Proton-Proton Central p-Wave Parameter from 6 to 10 MeV (lab)[a]

P. M. Hegland,[b] Ronald E. Brown, J. S. Lilley, and J. A. Koepke
John H. Williams Laboratory of Nuclear Physics, University of Minnesota, Minneapolis, Minnesota 55455
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We have measured the shape of the $p+p$ cross section at five energies from 6–10 MeV (lab) using solid targets. Our results resolve discrepancies in values of the shape-sensitive central p-wave parameter Δ_c obtained from the gas-target data of other groups. We agree particulary well with data which had suggested difficulties in reconciling both high- and low-energy data with one-boson—exchange models of the nucleon-nucleon interaction.

The study of the $p+p$ interaction to elucidate the fundamental properties of the nucleon-nucleon force has had a long history. This force proves to be exceedingly complex, and it is necessary to obtain precise experimental measurements of nucleon-nucleon scattering over a wide range of energy in order to determine its general phenomenology. Although considerable progress has been made in developing a field theory for the interaction, this goal is far from having been achieved, and it is likely that detailed experimental information will provide an essential guide to theorists for some time to come.

It was in this context that we studied the situation at energies near 10 MeV, where there remain disturbing discrepancies in the experimental data. Discussions of the status of our understanding of the $p+p$ interaction in this low-energy region include the work of Sher, Signell, and Sher,[1] Holdeman, Signell, and Sher,[2] Jarmie *et al.*,[3] Slobodrian,[4] Imai *et al.*,[5] and Naisse.[6] The reported[1,2,5] disagreements in angular shape of the experimental $p+p$ differential cross sections are of particular interest for the present work and appear as discrepancies in the extracted central p-wave parameter Δ_c. An example is a recent[5] comparison of Δ_c values extracted from four different data sets[3,5,7,8] in the 5–10-MeV energy range, which showed little agreement among the sets. We feel that such a situation is intolerable for an interaction of such fundamental importance to nuclear physics. Furthermore, the energy region near 10 MeV is particularly important because,[5] according to field-theoretic ideas, Δ_c in this energy range is sensitive to the competition between the repulsive (p-wave) force due to one-pion exchange, and the attractive force due to correlated (scalar, isoscalar meson) or uncorrelated two-pion exchange.

The emphasis in the present work was to measure accurate angular shapes of the $p+p$ differential cross section. This was accomplished by using solid targets (polystyrene, which contains C and H), good detector geometry, and monitor detectors. The main purpose was to perform an experiment of high accuracy which would not have sources of angle-dependent errors identical to those of the other (gas-target) experiments in this energy region. Our method did not yield an accurate absolute normalization; however, we chose to take measurements at lab energies (known to about 5 keV) of 5.957, 6.968, 8.030, 9.690, and 9.918 MeV at which gas-target data exist,[3,5,7,9] and for the purpose of performing phase-shift analyses, we normalized our results by using the gas-target data at lab angles of 20° and larger.

The experiment was carried out using the proton beam from the Williams Laboratory MP tandem accelerator. The targets were mounted at the center of a precision, sliding-seal scattering chamber[10] at the end of a beam line which had been designed specifically to produce a well-defined beam, stable in position and direction, and with a minimum of slit-edge scattering. An integral part of the scattering chamber is a large, wedge-shaped extension in which the main detector assembly was positioned about 1.14 m from the target. The angular position of the detectors relative to an optically determined beam line was known to ± 0.01°, and angular settings were reproducible to ± 0.0025°. The detector assembly consisted of a cooled stack of two Si surface-barrier detectors of thicknesses appropriate to the incident proton energy. The two amplified signals from these detectors were added, and their sum signal was gated by a signal derived from a 0.5-μsec, threefold coincidence between the signals from each detector separately and the sum signal. A proton resolution of about 20 keV (full width at half-maximum) was obtained. This resolution allowed an accurate determination of the $p + {}^1H$ yield even at very forward angles where the $p + {}^1H$ and $p + {}^{12}C$ peaks can interfere. We were thus able to cover thoroughly the important forward-angle region of nuclear-Coulomb interference.

Since the targets consisted of plastic films, which deteriorate under bombardment, careful monitoring was essential. This was done with two Li-drifted Si detectors mounted out of the scattering plane at equal angles of about 30° left and right of the incident beam direction. The important data from each monitor were the scaled outputs from three single-channel analyzers (SCA), one recording $p + {}^{12}C$ elastic scattering, a second $p + {}^1H$ elastic scattering, and the third being set to measure background in the immediate vicinity of the $p + {}^1H$ peak. The $p + {}^{12}C$ cross section varies rapidly with angle near 30°, and hence, the ratio of the left to right yields for that scattering served as a continual check on beam stability. The background-corrected, left-plus-right sum of the $p + {}^1H$ yields was used to normalize the data obtained with the variable-angle main detector system. Corrections to this sum due to beam instability were negligible, mainly because, at the chosen monitor angles, the $p + {}^1H$ cross section varies slowly with angle.

A total of at least 80 000 counts[11] in the main detector assembly were accumulated at each lab angle. For lab angles of 16° or less, half the counts were collected on the left side of the incident beam and half on the right. At each angle setting, half the counts were measured with the target in one position, normal to the beam, and half with the target rotated through 180°. This procedure essentially eliminated errors due to long-term beam instability or target distortion. At angles greater than 16°, where the $p + p$ differential cross section varies quite slowly with angle, data were taken on one side of the incident beam only. Small corrections (always < 0.07%) were made to these larger-angle data to allow for the fact that the actual beam direction rarely coincided with the optically determined line. We mention here the results of two of the most important tests of the system, both performed at the $\frac{1}{3}$ to $\frac{1}{2}$% level of accuracy: (i) Measurements of 8.030-MeV protons scattering by gold between 6° and 25° (lab) reproduced the expected Rutherford shape. (ii) A careful investigation of multiple-scattering effects was carried out using targets which ranged up to twice the thickness of those used to take the majority of the final data. No effects were observed.

In extracting the final relative cross sections from the data, considerable attention was paid to effects or procedures which could be sources of angle-dependent errors. These included (a) determination of background under the $p + {}^1H$ scattering peak, (b) dead time, both in the analog-to-digital converter and other equipment, (c) absolute angle uncertainty, (d) nuclear reactions in the detectors, (e) reactions from target contaminants, (f) beam-position uncertainties, (g) pulse pile-up, and (h) finite detection geometry. Further details are given elsewhere.[12,13] The minimun lab angle at which the cross section was measured varied from 9° at the lowest energy to 7.5° at the highest. The average relative error in the data is 0.44%, being larger at the more forward angles, but never exceeding 0.9%.

Our data, normalized as mentioned above, and the data of Refs. 3, 5, 7–9, were analyzed with a phase-shift code which included s, p, and d waves. The code uses phase parameters measured with respect to those of a point Coulomb interaction and thus does not treat explicitly higher-order nonnuclear effects, the largest of which is from vacuum polarization.[1,14] We corrected for this to some extent by subtracting the vacuum-polarization phase shifts[1,14] from the extracted phases. The resulting parameters still are not the "true" nuclear parameters (the so-called "electric" parameters[1]), because the truncation of the partial-wave expansion for $l \geq 3$ means that we have not taken into account completely the scattering amplitude for the long-range vacuum-polarization potential. Nevertheless, the procedure is perfectly adequate for our present purpose, which is to use the parameter Δ_c to compare the different data sets rather than to extract absolute Δ_c values.

The central p-wave parameter Δ_c is given by $\Delta_c = \frac{1}{9}(\delta_0 + 3\delta_1 + 5\delta_2)$, where δ_j is the p-wave phase shift of total angular momentum j. The angular shape of the $p+p$ cross section is critical in extracting Δ_c because the nuclear-Coulomb interference term in the scattering amplitude contains Δ_c, whereas Δ_{LS} and Δ_T, the other linear combinations of p-wave phase shifts,[1] do not occur there. The fitting procedure, at each energy, was to allow the s-wave phase shift, the parameter Δ_c, and a normalization factor to vary, but to hold fixed the d-wave phase shift and the parameters Δ_{LS} and Δ_T at the values obtained from the phase shifts of MacGregor, Arndt, and

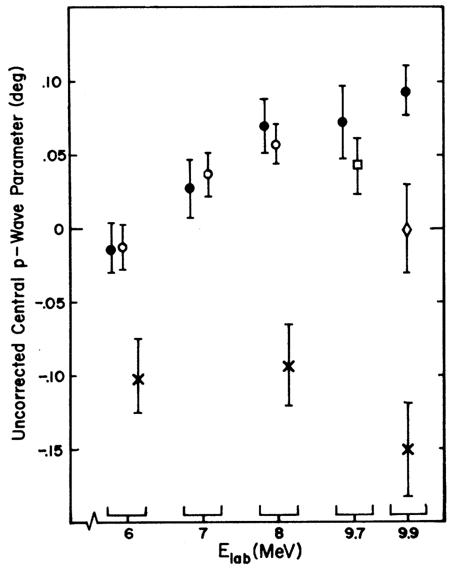

FIG. 1. Proton-proton central p-wave parameter, uncorrected for the truncation error mentioned in the text. The nonstandard laboratory-energy scale was chosen for convenience in display; and for clarity some points that actually occur at the same energy are shown separated. The solid circles show the values obtained from the present data, and the remaining symbols indicate the values which we have extracted from other data. The open circles are data from Refs. 5 and 9, the square is data from Ref. 7, the diamond is data from Ref. 3, and the crosses are data from Ref. 8. All points in the 9.9- and 9.7-MeV brackets are at 9.918 and 9.690 MeV, respectively; in the 8-MeV bracket, the circles are at 8.030 MeV and the cross is at 8.097 MeV; in the 7-MeV bracket, the circles are at 6.968 MeV; and in the 6-MeV bracket, the circles are at 5.957 MeV and the cross is at 6.141 MeV.

Wright.[15] The use of any other reasonable values for these latter three quantities would be expected to affect the absolute Δ_c values, but would not affect our comparison of the relative values of Δ_c.

The results obtained for the central p-wave parameter, uncorrected for the truncation mentioned above, are shown in Fig. 1. It is clear that our measurements firmly support the work of Imai *et al.*,[5,9] are in reasonable agreement with the measurements of Johnston and Young,[7] but disagree with the results of Jarmie *et al.*[3] and Slobodrian *et al.*[8] Thus it is appropriate to call attention to the statement of Ref. 5 that their data (and hence ours) pose problems for one-boson-exchange models of the nucleon-nucleon interaction. Their analysis indicates that, even at an energy as low as 5 MeV, the attractive force from scalar-meson exchange is stronger in the p state than the repulsive force from one-pion exchange, and they mention that this presents difficulties in fitting simultaneously high- and low-energy data with such models. Here we make no attempt to verify such conclusions, which are based on the extraction of absolute phase parameters, but we simply point out the importance of such questions and propose that the present measurements[13] be included in a careful reanalysis of the low-energy $p+p$ data.

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[b]Present address: Department of Physics, University of Pittsburgh, Pittsburgh, Penn. 15260.

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Proton Orbital $\frac{1}{2}^-$[521] and the Stability of Superheavy Elements[(a)]

I. Ahmad, A. M. Friedman, R. R. Chasman, and S. W. Yates[(b)]
Chemistry Division, Argonne National Laboratory, Argonne, Illinois 60439
(Received 24 March 1977)

We present experimental evidence for the identification of the deformed proton orbital $\frac{1}{2}^-$[521] in ^{251}Es and ^{247}Bk. The implications of this finding with respect to the stability of superheavy elements in the vicinity of $Z \approx 114$ are discussed.

In this Letter, we report on the experimental observation of the proton orbital $\frac{1}{2}^-$[521] and discuss the stability of superheavy elements in the light of this observation.

The proton orbital $\frac{1}{2}^-$[521] has been tentatively assigned in ^{249}Bk by Hoff.[1] In this nucleus, however, the observed decoupling parameter for the rotational band built on this orbital is ~0.0. This is in sharp disagreement with the value of ~1.0 expected[2] for the pure single-particle state. We believe that we have found this orbital in ^{251}Es and ^{247}Bk, where it is much purer than it is in ^{249}Bk. In ^{251}Es and ^{247}Bk, both the decoupling parameter and the signature observed in reaction spectroscopic studies are in good qualitative agreement with the values expected for the pure single-particle state.

The level structure of ^{251}Es has recently been investigated[3] by measuring the γ-ray and conversion-electron spectra arising from the electron-capture decay of ^{251}Fm (5.3 h). On the basis of the derived multipolarities and logft values the following proton single-particle assignments were made: $\frac{3}{2}^-$[521], 0 keV; $\frac{7}{2}^+$[633], 8.3 keV; $\frac{7}{2}^-$[514], 461.4 keV; and $\frac{9}{2}^+$[624], 777.9 keV. The ^{251}Es ground-state band is not populated directly in the electron-capture process. As $\Omega = \frac{9}{2}^-$ for the ground state of ^{251}Fm, rotational bands having $\Omega \leq \frac{5}{2}$ are not expected to be populated in ^{251}Es. The level at 461.4 keV is also populated by the favored α transition of ^{255}Md (27 min), which confirms the single-particle nature of this state. We have recently studied the reaction ^{250}Cf$(\alpha,t)^{251}$Es with 28.0-MeV α particles from the Argonne National Laboratory tandem Van de Graaff accelerator. The spectrum of outgoing tritons produced in this reaction was measured with an Enge split-pole magnetic spectrograph and is shown in Fig. 1. The three prominent peaks at 411, 452, and 548 keV are associated with an orbital or orbitals not populated in the electron capture and therefore have $\Omega \leq \frac{5}{2}$. Based on single-particle–model calculations,[2] the only logical assignment in this energy range is the proton orbital $\frac{1}{2}^-$[521]. This orbital is calculated to have large values of C_j^2 for $j = \frac{1}{2}, \frac{5}{2}, \frac{7}{2}$, and $\frac{9}{2}$ and a decoupling parameter of ~1.0. Assigning the 411-, 452-, and 548-keV levels as the $\frac{1}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$ members of the $\frac{1}{2}^-$[521] rotational band gives a rotational constant of 6.8 ± 0.3 keV and a decoupling parameter of $+1.0 \pm 0.1$ for this band, in excellent agreement with the expected values for the single-particle state $\frac{1}{2}^-$[521].

We have also studied the levels of ^{247}Bk as observed in ^{247}Cf electron capture and in the reaction ^{246}Cm$(\alpha,t)^{247}$Bk. In the electron-capture study, the following proton single-particle states were assigned[4]: $\frac{3}{2}^-$[521], 0 keV; $\frac{7}{2}^+$[633], 40.8 keV; $\frac{5}{2}^+$[642], 334.9 keV; and $\frac{5}{2}^-$[523], 447.8 keV. The spectrum of tritons produced in the reaction ^{246}Cm$(\alpha,t)^{247}$Bk is shown in Fig. 2. We assign the levels at 704, 743, 815, and 828 keV as the $\frac{1}{2}$, $\frac{5}{2}$, $\frac{7}{2}$, and $\frac{9}{2}$ members of the $\frac{1}{2}^-$[521] rotational band.

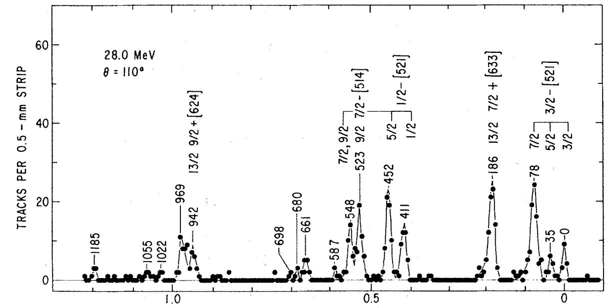

FIG. 1. The triton spectrum from the reaction ^{250}Cf$(\alpha,t)^{251}$Es.