TABLE I. Formation of gallium-65.

Reaction	Bombarding energy Mev	15-min Ga^{65} σ (mb)	$\left[\frac{\sigma(8\text{-min } Ga^{65})}{\sigma(15\text{-min } Ga^{65})}\right]$
$Cu^{63}(\alpha,2n)$	40.3–22.2	See Fig. 1	<0.10
$Zn^{64}(\alpha,p2n)$	39.2–27.1	See Fig. 1	<0.10
$Zn^{64}(d,n)+Zn^{66}(d,3n)$	20.4	40	<0.15
$Zn^{64}(d,n)$	10.6	149	<0.10
$Zn^{64}(p,\gamma)$	9.9	4	<0.25
$Zn^{64}(p,\gamma)$	4.8	7.0	<0.10
Ge^{65} decay	...	...	Branching to 8-min Ga^{65} <0.08

that of 15-minute Ga^{65}, assuming that the former decays mainly by positron emission, as reported by Crasemann. In those cases where the yield of 2.5-minute Ga^{64} is substantial, the upper limit is somewhat higher. In view of the fact that the reported 8-minute activity[4] was previously found to have a higher yield than 15-minute Ga^{65}, it is felt that the upper limits determined in the present work disprove the existence of an 8-minute isomer of Ga^{65}.

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Proton-Proton Scattering at 19.8 Mev*

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An experimental measurement of the angular distribution of the scattering of 19.8-Mev protons by protons is described. The scattering material was hydrogen gas and detection was by scintillation counters. The cross section as a function of center-of-mass scattering angle reveals a minimum at 26° where $d\sigma/d\omega=22.6\pm0.3$ mb/steradian. The measurements range from 14° where $d\sigma/d\omega=59.7\pm2.0$ mb/steradian to 90° where $d\sigma/d\omega=24.6\pm0.3$ mb/steradian and include measurements at 15 angles. The phase-shift analysis of the data is as yet incomplete.

THE experimental work summarized in this paper consisted of a preliminary experiment, and a final experiment performed with quite different apparatus, slit widths, etc. The results of both experiments are included in this paper although the description is confined to the final version. A preliminary report on the latter has been given previously.[1]

Previous work on proton-proton scattering near 20 Mev has been reported by Yntema and White.[2] Their results were obtained at 18 Mev with good accuracy, but they were able to extend their measurements only down to scattering angles of 30° in the center-of-mass system. The present experiment was designed to permit measurements at sufficiently low scattering angles so that the complete interference minimum in the scattering cross section could be observed. It was believed that this region of the scattering cross section *vs* angle curve would be particularly useful in discriminating against various alternative sets of phase shifts. This experiment was also complementary to that of Yntema and White in the sense that a gaseous hydrogen target was used here instead of the solid target (and coincidence counting) used by them.

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[1] Burkig, Schrank, and Richardson, Phys. Rev. **100**, 1805(A) (1955).
[2] J. L. Yntema and M. G. White, Phys. Rev. **95**, 1226 (1954).

THE COLLIMATOR

The deflected beam from the 41-in. UCLA FM cyclotron was brought into the scattering chamber through a collimator giving a beam divergence of 20 min of arc. The main collimation holes were 0.220 in. in diameter and spaced 42 in. apart. Additional larger holes were used as antiscattering baffles. The criteria to be met by the antiscattering baffles were as follows:

(1) The first collimating hole was to see no portion of the wall of the collimating tube except that between it and the first antiscattering baffle. This governed the position of two antiscattering baffles between the collimating holes and minimized effects of scattering from the walls of the collimator tube.

(2) The final antiscattering hole was located after the final collimating hole. Its location and size were governed by the following requirements: (a) It must be large enough to clear the main beam after the normal divergence (20′ from parallel) and multiple scattering in the gas are accounted for. (b) It must be small enough so that the first slit of the analyzer in the detection system sees no edges of the final collimating hole at the minimum angle at which measurements are to be made. This is an important requirement in

preventing unwanted particles from reaching the detector. Initially the final antiscattering baffle was designed on the basis that no straight-line path was to exist from the rim of the baffle through the analyzer. This resulted in the first analyzer slit "seeing" the edges of the final collimating hole and large numbers of particles of reduced energy were observed. When the previously mentioned criterion was adopted instead, this difficulty was overcome.

All collimating and antiscattering apertures were made of brass of sufficient thickness to stop the beam and were backed with graphite to minimize the production of secondary neutrons by protons impinging on those surfaces.

SCATTERING CHAMBER AND ACCESSORY EQUIPMENT

The scattering chamber was a heavy aluminum casting 30 in. in diameter and 4 in. deep. Holes existed in the sides of the chamber for beam entrance and exit, pumping, filling, and pressure measurement. The chamber was evacuated to an ultimate vacuum of about 5×10^{-5} mm of mercury. A thin Mylar window at the collimator entrance and a 2-mil Dural window at the exit permitted the proton beam to pass through the chamber while preventing escape of the target gas. A port for mounting a monitor counter was provided in the lid of the chamber. A Faraday cup of $1\frac{1}{2}$-in. diam was attached to the chamber at the exit and evacuated separately. A magnetic field of several hundred gauss was provided at the entrance to the cup to prevent the entrance or escape of secondary electrons.

The gas-filling system consisted of copper tubing and needle valves connected to a gas bottle through a silica gel drying tube and a DeOxo catalytic hydrogen purifier. An accurate aneroid barometer and a differential manometer were used in conjunction to measure the gas pressure. The chamber was also provided with a mercury manometer with a layer of diffusion pump oil over the exposed mercury surface. The latter was used in making counting rate *versus* pressure measurements. Temperature measurements were made with a mercury-in-glass thermometer which entered the chamber through a vacuum seal.

The analyzer structure was mounted on a movable arm which permitted the analyzer to be set to detect particles at any desired angle. The analyzer consisted of a pair of steel slits of equal width (about 0.10 inch) spaced to give an angular resolution of about 2°. (See Table I.) Shields were placed around the slits to prevent particles which did not go through both slits from entering the detector. The arm to which the analyzer was attached could be rotated from outside the chamber and its position determined from an accurately graduated circle attached to the shaft.

The detector was a DuMont 6292 photomultiplier tube with a thallium-activated sodium iodide crystal of

TABLE I. Slit geometry and other data.

Width of front slit	0.1018 inch
Width of rear slit	0.1030 inch
Height of rear slit	0.598 inch
Center to rear slit	8.96 inches
Distance between slits	4.51 inches
Diameter of beam at center	0.266 inch (divergence 12 mils/inch)
Initial pressure	1006 mb
Initial temperature	297.0°K
"Unit charge" corresponds to	5.867×10^{10} incident protons
Purity of gas according to Consolidated Engineering mass spectroscopic analysis: H_2: 100.00%.	

sufficient thickness to stop the scattered protons. An additional detector, using a plastic scintillator, was mounted on the lid and was used as a beam monitor. It was calibrated and used for beam integration at the lowest scattering angles where the analyzer structure interfered with the entrance of the beam into the Faraday cup.

The current collected by the Faraday cup was fed into an accurately calibrated integrator[3] which in turn fed into a Brown self-balancing potentiometer. Near the top of the scale the potentiometer automatically closed a microswitch which discharged the collecting capacitor and returned the integrator output to zero. Such a charge was taken for reasons of convenience as the unit of charge used in this paper.

The scattering chamber was aligned by the usual photographic centering methods with an accuracy estimated at ±0.005 inch and this was confirmed by the experimental results.

EXPERIMENTAL PROCEDURE

The chamber was flushed with hydrogen gas, pumped out again, and the silica gel drying agent baked until the ultimate vacuum was the same as with no drying agent present. The chamber was then refilled until the chamber pressure slightly exceeded the atmospheric pressure. Periodic pressure and temperature checks were made throughout the run.

The amplifier gains and photomultiplier voltages were adjusted to give a pulse of about 50 volts for the elastic scattering peak. At this setting the response of the amplifier is still reasonably linear. With the particular differential discriminator "window" used, the over-all resolution was about 5.7%; subtracting off the effect of finite "window" width gives about 4.5% for the crystal alone. Of more importance to the over-all accuracy of the experiment is the fact that a very small number of counts were always obtained at energies well below the beam energy. It was thus not possible to set discriminator biases in such a way as to assign a completely clear-cut lower limit to the elastic peak. This leads to some uncertainty in the absolute values of the measured cross sections and this is

[3] H. N. Royden and D. O. Caldwell, Rev. Sci. Instr. **27**, 91 (1956).

included in our final error estimates. Early troubles of this kind were traced to faulty collimator design, but when this had been corrected a small amount of the effect persisted. Such effects were observed at all angles up to 45° in the laboratory system and were absent with no gas in the chamber; they cannot therefore be attributed to protons entering the analyzer by scattering from other structures in the chamber. The amount of low-energy beam expected from collimator edge penetration is much smaller than what is observed here. There is some evidence of a small amount of low-energy component in the analyzed cyclotron beam, and the difficulties may therefore be associated with the cyclotron rather than the scattering chamber. This trouble was not completely overcome, and it forces the adoption of cutoff procedures which raise the upper limit of error.

After the sensitivity of the system had been set to give pulses of approximately 50 volts amplitude, the bias of the discriminator was set so that, as far as possible, all counts from the scattering peak went into the "elastic" output. (The "elastic" counts are all counts above the "window" of the discriminator.) The channel was set some distance below the elastic peak and as near to the minimum of the "counting rate *versus* pulse height" curve as possible. This is taken as the cutoff on the low-energy side of the elastic peak. The channel count serves to measure the imperfection of this cutoff and also serves to call attention to shifts in the over-all gain of the system, especially those which would cause more counts from the elastic peak to fall into the "channel."

Counting at various angles then proceeded, with a record being made of the outputs of both scalers at intervals of 5 charge units, which occurred approximately every 10 minutes. This permitted detection of malfunctions early and indicated whether troubles were making data unreliable. The monitor counter outputs were also recorded, and a graphical record of the integrator output was kept. The consistency of these two acted as a check on the integrating system and was also useful in calibrating the monitor as an indicator of total particle flux at low scattering angles where the analyzer structure prevented some of the beam from entering the Faraday cup.

Measurements were made on both sides of the "zero" angle for all angles considered. The averaging process accomplished by this tends to cancel out the first order effects of lack of symmetry of adjustment. The earliest such measurements were made in order to set the index on the angle-measuring disk to such a point that equal counting rates were measured for equal angular setting on either side of the zero. At small scattering angles the symmetry of counting rates is very sensitive, and the experimental results indicate that symmetry was achieved to within two minutes of arc.

TABLE II. Correction *vs* c.m. angle.

7°	1.9%	11°	0%	20°	−0.2%
8°	0%	12°	0%	30°	−0.3%
9°	0.95%	13°	−0.54%	45°	2.0%
10°	−0.3%	15°	−0.3%		

In this way data were accumulated to the extent of approximately 10 000 counts at symmetrical pairs of angles at 7, 8, 9, 10, 11, 12, 13, 15, 20, 30, and 45 degrees in the laboratory system of coordinates.

The beam energy was measured by a stacked aluminum foil method. A one-fourth mil Mylar film was placed in the center of the scattering chamber and the analyzer set at some convenient angle. With no additional stopping foils in front of the Faraday cup, the counting rate at the analyzer was calibrated against the integrating circuit. Stopping foils were then placed in front of the Faraday cup, and the charge collected by the cup was compared to the total charge as indicated by the counter. From this the percent transmission is readily found; the energy is obtained from the mean range by using the modified range-energy curves for aluminum.[4]

TABLE III. Differential cross section in the center-of-mass system for *p-p* scattering at 19.8 Mev (lab) (with standard error).

Center-of-mass angle	$d\sigma/d\omega$ (mb/sterad)	Center-of-mass angle	$d\sigma/d\omega$ (mb/sterad)
14°	59.7±2.0	36°	23.7±0.25
16°	38.1±0.6	40°	23.7±0.3
18°	29.8±0.5	50°	24.8±0.6
20°	26.1±0.4	60°	24.0±0.3
22°	24.3±0.4	70°	24.7±0.4
24°	23.4±0.3	80°	24.4±0.6
26°	22.6±0.3	90°	24.6±0.3
30°	23.6±0.25		

ERROR CONSIDERATIONS

At each angle, counting was interrupted at 5 charge unit intervals and the counts were recorded. This permitted the calculation of standard deviations and standard errors for a number of samples at each angle. These calculations indicated that the observed fluctuations lay well within two standard deviations. Runs of counting rate *versus* pressure were made. Within the statistical errors, no departure from linearity was noted, indicating that no significant beam loss resulted from gas scattering. This is also in accordance with the multiple-scattering calculations. The pressure-temperature data for various times during the run were consistent to 0.3% and showed no trend. This indicates that there was no change in gas composition or loss of target gas during the course of the run. Other evidence supports this.

As mentioned earlier, a number of counts always fell into the region well below the elastic peak, thereby making impossible the assignment of a completely definite lower limit to the counting. The "channel" counts were always made to fall in this region, with an

[4] D. O. Caldwell, Phys. Rev. **100**, 291 (1955).

attempt to keep the setting at about the same region of the curve for all data. Because of equipment drift and the shift of the peak with angle, and because a lack of equipment prevented continuous monitoring of the whole curve, this ideal was not always met, and there was some variation in the percentages of the total count which fell into the channel for different pieces of data. It is necessary to make some kind of correction to take account of this fact. Approximately 0.6% of the counts in the peak fall within any window of 10% pulse height opening in the lowest part of the curve, and the curve rises steeply enough so that if the channel is set just below the peak, a shift of 2% in the gain or bias could put 2% of the counts into the channel.

In general, the adjustment was such that about 1% of the counts fell in the channel, although on several occasions 2 or 3% were found there. Occasionally the number would fall to $\frac{1}{2}$%. The correction procedure finally adopted was as follows:

(1) It was decided that 1% in the channel would be adopted as a standard, and that these counts would not be included as part of the scattering peak.

(2) If more than 1% appeared in the channel the difference would be added to the total count. This should be a fairly good correction, because the rise is abrupt and the error occasioned by not trying to account for the shift in a more refined manner amounts to a few tenths of a percent. For example, a shift which would put 5% of the counts into the channel would, upon making the mentioned correction, give a result approximately $\frac{1}{2}$% low. The channel counts were much less than 5%, and the corrections hence correspondingly better.

(3) If less than 1% were present in the channel, the difference was subtracted from the total. This is not as good a correction as the first, but will always give errors of less than $\frac{1}{2}$%.

The net effect of these corrections was to change the yield at various angles as shown in Table II.

The counts below the elastic peak are attributed to low-energy particles from the cyclotron. A careful measurement by Dr. H. Howe of this laboratory indicates that $\frac{1}{2}$% of the particles are of energy below the main peak, although no reliable energy distribution was obtained. The effects of this small low-energy component are included in the final error estimates. They are based on an examination of the counting rate *versus* bias curve, the observed shifts in gain during the experiment, and the average number of counts appearing in the channel.

Geometrical corrections can be made to the counting yield to compensate for finite angular resolution of the analyzer slit system. These corrections are appreciable only for the smallest angle (14°) where they reduce the yield by 4.8%. The relation used was that developed by Critchfield.[5]

[5] C. L. Critchfield (private communication).

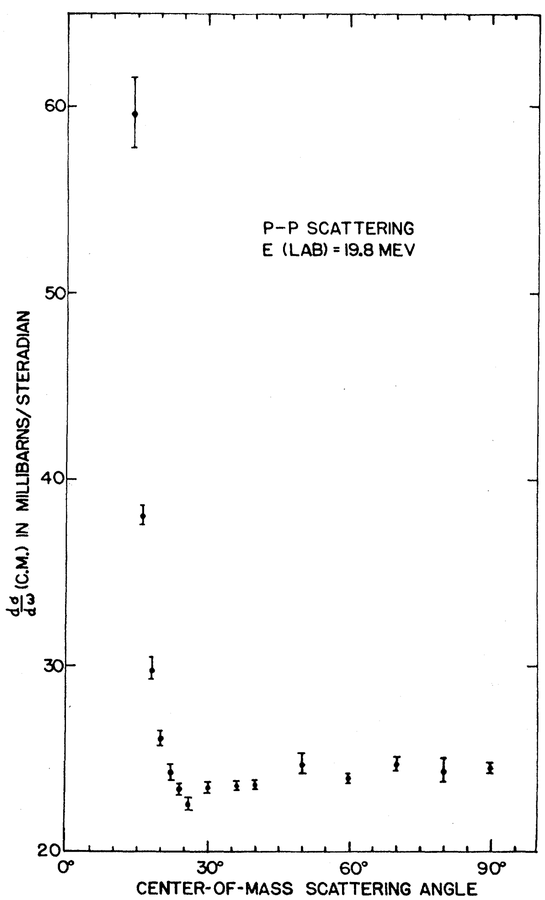

FIG. 1. The differential elastic scattering cross section of protons by protons in the center-of-mass system, where the incident proton energy is 19.8 Mev in the laboratory system. Note the displaced ordinate axis.

For several of the smaller angles data were taken at various periods throughout the run. This should give an indication of the over-all stability of the system. If results compare within expected statistical fluctuations, one may have some confidence that angles can be reset accurately, that drift is not appreciable, and that contamination does not change with time. The results obtained indicated that these conditions held in this experiment.

RESULTS

The combined experimental results are given in Table III, which shows the differential cross section with standard error for various center-of-mass scattering angles. These results are also plotted in Fig. 1. It is seen that the cross-section minimum is indeed well displayed. M. H. MacGregor of UCRL, Livermore is making a phase-shift analysis using these data and including interactions in the $^1S_0$, $^3P_0$, $^3P_1$, $^3P_2$, and $^1D_2$ states.