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PROTON-PROTON SCATTERING BETWEEN 4.2 AND 10 MeV AND THE $^1S_0$ SHAPE DEPENDENT SCATTERING PARAMETERS

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ABSTRACT

Proton-proton scattering angular distributions have been measured at 6.141, 8.097, and 9.981 MeV laboratory energy, in an experiment designed to achieve an absolute accuracy better than 1%. A phase shift analysis has produced preliminary values for the $^1S_0$ phase shifts, as well as split P and $^1D_0$ phase shifts. With this new information it is possible to reach substantially less ambiguous conclusions concerning the shape dependent parameters P and Q than was possible up to date.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

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Low energy proton-proton scattering has been the object of very accurate experimental investigation, and of refined and sophisticated theoretical analyses in recent years.[1] Particularly fruitful was the research carried out at Wisconsin, where the energy range between 1.397 MeV and 4.203 MeV (laboratory system) was covered by two separate experimental groups.[2,3] An accurate value of the $^1S_0$ phase shift was obtained recently at 0.3825 MeV through measurements of the interference minimum.[4] The $^1S_0$ phase shift at 0.3825 MeV has been used in conjunction with the KMBND data in order to attempt a determination of the shape parameter P,[5] in the expansion $C^2 k \cot \delta_0 + \frac{1}{R} h(\eta) = -\frac{1}{a_p} + \frac{1}{2} r_e k^2 - P r_e^3 k^4 + Q r_e^5 k^6 + \ldots$, where the symbols have the usual meaning. Several objections were raised concerning the certainty of the determination of P.[6,7,8] Gursky and Heller[7] reported an attempt to produce a four parameter fit, that resulted in unreasonable values for the shape dependent parameters P and Q.[9] Additional difficulties arise due to the uncertainty of the accuracy of the vacuum polarization correction[10] for S waves, since this correction dominates the curvature of the low energy limit of the expression.

It can be shown[11] that the WMF data reduce the ambiguities quite considerably, notwithstanding the reservations voiced by KMBND[3] concerning some systematic errors contained in the data and the shortcomings of early analyses

of them. Between 4.203 MeV and 10 MeV there is an additional accurate experiment at 9.69 MeV,[12] consistent with the trend indicated by the WMF data, but inconsistent with a set of data that will be called OC[1] (old cyclotron data), that range from 4.2 MeV to 8 MeV. Such OC data are inaccurate for the purpose of a determination of shape dependent parameters, but their trend could be interpreted as consistent with the KMBND data at 1.855, 2.425, and 3.037 MeV.

The present experiment and analysis was undertaken with the hope of providing clues to determine the shape parameters of the p-p interaction. It is well known that this point is relevant to the choice of a suitable shape of the potential in a Hamiltonian formulation of the interaction, or of a model in general. Clearly, the phase shifts themselves are sufficient for such purposes. Nevertheless, the parameterization provided by the expansion of $k \cot \delta_0$ is particularly suitable in order to visualize the degree of relevance of the information between 4.2 and 10 MeV, and also because predictions of P[1,13] and Q[1,14] are readily available in the literature.

The Berkeley 88-inch spiral ridge cyclotron was used to produce a beam of 6.141, 8.097, and 9.981 MeV at the center of the target, which consisted of 99.99% pure H_2 at about 0.1, 0.075, and 0.05 atmospheres, contained in a 20 inch scattering chamber. The pressure was measured to ±0.1% accuracy with a silicon oil manometer. The temperature was measured to ±0.1°K, and the total variation throughout the experiment was within ±0.25°K. The beam was accelerated as H_2^+ ions and conveyed through an analyzing magnet and quadrupole magnet lenses onto the scattering chamber. The beam was defined by Ni slits and carbon antiscatter baffles. The charge collection was accomplished with a Faraday cup and an integrating electrometer, accurate to

±0.1%. Calibrations of the integrating system were performed at regular intervals during the experiment. The beam direction was aligned to better than 2.5 minutes of arc. The beam energy was determined through its range in aluminum, and converted using Bichsel's experimental ranges[15]; such energy determination should therefore be accurate to about 0.1%. The detection of the scattered protons was accomplished with two lithium-drifted silicon detectors, one on either side of the beam. The positioning was accurate to 1 minute of arc. The gas geometry factor was approximately 6.7×10^{-6} cm-sr. Counting statistics were kept in the range of 0.3%. Dead time losses were kept below 1% and corrected by means of fast scalers. The spectra were stored in two RIDL 400 channel analyzers. Two monitor detectors were also used, one at 8° and the other at 25°, off the azimuthal plane. Their spectra were routed to a Nuclear Data 4096 channel PHA, into separate quadrants. Coincidences (prompt and delayed), between both detectors on the azimuthal plane were also recorded to obtain an indication of inelastic events. The net difference between real and accidental coincidences sets a limit on inelastic events at about 0.1% of the elastic cross sections. The background subtraction on the spectra is in the order of 1%. The peak due to impurities is separated from the proton-hydrogen peak at angles larger than 7°. The absolute error of the cross sections is 0.5%, resulting from the above mentioned sources, as well as from the geometrical factor.

A phase shift analysis was accomplished using a CDC 6600 computer and a version of the program developed by D. J. Knecht[16] for the analyses of the KMBND data. Table I contains the results which should be considered preliminary because some more exhaustive searches will be undertaken in the future. In

view of the searches already performed no drastic changes are anticipated. The limit of error of the $^1S_0$ phase shift can be set at 0.2°.

A discussion of the scattering parameters that can be obtained from the experimental phase shifts, without and with extended electromagnetic structure corrections,[17] is beyond the scope of this paper. Nevertheless Fig. 1 presents a plot of the nonlinear part of the expansion $K = \sum_{i=0}^{n} A_i E^i$, where E is the laboratory energy. The nonlinear part is obtained as $\Delta K = K_{exp} - (A_0 + A_1 E)$. The function K_{exp} is calculated from the experimental phase shifts, and is corrected for vacuum polarization effects[10]; A_0 and A_1 were obtained through a least squares fit effected on the WMF, KMBND and our data, without performing extended electromagnetic structure corrections. The resulting shape dependent parameters are P = 0.102 and Q = 0.014. If Q is set equal to zero one obtains P = 0.072. Such values may not be inconsistent with a Yukawa well. The above mentioned values are also to be understood as preliminary. Further refinements will still be made on the calculation of uncertainties of the experimental data and of the function K. Here again no important changes are anticipated.

Figure 1 illustrates the dramatic improvement over the old cyclotron data accomplished by the 88-inch variable energy cyclotron and its instrumentation.

There is an apparent discrepancy, beyond experimental error, with the phase shift obtained from the Minnesota data[11] by MacGregor (also reproduced by a calculation performed here with the CDC 6600 computer). It will require further clarification, although no relevant changes can be foreseen, as it is demonstrated in Fig. 1. It is also pertinent to note that an earlier experiment at 9.73 MeV agrees well with our data.[18]

Summarizing, it is reasonable to expect that the shape dependent parameters will be restricted to a much narrower range of values. Clearly, the nonlinear terms of the k cot δ_0 expansion contribute heavily between 4 and 10 MeV, and thus the ultimate accuracy of the Wisconsin experiments is not necessary in this energy range in order to settle the problem.

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*Work performed under the auspices of the U. S. Atomic Energy Commission.

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Table I. Values of the S, P, and D phase shifts, resulting from the analysis of the experimental data.

E_{LAB} (MeV)	Phase shifts (degrees)				
	$^1S_0$	$^3P_0$	$^3P_1$	$^3P_2$	$^1D_0$
6.141	55.89	0.78	-2.22	-1.02	-1.15
8.097	57.27	2.39	-1.81	-0.13	-0.17
9.981	56.57	3.09	-2.18	-0.07	-0.15

FIGURE CAPTION

Fig. 1. Plot of $\Delta K = K_{exp} - (A_0 + A_1 E)$ as a function of laboratory energy. The solid dots are the Wisconsin data.[2,3] The open triangle is the Minnesota datum.[12] The solid triangles are the OC data contained in ref. 1. The inverted solid triangle is the interference minimum datum.[4] The open circles correspond to the work reported here.

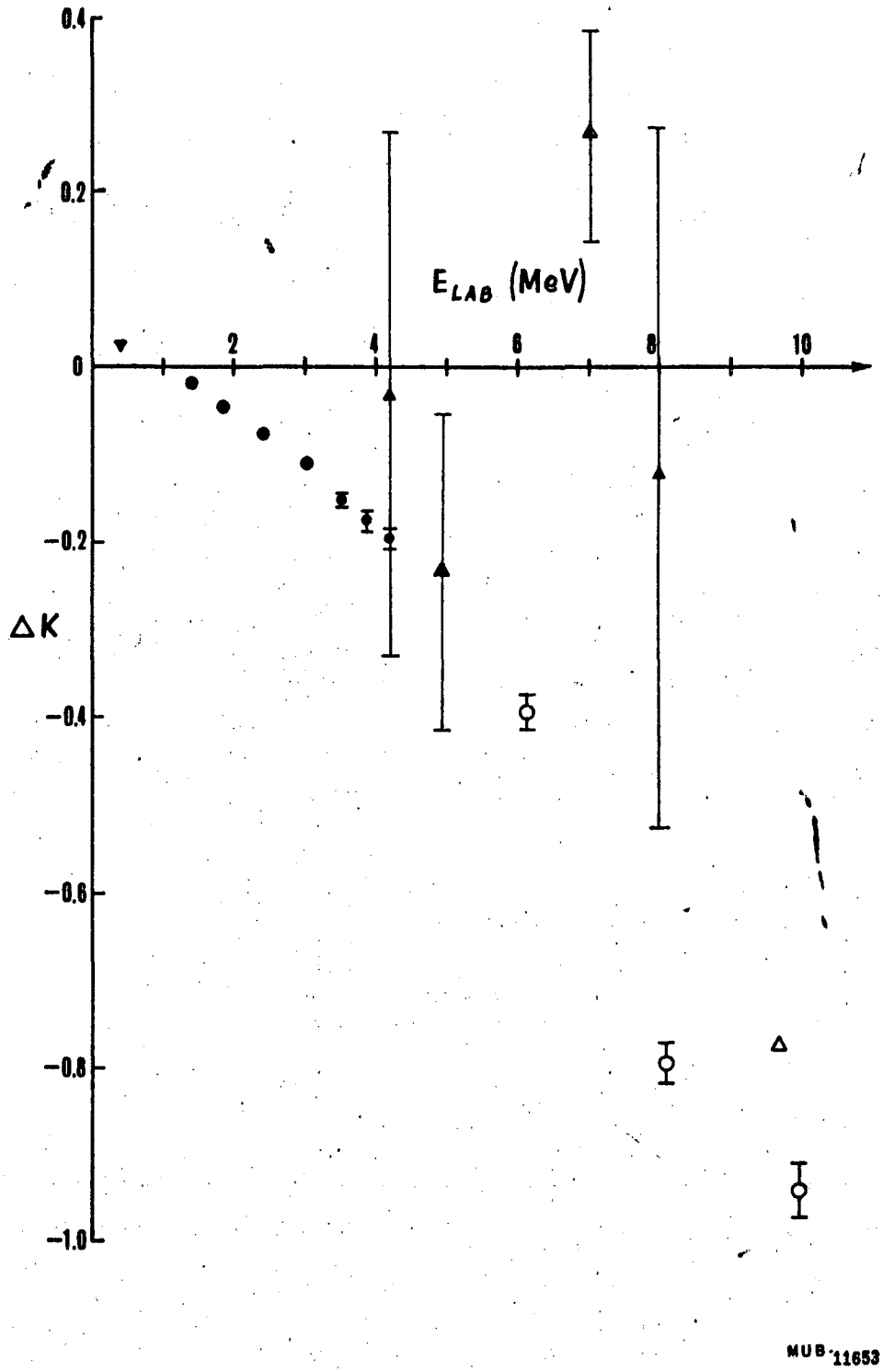

Fig. 1

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