which α was adjusted to fit the measurements for $E_d \leq 5.5$ MeV. This calculation[11] includes the corrections for vacuum polarization, atomic screening, relativistic effects, and nuclear effects (as given by the dotted and dashed curves in Fig. 2) as well as the dipole stretching effect. The value of α which we obtain in this way is

$$\alpha = 0.70 \pm 0.05 \text{ fm}^3. \tag{3}$$

Here the quoted error includes not only the uncertainties in the measured values of R but also the uncertainty in the calculation of the nuclear correction. This latter uncertainty is taken to be equal to the magnitude of the calculated correction. It should be noted that the solid curve in Fig. 2 accurately reproduces the measurements at 6.0 and 7.0 MeV in spite of the fact that no attempt was made to fit these data. This gives us confidence that our calculation of the nuclear effects is valid and that the value of α is correct.

Our empirically determined value of α is in fair agreement with theoretical predictions. Although we know of no calculation that predicts a value of α as large as 0.70 fm^3, several calculations[2,6,7] give 0.63 or 0.64 fm^3. At the present time it is not clear whether our measurement of α is of sufficient accuracy to place any meaningful new constraint on the deuteron wave function since most calculations performed to date have employed very simple deuteron wave functions. If future calculations were to show that measurements of the polarizability are useful in distinguishing various n-p interaction models, this would provide a strong motivation for further experiments. It is our belief that with sufficient care, one could make a significantly more accurate measurement of α.

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[8]To some extent the calculations are also sensitive to the real central potential. However, for $E_d \leq 5$ MeV the changes in R which result from reasonable variations in the parameters are less than 0.01%.

[9]For ^{208}Pb$(d,p)^{209}$Pb the strong transitions have spectroscopic factors of essentially 1. To predict the total cross section we selected out the five strongest transitions and employed the conventional distorted-wave Born approximation. The cross sections for deuteron breakup were taken from G. Baur, M. Pauli, and D. Trautman, Nucl. Phys. A265, 101 (1976).

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[11]The elastic scattering cross sections were calculated by applying quantum mechanical corrections (see Ref. 1) to the classical perturbation theory result.