Angular Distributions of Two Proton Groups from the Reaction $Na^{23}(d,p)Na^{24}$†

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The resolved angular distributions of $Na^{23}(d,p)Na^{24}$ protons leaving Na^{24} in the 0.472- and 0.564-Mev levels have been obtained with a double-focusing magnetic spectrometer, using a bombarding energy of 2.95 Mev (lab). The angular distribution corresponding to the transition to the 0.472-Mev level shows evidence of a large contribution from compound-nucleus formation. A Butler-type analysis of the angular distribution of protons leading to the 0.564-Mev level indicates that this level must have spin 1+ or 2+.

I. INTRODUCTION

CONSIDERABLE experimental interest in the angular distributions of reaction products from (d,p) and (d,n) type nuclear reactions has been expressed since the publication by Butler[1] of a method of theoretical analysis based on a stripping model. Butler's theory predicts angular distributions characterized by peaks, whose locations depend on the number of units of orbital angular momentum carried into the target nuclei by the stripped nucleons (l_n is commonly used to denote neutron orbital angular momentum; l_p, proton orbital angular momentum). From the values of l_n or l_p it is possible to make parity assignments and to set limits on possible spin values for residual nuclear levels.

Studied in this experiment were the relative yields, as a function of angle, of two proton groups from $Na^{23}(d,p)Na^{24}$ leading to the 0.472- and 0.564-Mev levels of Na^{24}. The 0.472-Mev level had been given different spin assignments by two groups of investigators; the spin of the 0.564-Mev level was uncertain. This section will summarize the various spin assignments and the experimental work on which they were based. Previously, these groups had been resolved at one angle, only, by Sperduto and Buechner.[2] Figure 1 shows the relevant Na^{24} energy levels,[2] the Ne^{24} beta decays,[3] $Na^{23}(n,\gamma)Na^{24}$ gamma-ray transitions between Na^{24} levels,[4,5] and the bombarding energy of this experiment.

Unresolved angular distributions of the $Na^{23}(d,p)Na^{24}$ protons leading to the 0.472- and 0.564-Mev Na^{24} levels have been obtained by Takemoto, Dazai, and Chiba,[6] Shapiro,[7] and Bretscher *et al.*[8]

Takemoto, Dazai, and Chiba, using a bombarding energy of 1.15 Mev, found an angular distribution that was approximately symmetrical about 90°, and peaked at 90°; they gave no interpretation. Shapiro, using a bombarding energy of 3 Mev, and Bretscher *et al.*, using a bombarding energy of 10 Mev, obtained angular distributions which they interpreted as indicating that one level was formed by $l_n=0$ capture and that the other was formed by $l_n=2$ capture. In addition, Bretscher *et al.* assigned the $l_n=2$ capture to the 0.472-Mev state, citing neutron-capture gamma-ray data reported by Kinsey *et al.*[4] Kinsey *et al.*, studying the energies and relative yields of gamma rays produced by the thermal neutron bombardment of Na^{23}, found no gamma-ray transitions to either the ground or first excited states of Na^{24}. The spin of the Na^{24} ground state had been reported as 4+.[9,10] The spin of the ground

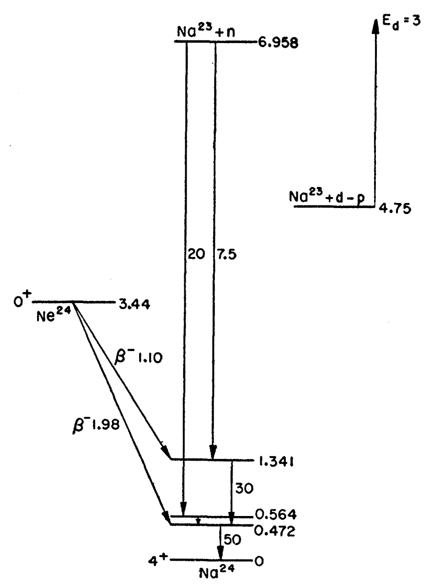

FIG. 1. Relevant energy levels and decays of Ne^{24}, Na^{24}, and $Na^{23}+d-p$. Numbers next to the gamma-ray arrows in the Na^{24} system give the number of transitions per 100 neutron captures by Na^{23}. The deuteron bombarding energy of this experiment is also indicated.

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[1] S. T. Butler, Phys. Rev. **80**, 1095 (1950), and Proc. Roy. Soc. (London) **A208**, 559 (1951).
[2] A. Sperduto and W. W. Buechner, Phys. Rev. **88**, 574 (1952).
[3] B. J. Dropesky and A. W. Schardt, Phys. Rev. **102**, 426 (1956).
[4] Kinsey, Bartholomew, and Walker, Phys. Rev. **83**, 519 (1951).
[5] H. T. Motz, Phys. Rev. **104**, 1353 (1956).
[6] Takemoto, Dazai, and Chiba, Phys. Rev. **91**, 1024 (1953).
[7] P. Shapiro, Phys. Rev. **93**, 290 (1954).
[8] Bretscher, Alderman, Elwyn, and Shull, Phys. Rev. **96**, 103 (1954).
[9] Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953).
[10] K. F. Smith, Nature **167**, 942 (1951), and confirmed by E. H. Bellamy and K. F. Smith, Phil. Mag. **44**, 33 (1953).

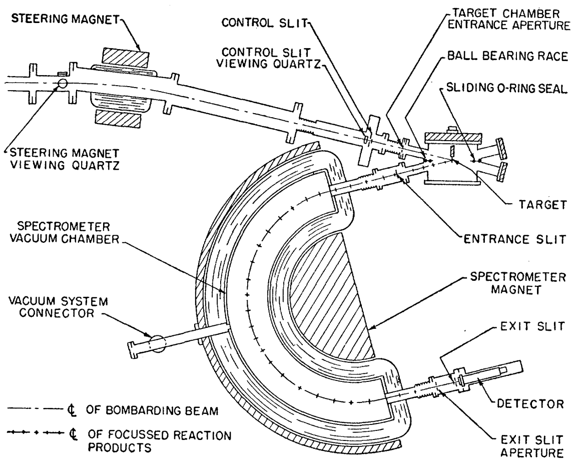

FIG. 2. Cross section through spectrometer assembly. (Spectrometer in 180° position.)

state of Na^{23} is $\frac{3}{2}+$[7,11]; thus the Na^{24} state formed from Na^{23} by thermal neutron capture has a spin of 1+ or 2+. Therefore, Bretscher *et al.* concluded, the spins of the ground and 0.472-Mev states of Na^{24} were similar; the 0.472-Mev state was assigned spin 3+ or 4+, requiring it to be formed by $l_n=2$ in the $Na^{23}(d,p)Na^{24}$ reaction, and the 0.564-Mev level was left with the $l_n=0$ capture and spin 1+ or 2+.

However, Dropesky and Schardt,[3] on the basis of a study of the beta decay of Ne^{24}, assigned the 0.472-Mev level a spin of 1+. Not only did this conclusion conflict with the Bretscher *et al.* assignment for the 0.472-Mev level, but it raised the possibility that the $l_n=2$ transition reported by Shapiro and Bretscher *et al.* belonged to the 0.564-Mev level; i.e., that the 0.564-Mev level could have spin 0+, 1+, 2+, 3+, or 4+. Later, Motz,[5] on the basis of all the data available, agreed with Dropesky and Schardt on the assignment of spin 1+ for the 0.472-Mev level. Motz suggested that a spin of 2+ for the 0.564-Mev state would most easily fit the capture gamma-ray data.

A double-focusing magnetic spectrometer with 16-inch central-ray radius, of the type developed at the California Institute of Technology,[12] has been constructed recently at the State University of Iowa. The high resolution and transmission of this instrument made it suitable for study of the $Na^{23}(d,p)Na^{24}$ proton groups leading to the 0.472- and 0.564-Mev levels of Na^{24}. Accordingly, the investigation of the angular distributions of these two groups was undertaken in the hope that the results might serve to clarify the spin assignments for the 0.472- and 0.564-Mev Na^{24} levels.

II. EXPERIMENTAL

A. Equipment

The State University of Iowa Van de Graaff accelerator was used as the source of the bombarding deuterons. A steering magnet deflected the deuteron beam 14° downward into the target chamber. The magnet current-beam energy calibration was made using several of the prominent $F^{19}(p,\alpha\gamma)O^{16}$ resonances, and the monatomic and diatomic hydrogen beams of the accelerator. The deuteron energy for the experiment was 2.95 Mev ±4%. Calibration shifts during the experiment were less than about ±1%.

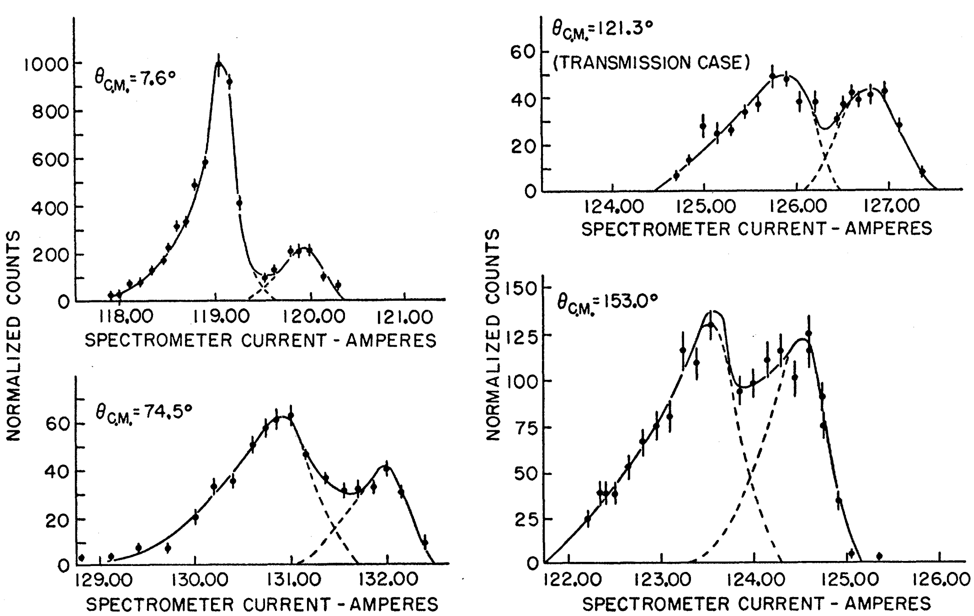

FIG. 3. Typical proton doublet profiles for $Na^{23}(d,p)Na^{24}$ protons leading to the 0.472- and 0.564-Mev states of Na^{24}.

[11] J. E. Mack, Revs. Modern Phys. 22, 64 (1950).
[12] Snyder, Rubin, Fowler, and Lauritsen, Rev. Sci. Instr. **21**, 852 (1950).

Figure 2 is a drawing of a section through the steering magnet, target chamber, and spectrometer. The target chamber is built in two halves separated by a sliding O-ring seal and a ball-bearing race; the top half is fixed with respect to the bombarding beam; and the bottom half, to which is attached the spectrometer, rotates. The target chamber ports are inclined at ±14° with the horizontal; hence laboratory angles of observation from 0° to 152° with respect to the beam are possible. A CsI(Tl) particle scintillation counter served as the spectrometer detector. Normalization of spectrometer counting rates was made using a CsI(Tl) particle-monitor counter located at one of the ports in the top half of the target chamber. Monitor normalization was used for the experiment because: (1) It was desired to obtain data at an angle near the beam in the forward direction, and a beam charge collector would have interfered with data-taking at such angles. (2) Monitor-counter normalization is sensitive to target changes while charge collection is not.

B. Procedure

A target was prepared by evaporating sodium on a 1000-A nickel[13] target backing inside the target chamber, under vacuum. Target thickness was checked during the evaporation run by scattering deuterons from the target and target backing. Following the evaporation, a survey of deuteron elastic scattering peaks from carbon and oxygen was made; none greater than 5% of the sodium scattering peak height was found.

Spectrometer counting rate *vs* spectrometer magnet current profiles of the two proton groups were taken at 12 angles of observation from 7.6° (center-of-mass) through 153° (center-of-mass). Four typical doublet profiles are shown in Fig. 3; errors indicated are standard deviations. For the bombarding energy used, the doublet groups have energies of about 7 Mev, and an energy separation of about 1.3%. At the start of each day's runs, deutron elastic scattering peaks were located as a function of spectrometer magnet current, and the current raised appropriately to locate the doublet profile.

Monitor and detector discriminator bias settings were made using a 10-channel pulse-height analyzer, and checked periodically during the experiment. Figure 4 shows a typical monitor pulse-height spectrum. The monitor bias point is indicated by the arrow. A buildup of contaminants on the target could produce two undesirable effects: introduction of appreciable numbers of counts from groups that could be confused, in the spectrometer, with the $Na^{23}(d,p)Na^{24}$ groups studied, and distortion of the results due to changes in the monitor counting rate.

Interference from alpha particles from the reaction $Na^{23}(d,\alpha)Ne^{21}$ occurred at laboratory angles between 40° and 75°. Accordingly, for these angles, the spectrometer amplifier output was fed into a 10-channel pulse-height analyzer, and the alphas and protons separated by pulse-height analysis.[14] Figure 5 shows a typical alpha-proton pulse-height spectrum from the spectrometer detector.

Repeat runs of one of the profile peaks were made at the following center-of-mass angles; 30.2° (twice), 74.5° (twice), and 121.3° (run once with the spectrometer accepting particles after they had passed through the target, and repeated once with the spectrometer accepting particles scattered backward from the target). These check runs are plotted as separate data points in Figs. 6 and 7.[15,16] Variations were observed on these repeat runs (see Figs. 6 and 7), but they were about what would be expected from statistical fluctuations, and they did not show the consistent changes (as a function of bombarding time) that would be

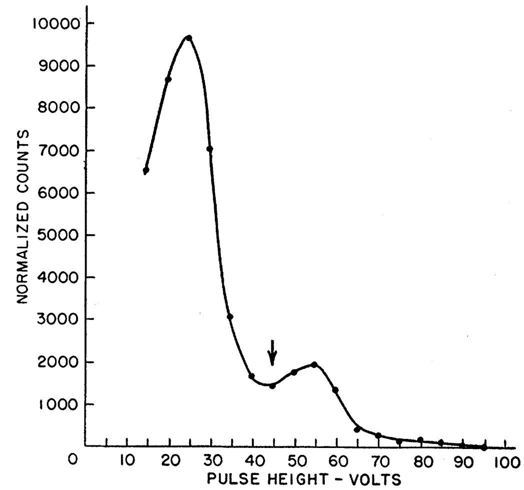

FIG. 4. Typical monitor detector pulse-height spectrum. The large peak is principally due to deutrons elastically scattered from the target and target backing; the small peak, to protons and alphas resulting from the deuteron bombardment of sodium. Monitor bias point is indicated by the arrow.

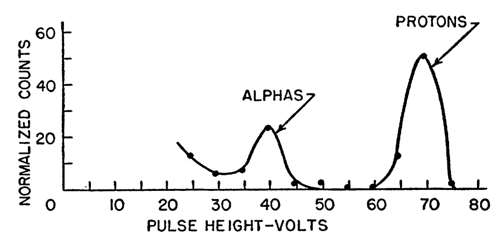

FIG. 5. Typical alpha-proton pulse-height spectrum from the spectrometer detector, for alphas and protons of about 7 Mev.

[13] S. Bashkin and G. Goldhaber, Rev. Sci. Instr. **22**, 112 (1951).

[14] For CsI(Tl) scintillation detectors, alphas give pulses about 0.6 times as high as those from protons of the same energy. Private communication from R. R. Carlson, who kindly made available the results of investigations into the response of CsI(Tl) crystals, to various types of particles, made by Bashkin, Carlson, Douglas, and Jacobs [Phys. Rev. **109**, 434 (1958), this issue].

[15] R. H. Helm, Ph.D. thesis, Stanford University, February 1956, referred to in R. Hofstadter, Revs. Modern Phys. **28**, 214 (1956).

[16] J. R. Holt and T. N. Marsham, Proc. Phys. Soc. (London) **A66**, 1032 (1953).

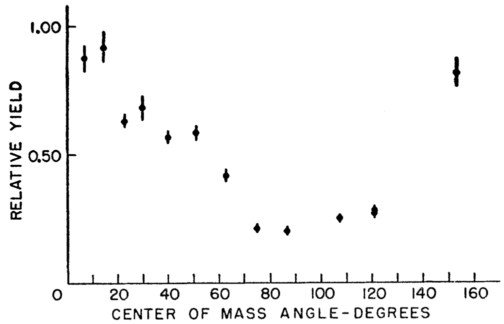

FIG. 6. Angular distribution of $Na^{23}(d,p)Na^{24}$ protons leading to the 0.472-Mev level of Na^{24}.

expected from appreciable contaminant buildup on the target.

III. RESULTS AND ANALYSIS

Each proton doublet was resolved into separate peaks by adjusting the normalization of one peak-shape curve to the two parts of the doublet until the two separated peaks formed the original profile when combined. The shapes used were typical spectrometer peak profiles, distorted to take into account the following two points: (1) The energy of a proton group is a function of angle; the spectrometer aperture is wide enough (about $\pm 2°$) to accept particles having an appreciable spread in energy due only to range of angle. (2) The spread in energy of protons leaving the target at one angle is a function of angle, because the emergent particles must travel through a thickness of target dependent on angle. Relative yields were determined by measuring separated peak areas and dividing each peak area by the mean spectrometer current for that peak.[17]

Figure 6 is the angular distribution of protons leading to the 0.472-Mev state of Na^{24}. The data could not be fitted by a Butler-theory analysis. No attempt was made at a combined analysis using the Butler theory and compound-nucleus theory,[18] because of the liberal number of parameters available for such an interpretation. Figure 7 is the angular distribution of

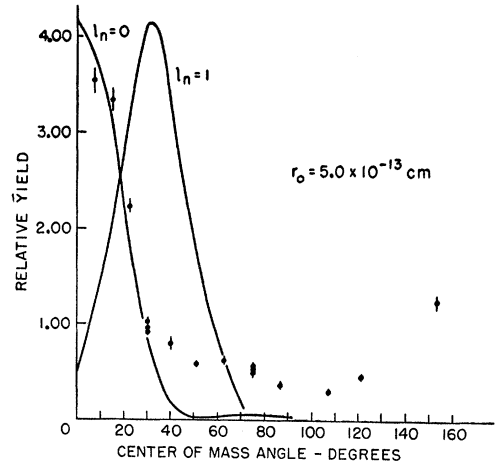

FIG. 7. Angular distribution of $Na^{23}(d,p)Na^{24}$ protons leading to the 0.564-Mev level of Na^{24}. The curves were computed from the Butler theory using $l_n=0$ and 1; r_0 was obtained from the equation $r_0=1.33(A^{\frac{1}{3}}+1)\times 10^{-13}$ cm, where A is the number of nucleons in the target nucleus. The constant, 1.33, was obtained from electron scattering results[15] which gave the nuclear radius of Mg^{24} as $1.33A^{\frac{1}{3}}$ and that of Si^{28} as $1.29A^{\frac{1}{3}}$. This value of r_0 is almost identical with that obtained from Holt and Marsham's expression,[16] $r_0=(1.7+1.2A^{\frac{1}{3}})\times 10^{-13}$ cm, which yields $r_0=5.1\times 10^{-13}$ cm.

protons leading to the 0.564-Mev level, which clearly is formed by $l_n=0$ capture.

Hence, the 0.564-Mev level of Na^{24} has spin 1+ or 2+, confirming directly the assignment, by Bretscher *et al.*,[8] for this level. This result is consistent with Motz's suggestion[5] that the 0.564-Mev level have spin 2+. No conclusion can be drawn concerning the 0.472-Mev level from the data of this experiment.

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[17] A derivation justifying use of current-normalized peak areas is given in reference 12.

[18] L. Wolfenstein, Phys. Rev. **82**, 690 (1951).