PHYSICAL REVIEW VOLUME 103, NUMBER 1 JULY 1, 1956

Interaction of 10-Mev Protons with Beryllium*

STANLEY W. RASMUSSEN†
University of Minnesota, Minneapolis, Minnesota
(Received March 30, 1956)

Differential elastic and inelastic scattering cross sections were measured for 10-Mev protons on beryllium, using a nuclear-emulsion technique. The Minnesota linear proton accelerator was used to provide a well-collimated monoenergetic beam. The results for elastic scattering are compared with other experiments, on the basis of a simple optical model, showing that, although the variation of elastic scattering cross section with angle is similar to that of other light elements, there are quantitative differences. The results on inelastic scattering are shown to be consistent with the currently accepted odd parity, $J=\frac{3}{2}$ or 5/2, for the 2.4-Mev state of Be^9. It appears, however, that a complex model of the Be^9 nucleus will be required to explain the results in detail. The (p,d) reaction cross section for Be^9 is also mentioned briefly.

INTRODUCTION

THE interaction of 10-Mev protons with various light elements has recently been studied by several investigators.[1–4] An optical model has been used to interpret the elastic scattering process, although the model does not reproduce all the details actually observed.[5,6] Inelastic scattering cross sections have also been measured as a function of angle for several light elements.[1–4] Although no theory has been developed specifically to explain the results on inelastic scattering, attempts have been made to interpret the observations in terms of a theory developed by Austern, Butler, and McManus[7] for (p,n) reactions.

An investigation of the reactions of Be^9 with 10-Mev protons should furnish a test of both theories in some detail. One would not expect the optical model to be accurate for beryllium, because one neutron is loosely bound so that the concept of a definite nuclear surface is probably not so meaningful as it would be for a nucleus such as C^{12}, where the nucleons are more nearly equivalent and more tightly bound. It should nevertheless be of some interest to see how the experimental data compare with predictions.

The results on inelastic scattering may also be compared with theoretical predictions. Several theoretical models are available,[7–9] each of which may perhaps be inadequate in detail. The simplest assumption is that there is a nuclear core which remains in essentially the same state, whether the nucleus as a whole is in its ground state or in some excited state. But a "core" consisting essentially of two alpha particles might be strongly influenced by the state of motion of one external neutron, and the alpha-particle model suggests that it actually is strongly influenced.[9] In spite of this, the theoretical predictions might still be qualitatively correct, so a comparison with experiment seems desirable.

EQUIPMENT AND PROCEDURE

The first section of the Minnesota Linear Proton Accelerator furnished 10-Mev protons. The output beam was characterized by determining a range spectrum in C-2 emulsion for the elastically scattered protons from the Be target itself. Using Rotblat's range-energy curve[10] for emulsion, the mean beam energy was determined to be 9.9±0.1 Mev. This agrees with the 9.89-Mev energy estimated theoretically from accelerator parameters.

Besides the primary group of 10-Mev protons, the output of the accelerator contains a small low-energy group, resulting from the acceleration of molecular hydrogen ions. Conditions are not favorable for accelerating these ions, but some do come out with a velocity half that of the high-energy proton group. After dissociation in a thin Be foil, the molecular ions appear as ordinary low-energy protons, which were removed by a deflecting magnet. The magnet did not improve energy resolution for the high-energy group, but no improvement was necessary for our purposes.

The proton energy spectrum was determined from some of the same plates that were used in measuring cross sections. The observed spread in range results from a finite energy spread in the beam and from the statistical nature of the slowing-down process, which causes straggling even in a monoenergetic beam. The amount of correction for range straggling was calculated from theoretical results given by Barkas and Young.[11] After applying this correction, the proton energy spectrum was found to have a full width at half-maximum of less than 75 kev for an exposure of about three hours.

---

* This work was supported in part by the U. S. Atomic Energy Commission.

† Now at University of California Radiation Laboratory, Livermore, California.

[1] Burcham, Gibson, Hossain, and Rotblat, Phys. Rev. **92**, 1266 (1953).

[2] G. E. Fischer, Phys. Rev. **96**, 704 (1954).

[3] Freemantle, Prowse, and Rotblat, Phys. Rev. **96**, 1268 (1954).

[4] Freemantle, Prowse, Hossain, and Rotblat, Phys. Rev. **96**, 1270 (1954).

[5] Fernbach, Serber, and Taylor, Phys. Rev. **75**, 1352 (1949).

[6] B. L. Cohen and R. V. Neidigh, Phys. Rev. **93**, 282 (1954).

[7] Austern, Butler, and McManus, Phys. Rev. **92**, 350 (1953).

[8] C. Longmire, Phys. Rev. **74**, 1773 (1948).

[9] R. R. Haefner, Revs. Modern Phys. **23**, 228 (1951).

[10] J. Rotblat, Nature **167**, 550 (1951).

[11] W. H. Barkas and D. M. Young, University of California Radiation Laboratory Report UCRL-2579 (Rev.), September, 1954 (unpublished).

Since the error in reading track length was considerably less than the range straggling, no other correction was made. The calculated energy spread of 75 kev may therefore be slightly high.

The beam had an initial divergence of ±14 minutes, which was reduced by collimation to ±12 minutes. During a run, the intensity was of the order of 10^{-9} amp through a $\frac{3}{16}$ in. collimator.

For a detector, the Los Alamos multiplate camera[12] with C-2 emulsions was used. This detection system is very economical of machine time, and is capable of providing accurately measured angles of observation. The camera originally had two sets of defining slits, which are necessary when a gas target is used. When a solid target is used as in the present experiment, however, the inner set of slits is unnecessary because the target volume is defined by the incoming beam and the target thickness. Only the outer slits, which define the direction of a scattered particle, were retained. In a beam of scattered particles as defined by a slit, the mean divergence of a ray from the nominal scattering angle has been calculated to be not more than 0.54°.

The current integrating circuit was calibrated by a current-time method, using a potentiometer and resistors measured to 1% accuracy.

The beryllium target, about 30 μin. thick, was obtained through the courtesy of Dr. Hugh Bradner of the University of California Radiation Laboratory. The same target was used for all the runs; analysis for carbon and oxygen was made by counting tracks due to elastic scattering from these elements and referring to previously published cross sections.[1,2] The corrections amounted to less than 10%.

A more complicated analysis was necessary to determine the inelastic scattering cross section for Be^9. Only one excited state of Be^9 was observed, namely the well-known one at 2.4 Mev.[13] There was a deuteron group of nearly the same range as the inelastically scattered protons, from the reaction $\mathrm{Be}^9+p\rightarrow\mathrm{Be}^8+d$. A continuous background of deuterons from the reaction $\mathrm{Be}^9+p\rightarrow 2\mathrm{He}^4+d$ was also present. A continuous spectrum of protons from the reaction $\mathrm{Be}^9+p\rightarrow 2\mathrm{He}^4+p+n$ might also have been present, though it was not intense enough to be observed. The continuous deuteron background has an upper energy limit almost the same as the energy of the deuteron group, because the production of $2\mathrm{He}^4$ in the reaction is energetically almost equivalent to the production of Be^8.

It was unfortunately not possible to distinguish unambiguously between proton tracks and deuteron tracks of the same length, when the range was less than 300μ. Separation of proton and deuteron groups was therefore accomplished by analysis of the range spectrum.

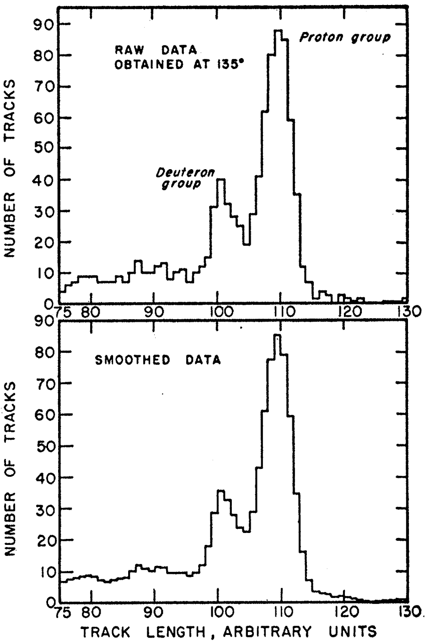

FIG. 1. Number of tracks as a function of track length. One "arbitrary unit" equals 1.385 microns. See text for explanation of the smoothing process.

A histogram showing the number of tracks as a function of track length is given for a typical case (135°) in Fig. 1. It will be seen that the proton group, while easily distinguished from the deuteron group, is not completely separated. For purposes of analysis, it was assumed that the observed spectrum consisted of: (1) a proton group, symmetric about some center but not necessarily following a Gaussian distribution, (2) a deuteron group, also symmetric about some mean range, (3) a deuteron background extending to shorter ranges, and (4) a low uniform proton background, mostly due to slit scattering in the collimator.

The "smoothed data" histogram of Fig. 1 represents an attempt to reduce the effect of statistical fluctuations in analyzing the double peak. Let the measured track length be L, and let the number of tracks whose length is between L and $L+1$ be represented by $n(L)$. Then the histogram labeled "raw data" (Fig. 1) is a plot of $n(L)$ *vs* L. Let the smoothed data be represented by another function $N(L)$. Then $N(L)=\frac{1}{2}n(L)+\frac{1}{4}n(L-1)+\frac{1}{4}n(L+1)$. Since $N(L)$ is less distorted by statistical fluctuations than $n(L)$, it is more amenable to analysis. It is true that any objective smoothing process will reduce the ultimate resolution available, but the loss in resolution was more than compensated by the increased certainty in locating the centers of peaks.

After making the appropriate background correction, it was possible to choose center positions for the two peaks so that they were both symmetric within the expected statistical errors, and of reasonable width. When this was done, the area under half the proton peak

---

[12] Allred, Rosen, Tallmadge, and Williams, Rev. Sci. Instr. **22**, 191 (1951).

[13] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

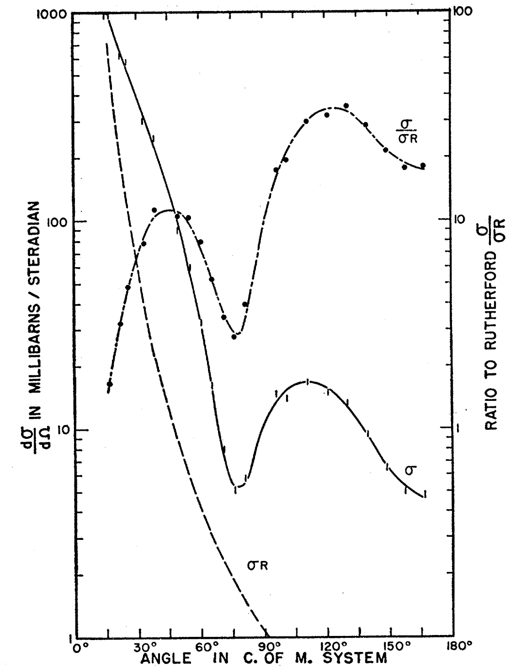

FIG. 2. Differential elastic scattering cross sections as a function of angle in the center-of-mass system. Probable error is indicated by the length of the vertical lines.

was measured, then doubled to find the total number of proton tracks at that range. In this way the uncertainty in background due to possible errors in the center position of the deuteron peak was reduced, at the cost of increased statistical fluctuations.

Near 80° the two groups overlap badly, so that no results on proton inelastic scattering are available in that region. The results on inelastic scattering have unexpectedly large uncertainties at all angles, because of the difficulty of separating the deuteron group quantitatively.

Other sources of error, both for elastic and inelastic scattering, were examined and found to be negligible.

RESULTS

Elastic Scattering

Figure 2 shows the differential cross section for elastic scattering as a function of angle. The curve does indeed have the general character of a diffraction pattern. Table I shows, however, that the results cannot be explained on the basis of a diffraction pattern alone. In the table are listed the angles at which various maxima and minima occur, together with various predictions for these angles. Each of the last five columns of the table represents the results of a different experiment, normalized to 10-Mev protons bombarding beryllium by the use of an R/λ law.[6]

TABLE I. Observed positions of maxima and minima in elastic scattering, compared with positions calculated from other experiments by using Cohen's R/λ rule.

Feature	θ_{obs}	θ_{calc} carbon[a]	θ_{calc} carbon[b]	θ_{calc} oxygen[b]	θ_{calc} nitrogen[c]	θ_{calc} Be[d]
Minimum σ	77°	77°	77°	79°	81°	...
Maximum σ	111°	121°	112°	130°	134°	...
First max. σ/σ_R	46°	55°	...	...	...	60°
Minimum σ/σ_R	77°	73°	...	...	...	95°
Second max. σ/σ_R	125°	132°	...	...	...	130°

[a] See reference 2.
[b] See reference 1.
[c] See reference 3.
[d] See reference 6.

The various columns do not agree well, so an optical model is clearly inadequate to explain the observed angular dependence of proton elastic scattering from Be^9. There is good qualitative agreement, however, as has already been observed.

Inelastic Scattering

Cross sections were measured only for those protons which leave Be^9 in the 2.4-Mev excited state. The results are shown in Fig. 3. No sharp peaks are observed at any angle, as opposed to the results of experiments at 7.1-Mev and at 31-Mev bombarding energy.[14,15] There is no evidence for a dip in cross section at extreme forward angles. If the results of Austern, Butler, and McManus[7] are applicable to the (p,p') reaction, a maximum at 0° indicates no parity change, $\Delta J=0$, ± 1, and $\Delta l=0$, provided l is a good quantum number. Thus these results, like those of Ribe and Seagrave,[16] are not inconsistent with the theoretical assignment of negative

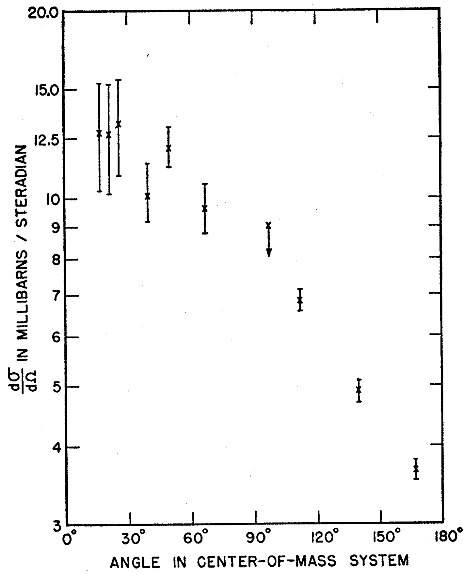

FIG. 3. Differential inelastic scattering cross sections as a function of angle. The point near 90° represents an upper limit, since at this angle a deuteron group was not separated from the proton group.

---

[14] K. E. Davis, Phys. Rev. **88**, 1433 (1952).

[15] R. G. Finke, Ph.D. thesis, University of California Radiation Laboratory Report UCRL-2789, November, 1954 (unpublished).

[16] F. L. Ribe and J. D. Seagrave, Phys. Rev. **94**, 934 (1954).

parity to the 2.4-Mev excited state of Be^9. (The ground state is almost surely a $P_{\frac{3}{2}}(-)$ state.)[17,18] Finke's results,[15] however, lead to the opposite conclusion about parity. Because of this, and because the Austern-Butler-McManus theory does not accurately predict the cross sections observed either with 10-Mev or 31-Mev protons, we can only conclude definitely that a more complete theoretical description of the inelastic scattering process would be desirable.

Earlier predictions by Longmire[8] also appear to be inadequate when compared to the present results. The total inelastic scattering cross section is predicted to be about 0.05 barn, which is too low by at least a factor of two. The predicted variation of cross section with angle is also inadequate in that the moderately high cross section near 90° and the sharp drop near 180° would not be expected from any combination of exchange and ordinary forces using Longmire's assumptions. Presumably the Be^8 core does not act sufficiently like a single potential well for the calculations on inelastic scattering to be quantitatively correct.

The alpha-particle model has been used to predict that Be^9 should have an excited state near 2.4 Mev with negative parity and $J=5/2$.[9] The present data are consistent with this prediction. More recently calculations have been made by French, Halbert, and Pandya[19] on the basis of a modified shell model, showing that a $5/2(-)$ state is compatible with the data, even if the state under consideration should turn out not to be the lowest excited state.

Other Reactions

Rough measurements on the angular dependence of the (p,d) cross section show a qualitative similarlty to that observed at other bombarding energies.[20–22] The results are shown in Fig. 4.

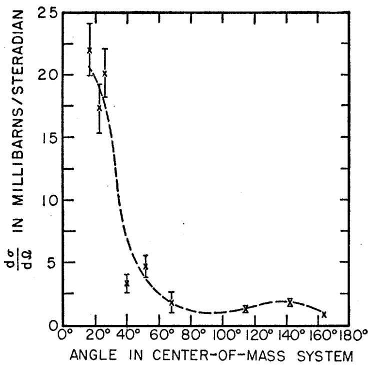

FIG. 4. Differential cross section for the $Be^9(p,d)Be^8$ reaction plotted as a function of angle in the center-of-mass system.

No other proton or deuteron groups were measured, although the broad deuteron group resulting from the reaction $Be^9+p\rightarrow d+Be^{8*}$ (2.9 Mev) was present. Two alpha-particle groups arising from the reaction $p+Be^9\rightarrow He^4+Li^{6(*)}$ were observed, but no cross sections were measured. Other groups corresponding to higher excited states of the recoil nuclei Be^9, Be^8, or Li^6 may have been present with small intensity, but they could not be observed above the continuous background of other particles.

ACKNOWLEDGMENTS

This work was done with the advice and encouragement of Dr. J. H. Williams, who has also directed the design and construction of the Minnesota Linear Accelerator. Thanks are due to Dr. L. H. Johnston, who designed the current-integrating circuit, and to Dr. E. E. Lampi, Dr. N. M. Hintz, Dr. E. B. Tucker, and Dr. H. J. Schulte, who have also contributed much of their own time to assure proper running of the accelerator. Robert Featherstone and Richard Evans have supervised the construction and installation of much electronic equipment, and the entire Linac crew has contributed to the experiment. It is a pleasure to acknowledge a special indebtedness to Dr. Louis Rosen of the Los Alamos Scientific Laboratory, through whose courtesy the multiplate camera was made available.

---

[17] E. Guth and C. J. Mullin, Phys. Rev. **74**, 832 (1948).

[18] Hatton, Rollin, and Seymour, Phys. Rev. **83**, 672 (1951).

[19] French, Halbert, and Pandya, Phys. Rev. **99**, 1387 (1955).

[20] J. A. Harvey, Phys. Rev. **82**, 298 (1951).

[21] Cohen, Newman, Handley, and Timnick, Phys. Rev. **90**, 323 (1953).

[22] J. B. Reynolds and K. G. Standing, Phys. Rev. **101**, 158 (1956).