Search for Color van der Waals Force in $^{208}Pb+^{208}Pb$ Mott Scattering

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In a high precision experiment, Mott scattering of the ^{208}Pb $+^{208}$Pb system was measured at $E_{\rm lab} = 873.40$ MeV and 1129.74 MeV with kinematic coincidences for angle pairs around $\theta_{\rm lab} = 30°$, 60° and $\theta_{\rm lab} = 45°$, 45°. The observed Mott oscillations exhibit an angular shift with respect to pure Mott scattering. A comparison with the angular shift produced by a color van der Waals force including nuclear polarizability, vacuum polarization, relativistic effects, and electronic screening provides a new upper limit for the strength of this force. Influence of atomic effects other than screening were identified for the first time.

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Precision measurements of sub-Coulomb-barrier scattering have been used successfully in the past to study the influence of vacuum polarization and relativistic effects. These have been clearly observed in the ^{16}O + ^{208}Pb [1] and ^{12}C + ^{12}C [2] elastic scattering and were found to be consistent with standard QED. The use of Mott scattering was found [2,3] to be especially sensitive to detect small effects via the angular shifts in the oscillatory Mott scattering pattern.

The possibility of the existence of long range forces between hadrons has been suggested in the framework of QCD [4–8], though they also have been disputed on theoretical grounds [9]. The exchange of two gluons may give rise to a color van der Waals force of the form

$$V = (\lambda_N/r_0)(r_0/r)^N \hbar c\,, \tag{1}$$

with a length scale $r_0 = 1$ fm and with $N \geq 7$. The limits on λ_N were established from the measurement of the bound state energies of exotic atoms such as kaonic, pionic, and antiprotonic atoms [5,7,8]. They depend strongly on the data analysis. It is thus of interest to develop new methods to extract the magnitude of these coupling strengths and to establish more precise upper limits for them. It thus was recently proposed [10] to determine the strength of the color van der Waals force in a study of Mott scattering of two heavy nuclei in which the expected effects are anticipated to be enhanced and their magnitudes have been calculated.

We report here on a high-precision measurement of the sub-Coulomb-barrier scattering of ^{208}Pb + ^{208}Pb at two energies around 5 MeV/nucleon in which we obtain a new upper limit on the existence of color van der Waals forces. The Mott scattering of ^{208}Pb+^{208}Pb is particularly suited for such an investigation since the Mott interference term gives rise to very rapid oscillations in the angular distributions due to the high Z of the target and projectile. This greatly increases the sensitivity as compared to Mott scattering of low-Z nuclei. Moreover, the large masses involved will lead to an "amplification" of the effects of the possible color van der Waals force. Effects of strong Coulomb fields in the scattering of two heavy nuclei have an additional interest in view of the unresolved problem of the discrete positron lines observed at GSI [11]. More generally, precision data could serve as a stringent test for the known and higher order QED effects.

The interference term of the Mott differential cross section is essentially determined by the term $\cos(2\eta \times \ln\cot\theta/2)$, where $\eta \propto 1/\sqrt{E_{\rm c.m.}}$ is the Sommerfeld parameter ($\eta \sim 480$ for ^{208}Pb+^{208}Pb at 5 MeV/nucleon). Thus the precision needed for measuring these effects, which has been obtained in the present investigation, is of the order of 10^{-4} for the absolute angle and for the absolute beam energy. Deviations of the elastic cross section from Mott scattering due to relativistic effects, nuclear polarizability, electron screening, and vacuum polarization are expected and can be calculated quantitatively [10,12].

The absolute energy was determined by a velocity measurement of the beam. This measurement and a detailed error analysis are discussed in a separate publication [13]. The time of flight (TOF) of the beam bunches was measured between two beam scanners, with the distance between them ($\sim$ 48 m) determined to an accuracy of 1 mm. Two fast BaF_2 scintillators were located close to the beam scanners at an angle of 90° to the beam, in order to detect the γ rays resulting from the Coulomb excitation of the tungsten wires of the scanners by beam particles. The incident energies used in the experiment and their standard deviations were $E_1^{\rm beam} = 873.48 \pm 0.06$ MeV and $E_2^{\rm beam} = 1129.86 \pm 0.09$ MeV, which corresponds to a relative error of 8×10^{-5}.

The target consisted of a 6 μg/cm^2 layer of enriched ^{208}Pb on a carbon backing of 15 μg/cm^2, with the lead

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facing the incident beam. The energy loss in the target was deduced from its thickness, which was monitored during the experiment using the number of counts in the detectors, the integrated charge of the beam, and the Mott cross section. The Pb target thickness corresponded to an energy loss of 0.17 MeV and 0.25 MeV at the lower and higher energies, respectively. Consequently the reaction energies were, respectively, $E_1 = 873.40 \pm 0.07$ MeV and $E_2 = 1129.74 \pm 0.10$ MeV.

The absolute precision in the angle measurement was obtained by making use of the well-known geometrical relation which states that the angle between two lines connecting two points on a circle with a third point on this circle is the same, independent of the position of the third point. It was thus possible to avoid the difficulty of having to control precisely the position, spot size, direction, and divergence of the beam on the target by placing the target, the detectors, and the beam scanner behind the target on a common circle with a diameter of 7 m (Fig. 1). The beam is not focused on the target but instead on the beam scanner. The influence of a homogeneous terrestrial magnetic field cancels nearly perfectly in the determination of the scattering angles.

The scattered particles were detected in four x-y position sensitive drift chambers [14] that were mounted such as to allow kinematic coincidence measurements at $\theta_{\text{lab}} = 30°$, $60°$ and $45°$, $45°$. The angle pair at 45° was

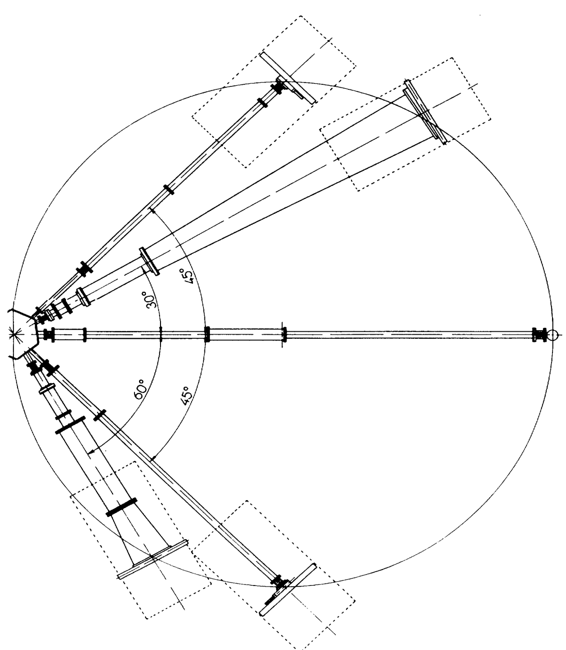

FIG. 1. Schematic drawing of the experimental setup. The beam arrives from the left. The central tube is the beam line with a scanner at its right-hand end. The other four tubes lead to the detectors, mounted on concrete blocks (broken lines). The target is situated on the intersection of the tubes. Target, beam scanner, and detectors are situated on a circle of 7 m diameter.

used to check the absolute angular calibration and the target position, since the identity of the particles implies symmetry of the scattering around $\theta_{\text{c.m.}} = 90°$. The angle pair at 30° and 60° was used to measure the shift of the Mott oscillations. The detectors covered an angular range of 6° and 0.6°, respectively, in the horizontal plane. Their distances from the target were respectively 6, 5, and 3.5 m for the detectors at 30°, 45°, and 60°. The position resolution of the detectors amounted to better than 1 mm.

The determination of the absolute scattering angles to a precision of the order of 0.001° was achieved by precise measurements of the distances to 0.1 mm between all components of the experimental setup using INVAR filaments calibrated at the Saclay laboratory. The angular calibration of the detectors then was made at the beginning of the experiment by use of carefully aligned slotted plates in front of the detectors. The direction and focusing properties of the incident beam were continuously checked by reading out the beam profile of the scanner placed downstream of the target on the common circle discussed above.

The angular straggling of 0.025° FWHM due to the target was determined by comparing the shape of the beam profile on the scanner downstream measured with and without target. The observed distribution is not Gaussian and is well fitted by the formalism of Meyer [15]. It should be noted that the angular straggling does not affect the position of the oscillations but only their magnitude, independent of the analytical form of the distribution.

By measuring kinematic coincidences between the recoiling and the scattered nuclei events from other reactions could be effectively eliminated. A comparison of the laboratory angles between the two lead nuclei measured in coincidence ("folding" angle) and those calculated by relativistic kinematics reveals a systematic difference of several 10^{-2} deg in all cases. A possible origin of these discrepancies could be a displacement of the target in the direction of the beam. A hypothetical target displacement of 3.1 ± 0.3 mm is obtained from the fit of all angle measurements at both energies. The target deformation observed at the end of the measurements was, however, a factor 5 less than this value.

An alternative and more likely origin of the smaller folding angle is the energy loss due to atomic excitations, whereby we refer to the folding angle as the angle in the laboratory frame between the scattered and the recoiling nucleus. The strong excitation of internal atomic energy shells and the emission of energetic electrons are well-known processes in heavy systems [16]. Using the analytical formula that describes the emission probability of electrons and their energy distribution in the case of U + Au scattering [16], we find a mean energy loss of more than 1 MeV due to these inelastic atomic processes. This atomic energy loss results in an effective negative Q value for the scattering process, which leads to a smaller folding angle between the coincident particles, thus explaining the observed effects. The Q values which give the right correction for the angular correlation were found to be ~ 0.850 MeV and ~ 0.950 MeV for the lower and higher energies, respectively, assuming no displacement of the target. The effect of the target displacement or of the atomic excitations on the absolute angular calibrations are shifts of 1.4×10^{-2} deg and 1.7×10^{-2} deg, respectively. Thus correcting the observed laboratory angles by 1.55×10^{-2} deg with an estimated uncertainty of $\pm 2 \times 10^{-3}$ deg will account for these effects, whatever their physical origin.

The measured elastic scattering angular distributions at angles close to 30° and obtained over a restricted angular range are shown in Fig. 2. The rapid oscillations of the differential cross sections are clearly visible. Their periods are about 0.14° and 0.18° at the two energies of 873.40 and 1129.74 MeV, respectively. The measured oscillations are found to be out of phase by almost half a period with those calculated at the correct energies with pure Mott scattering, relativistically transformed into the laboratory frame. The solid curves in Fig. 2 are fits to the data with the overall normalization, the damping of the Mott interference term, and the incident energy taken as free parameters. The damping of the Mott oscillations by factors of 3 and 2.1, respectively, is mainly due to fluctuations of the atomic excitations. The sum of these fluctuations together with the angular straggling and the finite angular resolution provides a quantitative explanation.

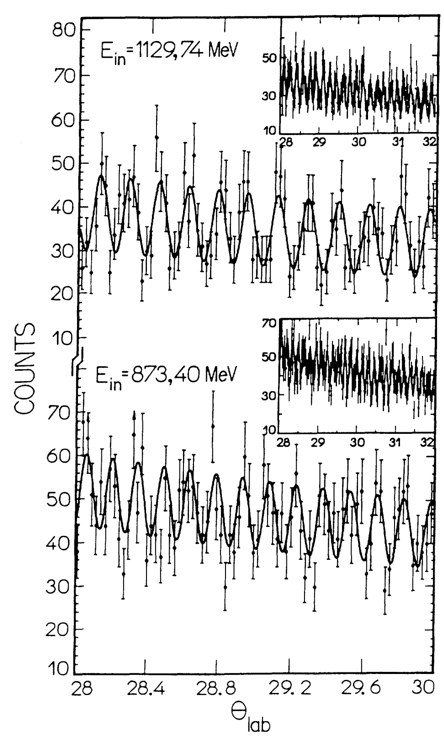

FIG. 2. Mott scattering angular distributions at two bombarding energies. The insets show the total angular domain covered. The solid lines are the best fits to the experimental measurements.

Changing the bombarding energy introduces an angle shift in the oscillatory pattern. To first order angle and energy shifts are equivalent for the effects studied here [17]. The deviation in energy required to fit the data can thus be taken as a measure of the non-Coulombic effects. As a result of the periodic structure of the Mott cross section the χ^2 value of the fit has several minima as a function of the energy. For the higher incident energy these minima of interest are located at the energies of 1116.5, 1144.4, and 1173.2 MeV, with χ^2 values of 1.42, 1.02, and 1.31, respectively, and for the lower incident energy at 861.4, 880.5, and 900.5 MeV with χ^2 values of 1.46, 1.04, and 1.10. Thus for the higher energy there exists only one acceptable solution, 1144.4 MeV. For the lower energy the strongly favored solution by the χ^2 criterium is 880.5 MeV; the other unfavored but not

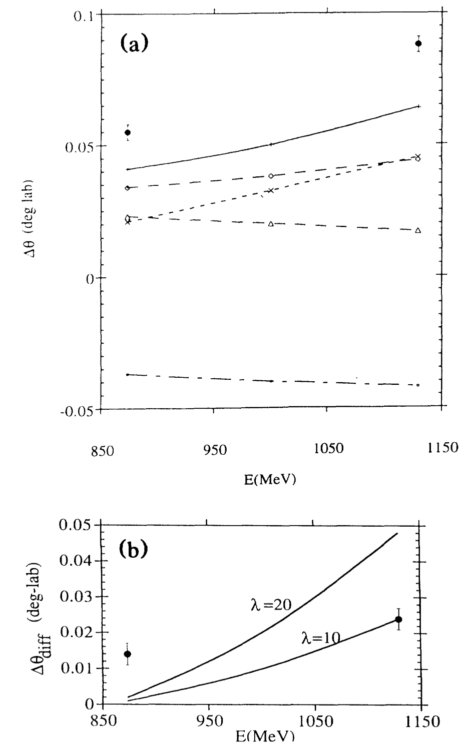

FIG. 3. (a) Comparison of the measured angular shift at the two energies with the theoretical predictions including vacuum polarization (dash-dotted line), nuclear polarizability (short-dashed line with crosses), relativistic effects (long-dashed line), and electronic screening with $^{+}23$ charge (long-dashed line with triangles). The sum of these effects is shown by the solid line. The points with error bars are the result of the present experiment. (b) The full dots represent the differences between the measured angular shifts and the sum of the predicted shifts of (a). The solid curves are the shifts produced by the color van der Waals force with strengths $\lambda_7 = 10$ and 20.

completely excluded solution at 900.5 MeV would correspond to an angular shift of 0.195°, a value completely out of reasonable range as can be seen in Fig. 3(a).

The final effective energies obtained are $E_1^{\rm eff} = 880.5 \pm 0.4$ MeV and $E_2^{\rm eff} = 1144.4 \pm 0.6$ MeV, which correspond to the following energy shifts: $\Delta E_1 = 7.1 \pm 0.4$ MeV and $\Delta E_2 = 14.7 \pm 0.6$ MeV. They are equivalent to angular shifts at $\theta_{\rm lab} = 30°$ of $\Delta\theta(E_1) = (0.055 \pm 0.003)°$ and $\Delta\theta(E_2) = (0.088 \pm 0.003)°$ (we considered positive the angular shift moving away from $\theta_{\rm c.m.} = 90°$). These are compared in Fig. 3(a) with theoretical predictions that include vacuum polarization, relativistic effects, nuclear polarizability of target and projectile, and electronic screening with atomic charge state 23^+. The sum of all the above mentioned effects corresponds to a positive shift in angle, that is, to a displacement to larger angles for $\theta_{\rm c.m.} > 90°$ and to smaller angles for $\theta_{\rm c.m.} < 90°$. The effect of energy on the oscillatory angular distributions of Mott scattering is opposite to the effect on Frauenhofer scattering. Comparing the measured angular shift with the result of the calculations we find that at both energies the sum of the four effects mentioned above is lower [see Fig. 3(a)] than the measured angular shifts. Calculations with the code ECIS [18] with and without a realistic optical potential show that the effects of the nuclear potential are negligible even at the higher energy. The main error comes from the uncertainty in the screening since the angular shifts differ by a factor of 2 for the charge states considered. One should consider the screening for the 23^+ charge state as an upper limit of this effect. For a higher charge state this correction would be lower and thus the difference between experiment and the theoretical prediction would increase.

The effects of a color van der Waals force (CVDWF) have been calculated by folding the expression of Eq. (1) into the nuclear matter distribution of target and projectile. In Fig. 3(b) the differences between the measured angle shifts at 30°, and the sum of the predicted shifts including all effects except for the CVDWF are plotted. The solid curve is the shift produced by the hypothetical CVDWF with the strength $\lambda_7 = 10 \pm 1$ adjusted such as to be consistent with the higher energy data. Previous upper limits obtained with pionic (antiprotonic) atoms range between 23 and 100 and (3 and 19) [5,7,8].

An additional effect that might possibly give rise to deviations from pure Mott scattering is the production of δ electrons during the atomic collision. As discussed above in conjunction with the angle measurements, we had noted that the introduction of an effective negative Q value that takes into account the production of δ electrons was necessary to explain the angle measurement data. The coupling to the δ electron channel and to other atomic effects might well lead to an effective potential similar to that of the nuclear polarizability. These dynamical effects have so far been ignored in the analyses of sub-Coulomb scattering data [1,2,10].

In summary, Mott scattering data of high precision have been obtained for the ^{208}Pb + ^{208}Pb system at two energies. At the lower energy the observed shift of the Mott oscillations is slightly larger than those predicted by taking into account vacuum polarization, nuclear polarizability, relativistic effects, and electron screening. At the higher energy a stronger shift is observed. If the shifts were due to the hypothetical color van der Waals force, this would require for the higher energy a strength of λ_7 =10. However, the energy variation of the shift is not compatible with the van der Waals force, since this strength explains the shift at 1129.74 MeV and greatly underestimates the shift at 873.40 MeV. Our high quality data for the first time show clearly the influence of atomic effects other than screening in this type of experiment and call for a careful theoretical analysis.

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