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A search for colour van der Waals interaction

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Abstract. It is suggested that the strength of nuclear colour van der Waals interaction, if present, can be determined by measuring deviations from Rutherford scattering of charged hadrons from nuclei, at energies well below the Coulomb barrier. Experimental limit on the strength of such a potential is obtained as $\lambda < 50$, when the colour van der Waals potential is given by $V(r) = \lambda(\hbar c/r_0)(r_0/r)^7$, with r_0, the scaling length, taken as 1 fm. This limit is obtained from an analysis of existing experiments and by performing scattering experiments of 3–4·6 MeV protons from a ^{208}Pb target.

Keywords. Nucleon-nucleon potential; colour van der Waals interaction; Rutherford scattering.

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1. Introduction

The nature of nucleon-nucleon (N-N) strong interaction has been under intense study for the past five decades. One of the main features of the N-N interaction is its range which is given by the pion Compton wavelength. The interaction has also spin and isospin dependence. The radial dependence of the central part of the N-N potential has been parametrized and understood on the basis of one and multi-meson exchange. The short range repulsion, which has a range of $\sim 0{\cdot}4$ fm and has been variously parametrized as a hard or a soft core, supposedly results from the exchange of heavy vector mesons. The nucleon-nucleus potential is basically understood as a folding of a N-N potential with suitable modifications.

The nucleon itself is now known to have an internal structure being composed of quarks and gluons interacting with each other. Quantum chromo dynamics (QCD) is supposed to be the theory for strong interactions. QCD has enjoyed a great deal of success in hadron physics in terms of potential models, in which the form of the q-q potential is specified, e.g. the linear potential in which the q-q potential is proportional to the distance between them. Such a linear potential gives rise to linear Regge trajectory in agreement with the data. It is natural to attempt to understand the N-N interaction at a more basic level involving quarks and gluons. In this regard there has been some success as far as the short range repulsion is concerned. Attempts to understand the longer range attractive part of the interaction have been beset with many problems. The mechanism for the implementation of confinement is one of them.

In models that attempt to obtain the N-N potential from a q-q potential, there is an analogue of the van der Waals (V-W) potential.

When two nucleons are at a distance larger than their size, they cannot exchange a single colour gluon, which belongs to a SU(3) colour octet because the nucleons themselves are colour neutral and belong to a colour singlet. Thus no long range interaction can occur between two nucleons through a single gluon exchange. However the exchange of a pair of gluons coupled to form a colour singlet is allowed. This is analogous to the situation of a two photon exchange between two atoms which are neutral. Since this is an interaction obtained in second order perturbation theory, it is attractive. Such a two-gluon exchange potential falls off as some inverse power of distance. This is true if the gluons are massless. It is conceivable that a pair of gluons acquires a mass, in which case the interaction is no longer of the V-W type but has a shorter range.

Many studies (Appelquist and Fischler 1978; Fishbane and Grisaru 1978; Fujii and Mima 1978; Willey 1978; Feinberg and Sucher 1979; Matsuyama and Miyazawa 1979; Gavela *et al* 1979; Liu 1983) attempted to calculate the form and magnitude of such a strong V-W potential, based on different approaches. Some of them also analysed existing data to draw conclusions on the existence of such a potential. The potential models give rise to a V-W potential $\propto 1/r^n$ where r is the internuclear distance, the value of n depending on the assumed q-q potential. The strength of such a potential is usually given by a dimensionless quantity λ_n corresponding to a $1/r^n$ potential. The van der Waals N-N potential is given by

$$V_n(r)=\lambda_n\left(\frac{\hbar c}{r_0}\right)\left(\frac{r_0}{r}\right)^n \tag{1}$$

r_0 being a scaling distance usually taken as 1 fm. While the interaction could have spin and isospin dependences, we shall neglect them in the following discussion. There are many ways (Greenberg and Hietarinta 1980) of avoiding such long range interactions; but it is of interest to look for a V-W interaction purely from an empirical point of view.

Feinberg and Sucher (1979) analysed Eötvos and Cavendish experiments on gravitational interactions to set the limits $\lambda_2 \leqslant 10^{-23}$ and $\lambda_3 \leqslant 10^{-12}$. The limits from gravitational experiments for higher values of n are not very stringent. Feinberg and Sucher (1979) and Batty (1982) analysed the existing data on hadronic atoms, viz, π^-, p^-, K^- and Σ^- atoms. If there is a long range V-W type interaction in addition to the electromagnetic interaction, the energy levels and the transition energies in such atoms will be affected. Analysing the data and considering corrections where necessary for the 'normal' nuclear interactions, Batty (1982) set limits of $\lambda_4 \leqslant 10^{-3}$, $\lambda_5 \leqslant 10^{-2}$, $\lambda_6 \leqslant 1$ and $\lambda_7 \leqslant 20$. The only positive signal for such an interaction is presented by Sawada (1980) by analysing the π-π, π-p and p-p scattering data. Sawada argued that a $1/r^n$ potential gives rise to a logarithmic divergence for the scattering amplitude as the momentum transfer goes to zero. He concluded that the scattering experiments on the above three systems are consistent with a $1/r^7$ potential and the value for the strength corresponds to $\lambda_7 \simeq 100$ for the N-N potential. The ratios of strengths of the above three types of systems are indeed what one expects (Sawada 1980).

In view of the importance of the problem, one should look for such a V-W interaction in different experimental situations. In the following we shall investigate the effect of such a V-W interaction on the scattering of charged hadrons from nuclei at energies well below the Coulomb barrier, where the 'normal' (short range) nuclear interaction is negligible. We shall show that such experiments indeed can give useful information about the presence or absence of such long range nuclear interaction. We also analyse some existing experiments, done in different contexts, to extract limits on the strength of such a V-W interaction. At the end we shall describe a preliminary experiment to look for such effects, using the 5·5 MeV van de Graaff accelerator at BARC, Trombay. A preliminary account of this work was reported earlier (Baba *et al* 1985).

2. Deviations from Rutherford scattering

A straightforward way of looking for V-W nuclear potential is to study the deviation in Coulomb scattering at energies well below the Coulomb barrier i.e. at energies where the distance of closest approach is much longer than the range of the normal short range nuclear interaction. If the interaction were only the Coulomb interaction, $(Z_1Z_2e^2)/r$, between point particles the cross section is the well-known Rutherford cross section.

We can now calculate classically, the deviation of the cross section from the above if we have an additional attractive potential of the type $-\beta_n/r^n$. From the previous expression for the potential, we see that $\beta_n = 197\,\lambda_n$ MeV $(\mathrm{fm})^n$. We define $\Delta(E,\theta)$ as the fractional deviation from Rutherford scattering, viz,

$$\Delta(E,\theta) = \frac{\sigma(E,\theta) - \sigma_R(E,\theta)}{\sigma_R(E,\theta)}, \tag{2}$$

where $\sigma(E,\theta)$ denotes the differential cross section at a c.m. angle θ, and c.m. energy E including the $-\beta_n/r^n$ potential and $\sigma_R(E,\theta)$ is the differential cross section with the Coulomb potential alone. This deviation is larger at larger scattering angles, because the distance of closest approach decreases with the scattering angle and the effect of a $-\beta_n/r^n$ potential is greater. We calculate an expression for this deviation and obtain for $\theta = \pi$,

$$\Delta(E,\pi) = \frac{A_n\beta_n E^{n-1}}{(Z_1Z_2e^2)^n} = \frac{A_n B_n}{E} \cdot \left(\frac{1}{R_a}\right)^n, \tag{3}$$

where A_n is a constant depending on the power n of the potential and R_a the distance of closed approach for the energy E, i.e., $R_a = Z_1Z_2e^2/E$. The values of A_n are 3·2, 3·66, 4·06, 4·44 and 4·77 for $n = 3, 4, 5, 6$ and 7. Let us consider the scattering of protons on ^{208}Pb as an example. For a c.m. energy $E = 5{\cdot}5$ MeV, the distance of closed approach, $R_a = 21{\cdot}4$ fm which is very much larger than the range of the 'normal' nuclear potentials for p on ^{208}Pb. The deviation expected at $\theta = \pi$ is Δ_π ($E = 5{\cdot}5$ MeV, $n = 7$, $p + {}^{208}$Pb$) = -0{\cdot}17\%$ for $\lambda_n = 100$, which is the value suggested by Sawada (1980). The finite size of the nucleus increases this to $-0{\cdot}26\%$. This is a measurable deviation. In fact a fifth of this value, corresponding to $\lambda_7 \sim 20$ is measurable in a careful experiment, as shown below. Much smaller limits on λ_n for $n < 7$ can be placed from such measurements.

These expressions get slightly modified in a quantum mechanical calculation (Baur *et al* 1977). However these corrections are not large as shown by Baur *et al* (1977). In any case these are calculatable through numerical computations.

There are other effects that can contribute to deviations from Rutherford cross sections. The most important of these effects are listed and discussed below. A discussion of these effects is given by Alder and Winther (1975).

(i) *Effects due to 'normal' nuclear interactions*: There are of course deviations from Rutherford scattering if the 'normal' short range nuclear potential comes into play. Thus it is necessary to restrict to energies well below the Coulomb barrier. The correction due to this in the example of protons at 5·5 MeV on ^{208}Pb, considered above, is less than 0·02%. This effect however becomes important for higher incident proton energies.

(ii) *Atomic screening*: The effect of screening by the atomic electrons can be described by a screening potential which can be approximated (Alder and Winther 1975) by $V_{sc} = -4{\cdot}8 \times 10^{-5}\ (Z_1 Z_2^{4/3} + Z_1^{4/3} Z_2)$ MeV for distances smaller than the Thomas-Fermi radius. Its effect is largest at forward angles and is almost constant for angles larger than 30° and also is a very slowly varying function of beam energy (see Lynch *et al* 1982).

(iii) *Vacuum polarization*: This effect can be taken care of to a good approximation by the Uehling potential

$$V_{\text{vac-pol}} = \frac{Z_1 Z_2 e^2}{r} \cdot \frac{2\alpha}{3\pi} I\left(\frac{2r}{\lambdabar}\right) \tag{4}$$

with
$$I\left(\frac{2r}{\lambdabar}\right) = \int_1^\infty \exp(-2r\hbar/\lambdabar)\left(1 + \frac{1}{2t^2}\right)\frac{(t^2-1)^{1/2}}{t^2}\,\mathrm{d}t \tag{5}$$

and where $\lambdabar$ is the Compton wavelength of the electron divided by 2π and α, the fine structure constant. The integral is evaluated in terms of Chebeshev polynomials (Baur *et al* 1977). For the cases considered here, the correction is again constant for angles larger than 40° and is only weakly energy dependent.

(iv) Relativistic effects: The Schrödinger equation for the scattering of a particle in a potential has to be replaced by Dirac or Klein-Gordon equation depending on the nature of the projectile. The essential difference is the addition of a potential $-V_{\text{Coul}}^2/2m_0c^2$, which $\propto 1/r^2$. Thus this gives an effect $\Delta(E) \propto E$ (see equation 3).

(v) *Nuclear polarizability*: When the target and projectile are in close proximity, there are other electrostatic potentials in addition to the Coulomb potential $Z_1 Z_2 e^2/r$ due to the polarizabilities of the target and the projectile. It is possible to have both the nuclei in virtually excited states and this gives rise to a potential through a second order perturbation. In principle all the excited states in the nuclei can contribute. However, for nuclei, which do not have low-lying collective states, the main contribution comes from the excitation to the giant dipole resonance states giving rise to dipole polarizabilities. The resulting attractive potential in this case has a $1/r^4$ dependence:

$$V_{\text{pol}} = -\frac{1}{2}\frac{e^2}{r^4} P \tag{6}$$

with
$$P = (\alpha_1 Z_2^2 + \alpha_2 Z_1^2) \tag{7}$$

where α_1 and α_2 are the polarizabilities of the projectile and the target. The polarizability is given by

$$\alpha = 2\sum_n \frac{|\langle n|D_z|0\rangle|^2}{(E_n - E_0)} \tag{8}$$

D_z being the z-component of the dipole operator exciting the nucleus from the ground state to an excited state n with energy E_n. One can relate the polarizability to the E^{-2} weighted photo sum rate (Baur *et al* 1977):

$$\alpha \leqq \frac{\hbar c}{2\pi^2}\sigma_{-2} = \frac{\hbar c}{2\pi^2}\int \frac{\sigma(E)\mathrm{d}E}{E^2} \tag{9}$$

where $\sigma(E)$ is the total photo cross section to a state at energy E. One can insert the empirical value of σ_{-2} and the polarizabilities can be estimated.

Of the corrections that have been discussed, the first four can be calculated rather accurately. The nuclear polarizability is however not so well determined because of the incomplete knowledge of the nuclear properties of the target and the projectile.

3. Analysis of the existing experiments

Two accurate experiments have been reported in which deviations from the Rutherford scattering cross sections has been studied. In one of these (Rodning *et al* 1982), scattering of deuterons from $^{208}P_{8b}$ was studied. The motivation was to measure the electric dipole polarizability of the deuteron. In the other experiment (Lynch *et al* 1982) the elastic scattering of ^{16}O, ^{14}N and ^{12}C on ^{208}Pb was studied in order to understand the nuclear polarization effects. In the following we shall analyse these experiments in order to draw conclusions on the $1/r^n$ type of potential. We shall consider $n = 7$ and extract the limits from their experiments. Limits on smaller values of n can similarly be obtained.

3.1 $d + {}^{208}Pb$ (*Rodning et al* 1982)

For sub-Coulomb barrier energies of d on ^{208}Pb, the major potential is, of course, the Coulomb potential. However, there is an additional potential due to the dipole polarizabilities of d and ^{208}Pb. The resultant potential is

$$V(r) = \frac{Z_d Z_{\mathrm{Pb}} e^2}{r} + V_{\mathrm{pol}}(r)$$

where $$V_{\mathrm{pol}}(r) = \frac{-e^2}{2r^4} P$$

with $$P = \alpha_d Z_{\mathrm{Pb}}^2 + \alpha_{\mathrm{Pb}} Z_d^2$$

where Z_{Pb} and Z_d are the atomic numbers, α_{Pb} and α_d are the electric dipole polarizabilities of ^{208}Pb and d, respectively.

Theoretical estimate for the α_d is 0·64 fm^3 (Clement 1962; Levinger 1957) and for ^{208}Pb it is $\alpha_{\mathrm{Pb}} = 25{\cdot}2$ fm^3 (Baur *et al* 1977). Thus we see that mainly the deuteron polarizability contributes to the polarization potential. Rodning *et al* (1982) measured the double ratio for energies E_1, E_2;

$$R(E_1, E_2) = \frac{R(E_1)}{R(E_2)}$$

with
$$R(E) = \frac{C(E, \theta_f)}{C(E, \theta_b)}$$

where $C(E, \theta_f)$ and $C(E, \theta_b)$ are the counting rates in two detectors at forward angle θ_f (60°) and backward angle θ_b (140°–160°) respectively. Such a ratio is independent of the solid angles used and represents the deviation as a function of angle and energy. Taking $E_2 = 3$ MeV and $E = 4$ to 6 MeV, the deviation $\Delta(E) = (R(E, 3\ \text{MeV}) - 1)$ is plotted as a function of E in figure 1. The points are read off from (Rodning *et al* 1982) and are corrected for atomic screening, vacuum polarization and relativistic effects. If the effect is only due to the polarization potential, $\Delta(E)$ should vary as $[E^3(\text{MeV}) - (3\ \text{MeV})^3]$. If there is an additional effect to a potential of the type $-\beta/r^7$, the energy dependence of $\Delta(E)$ has an additional term of the form $[E^6 - (3\ \text{MeV})^6]$. (see equation 3). The data of Rodning *et al* (1982) presented in figure 1 is fitted with these two terms. A contribution of $-1/r^7$ type potential with $\lambda_7 \leq 50$ cannot be ruled out as can be seen from the figure.

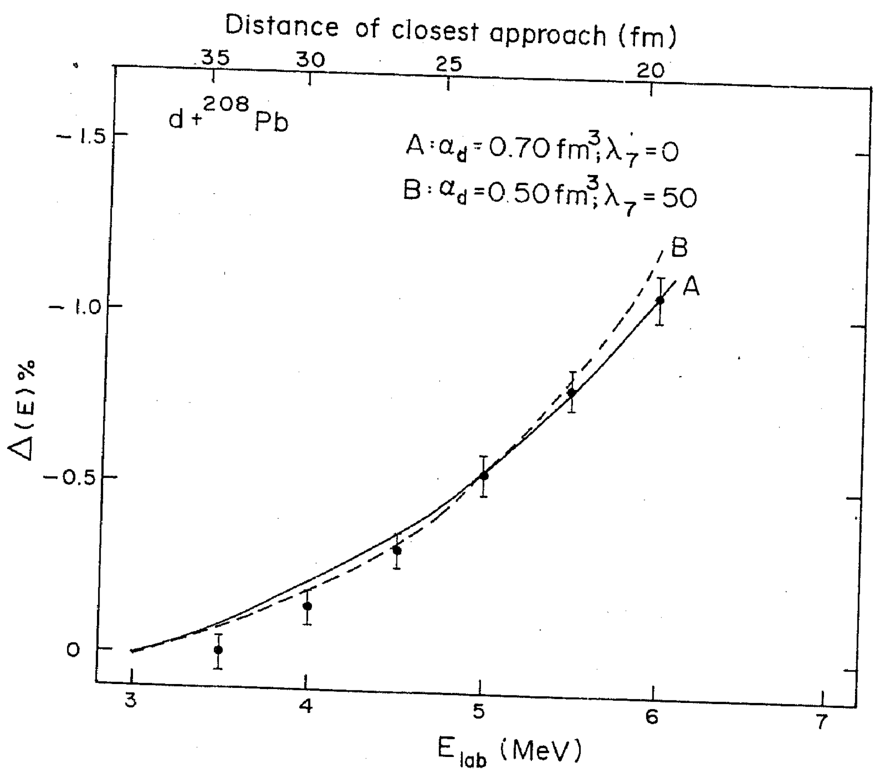

Figure 1. Deviation from Rutherford scattering represented by $\Delta(E)$ (see text) as a function of energy for deuteron scattering from ^{208}Pb. The experimental data are from Rodning *et al* (1982) and are corrected for atomic screening, vacuum polarization and relativistic effects. Curve A represents the fit with only deuteron polarization contribution and no long-range r^{-7} component whereas curve B represents the fit with such a contribution with $\lambda_7 = 50$.

3.2 $^{16}O+^{208}Pb$ (*Lynch et al* 1982)

Lynch *et al* (1982) studied sub-Coulomb scattering of ^{12}C, ^{14,15}N and ^{16}O projectiles on ^{208}Pb in order to measure and understand deviations from Rutherford scattering. The deviation Δ, defined as

$$\Delta=\frac{\sigma(b)/\sigma_R(b)}{\sigma(30°)/\sigma_R(30°)}-1$$

where $\sigma(b)$ and $\sigma(30°)$ are the measured cross sections at backward angle (average of 5 angles between 140° and 170°) and at 30°, respectively, corrected for atomic screening, vacuum polarization and relativistic effects, is plotted in figure 2 as a function of the laboratory energy of ^{16}O incident on a ^{208}Pb target. The expected dependence of Δ due to nucelar polarization effects is indicated by the curve A. The values of 0·585 and 16·0 mb/MeV were used for σ_{-2} for ^{16}O and ^{208}Pb respectively (Lynch *et al* 1982, Clement 1962). Curve B shows a calculated curve with an additional $-\beta/r^7$ potential with a value $\lambda_7=25$. As can be seen from figure 2, such a value for λ_7 cannot be ruled out from this experiment. Similar measurement with ^{12}C, ^{14}N projectiles on ^{208}Pb target were also made by Lynch *et al* (1982).

In both of the experiments above it is difficult to make unambiguous conclusions as to the value of λ_7, because of the uncertainties associated with the nuclear polarizabilities. It can however be concluded that a value of $\lambda_7 \leqslant 25$ cannot be ruled out on the basis of these experiments. An experiment involving proton is essentially free

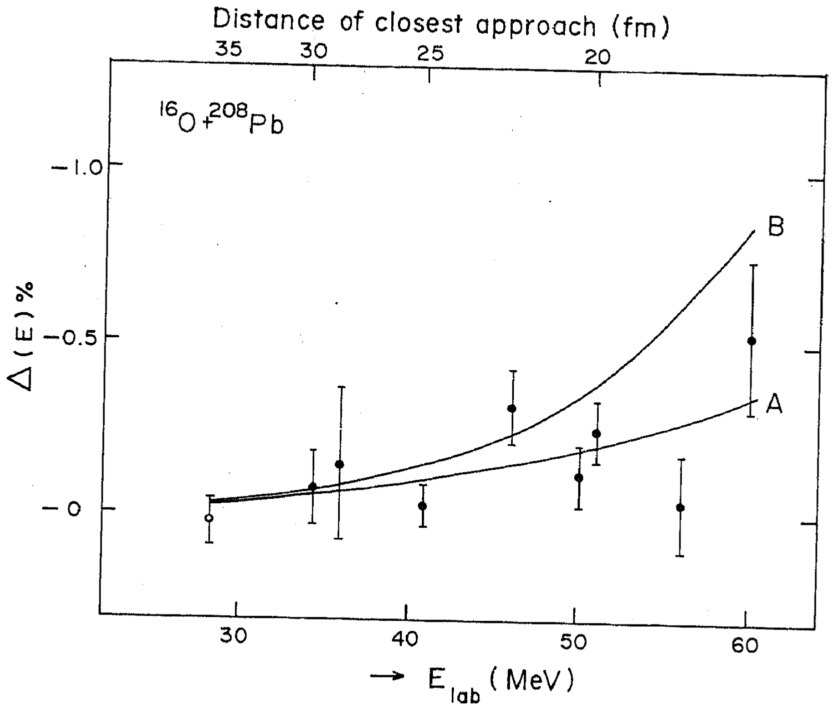

Figure 2. Deviation of Rutherford scattering represented by $\Delta(E)$ (see text) for the system $^{16}O+^{208}Pb$. Experimental data are from Lynch *et al* (1982). The data are corrected for atomic screening, vacuum polarization and relativistic effects. Curve A is with only nuclear polarization and curve B includes the contribution from a long range component with $\lambda_7=25$.

from these nucelar polarizability effects as the polarizability of proton is known to be less than $2{\cdot}20 \times 10^{-4}$ fm^3 (Baramov *et al* 1974), and the contribution due to polarization of ^{208}Pb in the field of proton is extremely small. With these considerations in view, an experiment to look for deviations from Rutherford scattering in the sub-barrier scattering of proton on ^{208}Pb is attempted.

4. Present experiment

It was argued earlier that the sub-Coulomb scattering of protons does not suffer from the ambiguities associated with nuclear polarization. An experiment therefore was attempted using the proton beam from the 5·5 MeV Van de Graaf accelerator at BARC, Trombay. Isotopically enriched (>99%) ^{208}Pb of thickness $\sim 70\ \mu$g/cm^2 deposited on a 20 μg/cm^2 C foil was used as a target. The target was mounted centrally in a cylindrical scattering chamber maintained at a pressure of 2×10^{-6} torr. The elastically scattered particles were detected at $\pm 55°$ and $\pm 150°$ with respect to the beam direction, using four 300 μm Si surface barrier detectors. The two forward detectors (f) were at a distance of 30 cm from the target while the backward detectors (b) were at 20 cm. The experimental arrangement is shown schematically in figure 3. The energy resolution of the forward detectors (effective area 25 mm^2) was 14 keV and that of backward detectors (effective area 200 mm^2) was 20 keV for the 5·486 MeV α-particles from ^{241}Am source.

As discussed earlier, one should measure the ratio $\Delta = [\sigma(b)/\sigma_R(b)]/[\sigma(f)/\sigma_R(f)]$ as a function of energy. Since $\sigma_R(b)/\sigma_R(f)$ is independent of energy, it is enough to measure the ratios of the counts in the forward detectors to the counts in the backward detectors. In order to measure this ratio to an accuracy better than 0·1%, special care had to be taken to minimise the sources of error which are described below.

Since only the ratio of forward and backward scattering cross sections is measured, the determination of the absolute thickness of the target is not necessary. However, the target must be thin enough to reduce the effect of multiple scattering. The absolute beam intensity and the solid angles similarly need not be known very accurately. However the relative solid angles subtended by the detectors at the interaction of the beam and the target should remain constant to the level of 0·02%. Similarly the angle of scattering should not change by more than one-tenth of a degree. These conditions demand that the position of the beam spot on the target should be stable to within a

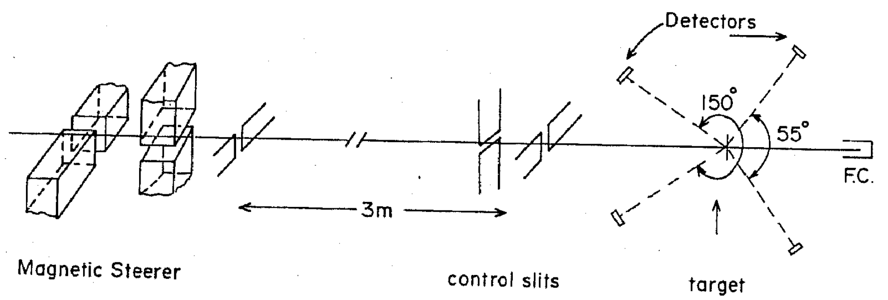

Figure 3. Schematic diagram of the experimental arrangement. The magnetic steerers are controlled by the feedback from the difference signals from the control slits.

fraction of a mm. This was accomplished by using a four slit system preceded by a (2 × 5 mm) collimator 3·5 metres upstream. The currents from those four slits were used in a fast feedback loop of the beam steerers in order to keep the beam at the centre of the slits. Further, by taking the geometric averages

$$\sigma_F(E)=[\sigma_{F_1}(E)\,\sigma_{F_2}(E)]^{1/2}$$

where F_1 and F_2 correspond to the two angles of forward detectors, viz, $\pm 50°$, the first order correction to a possible beam wandering was eliminated. A similar procedure was used for the backward detectors.

The elastic scattering peaks in the detectors should be free of interferences from impurities in the target and events from inelastic scattering etc. The detectors employed had good enough resolution to separate clearly the elastic scattering peaks from ^{208}Pb

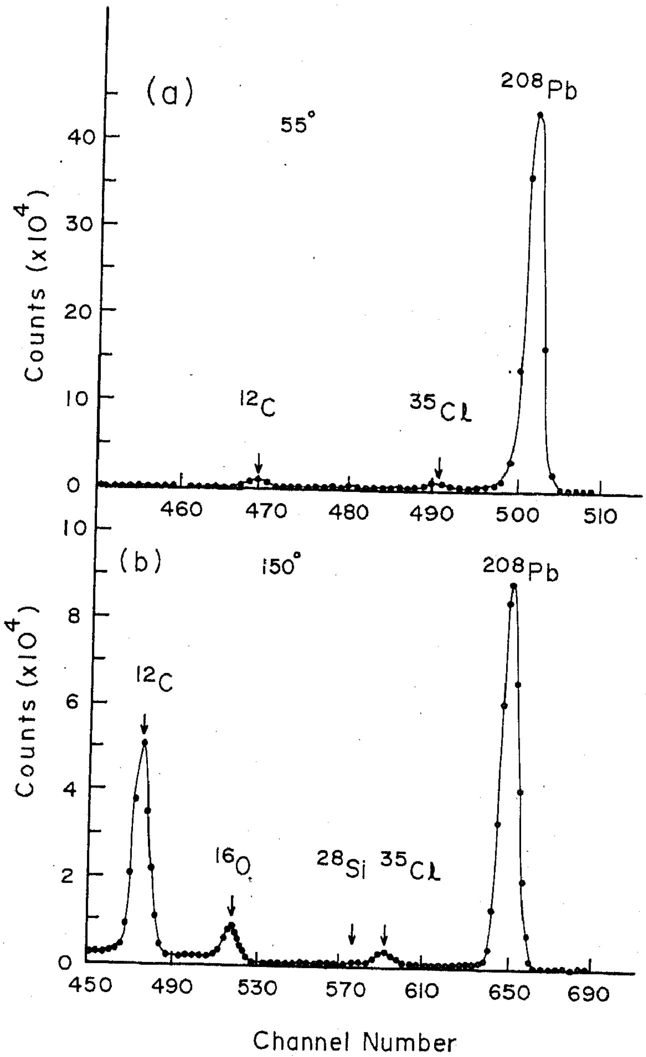

Figure 4. Typical spectra of 4·6 MeV protons scattered from ^{208}Pb target at forward (55°) and backward (150°) angles. The peaks due to elastic scattering from different elements are marked. The energy calibrations for the two spectra are different.

and other contaminants like C, O, Si and Cl, even at 55°. Typical proton spectra measured at 55° and 150° are shown in figure 4. The inaccuracy in subtraction due to any counts under the elastic peak is less than 0·02%.

Signals from all the four detectors were routed through a mixer router to the four quadrants of a Tracor Northern 4096 channel pulse height analyser, using only one ADC. In this way, the dead time corrections were the same for all the detectors. Further the quadrants used for individual detectors were periodically interchanged. The solid angles of the detectors were so adjusted as to make the counting rates of all the four detectors equal to within 10%. Average counting rate was kept at ~ 300 Hz in each detector. All the measurements were made without moving the detectors or altering the experimental set up in anyway.

In order to check the accuracy and the reproducibility of the system, the ratio σ_b/σ_f was measured at the same energy several times. The effect of directional variation of the beam from the machine was also studied. The measured ratio remained constant to within 0·07%, which was also the statistical accuracy, thus showing the absence of instrumental effects to this level.

Measurements were first made with a deuteron beam on a ^{208}Pb target in order to repeat the measurements of Lynch *et al* (1982). The value of $\Delta(E) - \Delta(E = 3{\cdot}26 \text{ MeV})$ was measured to be $(-0{\cdot}44 \pm 0{\cdot}11)\%$ at $E = 4{\cdot}8$ MeV. This is in agreement with the value $(-0{\cdot}5 \pm 0{\cdot}1)\%$ reported by Lynch *et al.*

The measurements for the $p + {}^{208}$Pb system were made at $E = 3$, 4·2 and 4·6 MeV. At each energy, measurements were made a number of times and the internal consistency of these measurements was checked. A preliminary value for Δ (4·2 MeV) and Δ (4·6 MeV) referred to $E = 3$ MeV was found to be $(-0{\cdot}10 \pm 0{\cdot}05)\%$. At the energies and angles used in experiment, the relativistic correction is the most important of the corrections discussed above and this amounts to $-0{\cdot}13\%$. Thus the net deviation from the Rutherford scattering is $< 0{\cdot}1\%$. From this the limits derived on the coefficients of the r^{-n} potentials are $\lambda_6 \leqslant 5$ and $\lambda_7 \leqslant 50$.

5. Summary and conclusions

The question whether there are experimental indications for a colour van der Waals interactions is examined. Theoretically, some authors (Feinberg and Sucher 1979 and Batty 1982) can only place upper limits on such an interaction, while Sawada (1980) conclude that such interaction is in fact present and gave a number of $\lambda_7 \simeq 100$. It is pointed out in the present paper that deviations from Rutherford scattering due to potentials of this magnitude can be observed experimentally in charged hadron scattering from nuclei at energies well below the Coulomb barrier. Analysis of reported experiments has been made and upper limits on λ_7 were placed ($\lambda_7 \lesssim 25$–50). Such experiments which use complex nuclear projectiles have an inherent ambiguity in that their dipole polarizabilities are not precisely known. An experiment with proton as the projectile, where the polarization effects are negligible, has been attempted and an upper limit of 50 is placed on λ_7. Thus it seems that the conclusions of Sawada (1980), that $\lambda_7 \simeq 100$, are not borne out by the reanalysis of the existing experiments and by the present experiment. It is in principle possible to improve the limits on λ_7 from similar experiments done with higher proton energies.

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