Electrostatic Analysis of Nuclear Reaction Energies. III*

D. J. DONAHUE,† K. W. JONES, M. T. MCELLISTREM, AND H. T. RICHARDS
University of Wisconsin, Madison, Wisconsin

(Received October 27, 1952)

Electrostatic analysis of incident and product particles has been used to measure the following reaction energies: $Na^{23}(p,\alpha)Ne^{20}$ (2.379±0.003 Mev); $Na^{23}(p,\alpha)Ne^{20*}$ (0.745±0.002); $Na^{23}(p,p')Na^{23*}$ (−0.439 ±0.001 Mev); $Mg^{24}(p,p')Mg^{24*}$ (−1.371±0.002 Mev); $Al^{27}(p,p')Al^{27*}$ (−0.843±0.002 Mev); $Al^{27}(p,\alpha)Mg^{24}$ (1.594±0.002 Mev); $Al^{27}(p,\alpha)Mg^{24*}$ (0.228±0.003 Mev).

I. INTRODUCTION

ACCURATE measurements of nuclear reaction energies by electrostatic deflection of incident and product particles in high resolution cylindrical[1] and spherical analyzers[2] have been reported in previous communications[3,4] which shall henceforth be referred to as I and II. The present paper reports further measurements using the same equipment and procedures (except for minor modifications which will be explicitly stated). In the present work thin targets of Na^{23}, Mg^{24}, and Al^{27} have been bombarded with protons and various ground-state and excited-state reactions observed and measured. These are individually discussed below and the results summarized in Table I. Figures 1 and 2 are typical figures showing some of the observed reaction edges.

II. PROCEDURE

The only significant change in procedure over that described in I and II is that the spherical analyzer calibration was used as a secondary voltage standard rather than the cylindrical analyzer. In the earlier work (I, II) extreme fluctuations of 0.1 percent in over-all calibration (cylindrical plus spherical analyzer) had been observed over an extended period of time. Insufficient data were then available to determine which of the analyzers was at fault. In the present work observations of narrow resonances in the $Al^{27}(p,\alpha)Mg^{24}$ and $Mg^{24}(p,p')Mg^{24*}$ reactions definitely established that it was the cylindrical analyzer which was drifting. The cause of the drifting was not easily established. Therefore, instead of constant recalibrations of the cylindrical analyzer with the $Li^7(p,n)Be^7$ threshold, the spherical analyzer was calibrated with protons scattered by platinum immediately before and after the cylindrical analyzer was checked with the $Li^7(p,n)Be^7$ threshold. Then, subsequently, the cylindrical analyzer was checked before and after each reaction edge in terms of the spherical analyzer measurement of the elastically scattered protons from a platinum foil. With this arrangement the over-all calibration fluctuation was in general less than 0.03 percent, although occasionally larger fluctuations did occur. To cover these we have assigned an uncertainty in T_1 of 0.05 percent.

We have continued to include an error of 0.1 percent in the final Q value as representing the uncertainty in the absolute voltage scale, though there are probably

TABLE I. Summary of present measurements. T_1 is the energy of the incident particle; T_2 is the energy at 134° 33′ of the light outgoing particle.

Reaction	T_1 (Mev)	T_2 (Mev)	Q (Mev) Q	dQ
$Na^{23}(p,\alpha)Ne^{20}$	1.458	2.893	2.378±0.003	
	1.457	2.894	2.380±0.003	
$Na^{23}(p,\alpha)Ne^{20*}$	2.925	2.610	0.745±0.002	
$Na^{23}(p,p')Na^{23*}$	1.457	0.849	−0.439±0.001	
$Mg^{24}(p,p')Mg^{24*}$	2.412	0.822	−1.371±0.002	
$Al^{27}(p,p')Al^{27*}$	2.309	1.244	−0.843±0.002	
$Al^{27}(p,\alpha)Mg^{24}$	1.187	2.179	1.594±0.002	
	1.187	2.179	1.594±0.002	
$Al^{27}(p,\alpha)Mg^{24*}$	2.742	2.200	+0.230±0.003	
	3.405	2.684	0.225±0.003	
	3.402	2.684	0.229±0.003	

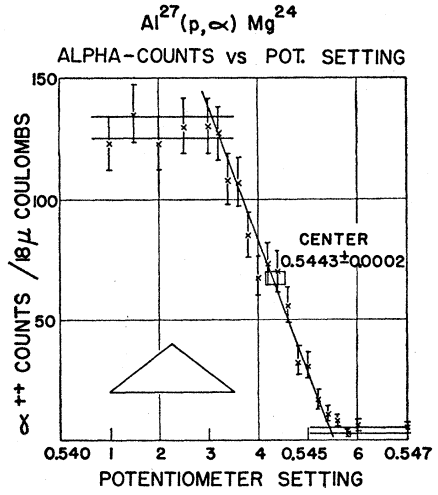

FIG. 1. Doubly ionized alphas from $Al^{27}(p,\alpha)Mg^{24}$.

* Work supported by the U. S. Atomic Energy Commission and the Wisconsin Alumni Research Foundation.

† Now at General Electric, Hanford, Washington.

[1] Warren, Powell, and Herb, Rev. Sci. Instr. 18, 559 (1947).

[2] Browne, Craig, and Williamson, Rev. Sci. Instr. 22, 952 (1951).

[3] Williamson, Browne, Craig, and Donahue, Phys. Rev. 84, 731 (1951), referred to as I.

[4] Craig, Donahue, and Jones, Phys. Rev. 88, 808 (1952), referred to as II.

enough independent checks[5] of this scale that one could with fair assurance reduce this uncertainty by perhaps a factor of two.

The angle between the incident beam and the reaction particles was 134° 33±3′ as in II.[4] The error quoted in all of our present results is simply the square root of the sum of the squares of all the estimated individual uncertainties. This is the error which has been referred to as the "probable" error in I and II. For most of the reactions the largest individual uncertainty is the 0.1 percent of Q which arises from the 0.1 percent systematic uncertainty in the absolute voltage scale.

III. RESULTS AND DISCUSSION

Targets of sodium, magnesium, and aluminum were prepared by evaporation of the metal upon 1000A

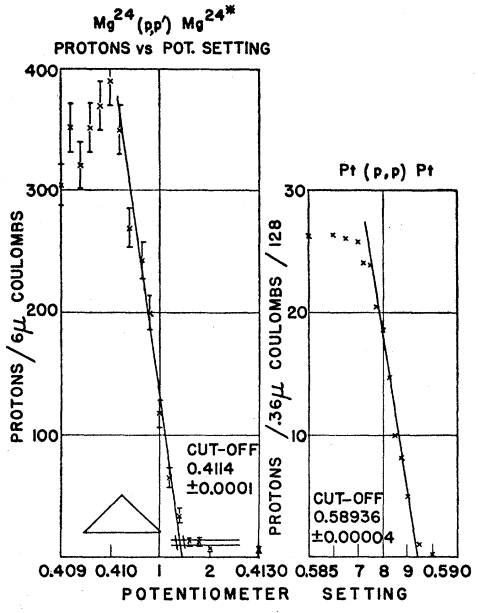

FIG. 2. Protons scattered inelastically from the ~1.37-Mev level of Mg^{24} and the elastically scattered protons from platinum used for analyzer calibration.

nickel foils.[6] For some of the sodium and aluminum data, targets were also prepared by evaporation of the metal upon thick diamond backings. These targets were used when the reaction products happened to come at energies close to that of the elastically scattered protons from the thin nickel backing.

In general targets were "thin" with respect to the energy of the incident particle but were "thick" compared to the spherical analyzer resolution. (The magnesium target was an exception in this respect. The reason for choice of a target "thick" compared to spherical analyzer resulution is discussed in I. The thinness of the magnesium target required an analysis of the reaction data in terms of the extrapolated cut-off energy rather than the half-yield point used for the "thick" target.) To avoid contamination build-up, freshly evaporated targets were used for each reaction edge. In addition, whenever feasible the targets were checked for contamination build-up by examination of the elastically scattered protons from carbon. Targets were kept heated to ~200°C, and only in one case was any measurable carbon build-up observed. In that instance the correction to the Q value necessitated by the contamination was only 0.4 kev.

First-order relativistic corrections were applied throughout the analysis as in I and II.

Table II displays the component errors making up the over-all uncertainty in the Q value for the $Al^{27}(p,\alpha)Mg^{24}$ reaction and is typical of the other data.

Table III compares our present reaction measurements with the best of the other available data. In general, there is very satisfactory agreement of most

TABLE II. Tabulation of component errors for the $Al^{27}(p,\alpha)Mg^{24}$ reaction.

Source of error	Magnitude	Error in Q (Mev)
Relative calibration of the analyzers	0.05 percent of T_1 0.02 percent of T_2	0.00059 0.00044
Angle of observation	±3′	0.00032
Location of half-value of reaction edge	±0.00088 Mev	0.00106
Absolute calibration [$Li^7(p,n)Be^7$]	0.1 percent of Q	0.00159
		$(\Sigma\epsilon^2)^{\frac{1}{2}}=0.0021$

TABLE III. Comparison with other measurements.

	Present data	Other measurements	Method	Reference
$Na^{23}(p,\alpha)Ne^{20}$	2.379±0.003	2.34±0.04	mag. spect.	c
		2.372±0.008	mag. spect.	d
Ne^{20*}	1.634±0.004	1.66±0.02	photo plate	e
		1.63±0.02	$-F^{20}$ decay	f
		1.631±0.006	$-F^{20}$ decay	g
Na^{23*}	0.439±0.001	0.45±0.01	gamma-spect.	h
		0.43±0.02	mag. spect.	i
Mg^{24*}	1.371±0.002[a]	1.3680±0.0010	$-Na^{24}$ decay	j
	1.366±0.004[b]	1.3697±0.0003	$-Na^{24}$ decay	k
Al^{27*}	0.843±0.002	0.844±0.020	mag. spect.	l
		0.837±0.016	mag. spect.	m
$Al^{27}(p,\alpha)Mg^{24}$	1.594±0.002	1.595±0.007	mag. spect.	d
		1.585±0.015	mag. spect.	c

[a] From Q of $Mg^{24}(p,p')Mg^{24*}$.
[b] From Q's of $Al^{27}(p,\alpha)Mg^{24}$ and $Al^{27}(p,\alpha)Mg^{24*}$.
[c] J. M. Freeman, Proc. Phys. Soc. (London) **A63**, 668 (1950).
[d] Van Patter, Sperduto, Endt, Buechner, and Enge, Phys. Rev. **85**, 142 (1952).
[e] R. Middleton and C. T. Tai, Proc. Phys. Soc. (London) **A64**, 801 (1951).
[f] J. V. Jelley, Phil. Mag. **41**, 1199 (1950).
[g] D. Alburger, Phys. Rev. **88**, 1257 (1952).
[h] Stelson, Preston, and Goodman, Phys. Rev. **86**, 629 (1952).
[i] Endt, Haffner, and Van Patter, Phys. Rev. **86**, 518 (1952).
[j] A. Hedgran and D. A. Lind, Arkiv Fys. **5**, 177 (1952).
[k] Same as j but recalculated for revised Au^{198} gamma-energy (see reference 10) and making use of Co^{60} to Au^{198} ratio determined by D. A. Lind and A. Hedgran, Arkiv Fysik **5**, 29 (1952).
[l] Reilley, Allen, Arthur, Bender, Ely, and Hausman, Phys. Rev. **86**, 857 (1952).
[m] D. M. Van Patter and W. W. Buechner, Phys. Rev. **87**, 51 (1952).

[5] W. J. Sturm and V. Johnson, Phys. Rev. **83**, 542 (1951).
[6] S. Bashkin and G. Goldhaber, Rev. Sci. Instr. **22**, 112 (1951).

observers within their stated errors. Our values for the excited states are obtained either from inelastic proton scattering or from (p,α) reactions to the ground and first excited states.

Only in the case of the Mg^{24} level at $\sim$1.37 Mev is there an independent measurement which is of higher precision than that here reported. This high precision measurement comes from a Na^{24} gamma-ray energy measurement[7] in terms of the absolutely determined Co^{60} gamma-radiation,[8] or the Au^{198} radiation.

This comparison involves also a comparison of two absolute voltage scales, namely, that of Herb, Snowden, and Sala[9] and that of DuMond's curved crystal gamma-spectrometer.[8] It is of interest that DuMond's recent revision[10] of his Au^{198} gamma-energy significantly improves the agreement of the two scales.

We hope in the near future to obtain higher precision in the measurement of this Mg^{24} level so that a really good consistency check of the two scales will be possible.

[7] A. Hedgran and D. A. Lind, Arkiv Fysik **5**, 177 (1952).
[8] Lind, Brown, and DuMond, Phys. Rev. **76**, 1838 (1949).
[9] Herb, Snowden, and Sala, Phys. Rev. **75**, 246 (1949).
[10] Muller, Hoyt, Klein, and DuMond, Phys. Rev. **88**, 775 (1952).

PHYSICAL REVIEW VOLUME 89, NUMBER 4 FEBRUARY 15, 1953

The Secondaries of Penetrating Showers*

C. C. DAMM†
Brookhaven National Laboratory, Upton, Long Island, New York
(Received September 19, 1952)

The momentum spectrum of penetrating shower secondaries at 11 200 feet altitude has been measured by means of the distribution in projected angle of the multiple Coulomb scattering of those particles in a lead plate of a cloud chamber. The resulting spectrum is compared to that obtained for the meson secondaries of stars in photographic plates exposed at 70 000 feet. For mesons above 500 Mev, the two spectra coincide within the errors. At lower energies, and especially around 100 Mev, a marked difference exists. The respective average energies are also different by a factor of about two. All of these differences appear to to result both from selecting particles emitted in the forward direction, and from higher energies of the particles producing the primary event in the present experiment. The average "primary energy" appears to be less than 8 Bev, which is a lower value than one might deduce from the latitude effect of penetrating showers.

A production of photons in carbon by the penetrating shower secondaries has been observed. Interpreted in terms of π^0 production, this is consistent with the photographic plate work that has suggested inelastic charge exchange scattering.

Three decays of neutral V^0 particles observed show that the cross section for V^0 production by the penetrating shower secondaries is most likely an appreciable fraction of the geometrical cross section.

I. INTRODUCTION

IN recent years a considerable amount of experimental effort has been devoted to the study of penetrating showers (PS). Various assemblies of lead and counters have been used to determine the absorption mean free path of PS producing radiation, as well as to determine the collision cross section of such particles with various nuclei. However, the energy of those particles, or the energy spectrum of the secondaries produced in the penetrating shower, cannot be readily measured because the best experimental methods which can be thought of are hampered by too low a rate of occurrence. Also, one hesitates to build a complex apparatus which yields an answer that is not simply interpretable. With a relatively simple apparatus, some data have been collected on the momentum distribution of the PS secondaries.

On the subject of the spectrum of penetrating secondaries, one recalls immediately the photographic plate work of Camerini *et al.*[1] Their data concern stars detected in photographic emulsions at 70 000 feet altitude. *A priori*, the spectrum of the particles produced in PS, and the spectrum of the shower particles of Camerini *et al.* could be quite different; thus a comparison of the present data and theirs is of interest.

Barker and Butler[2] used a magnetic cloud chamber at sea level to measure the momenta of 135 particles under 25 cm of lead; of these, 85 had momenta >1 Bev/c. Their apparatus required sevenfold coincidences and so selected PS events on a fairly rigid basis.

In the present experiment, performed at 11 200 feet altitude, the momentum spectrum of PS secondaries is measured with a geometry such that the minimum number of particles required to arise from the primary interaction is two, although the average number is

* The present research has been carried out under the auspices of the U. S. Atomic Energy Commission.
† Work performed in partial fulfillment of the requirements of New York University for the degree of Doctor of Philosophy.

[1] Camerini, Fowler, Lock, and Muirhead, Phil. Mag. **41**, 413 (1950).
[2] K. H. Barker and C. C. Butler, Proc. Phys. Soc. (London) **A64**, 4 (1951).