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Spin and Parity of the First Excited State of Na^{23}

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The angular distributions of the 440-kev gamma radiation resulting from the $Na^{23}(p,p'\gamma)Na^{23}$ reaction have been measured for proton bombarding energies of 1.288 and 1.460 Mev. Decay by inelastically scattered protons is particularly favorable for these two well-isolated resonances in Mg^{24}. The results show a marked anisotropy, thereby ruling out the possibility that the first excited state of Na^{23} has spin $J=\frac{1}{2}$. Otherwise the experiments do not permit a completely unambiguous assignment. Evidence is presented, however, showing that the most plausible assignment is $J=5/2+$.

INTRODUCTION

It is well known that the ground-state spin of Na^{23} cannot be obtained from a simple theory based on the single-particle model. This anomalous behavior is usually explained by asserting that the ground state configuration is $[(d_{\frac{5}{2}})^3]_{\frac{3}{2}}$. No obvious predictions may be made concerning the spin of the first excited state which is known to be 440 kev above the ground state. The choice between the various possibilities is therefore left largely to experimental determination. On the basis of shell model theory, one would expect the spin to be either $J=\frac{1}{2}$ or $J=5/2$, the former value corresponding to an excited state configuration $(s_{\frac{1}{2}})$, the latter to an alternate spin state of the ground state configuration $(d_{\frac{5}{2}})^3$. Less likely, although not ruled out entirely, would be the choice $J=\frac{3}{2}$ which could result from a $(d_{\frac{3}{2}})$ configuration. It is evident that for all cases mentioned the parity of the excited state must be even. Experimental evidence in contradiction with this result would seriously impair one's faith in the validity of nuclear shell structure.

One possible method by which such an assignment might be obtained is through a study of the $Na^{23}(p,p'\gamma)Na^{23}$ reaction. From the experimental point of view the simplest way of obtaining this kind of information is to do a triple correlation measurement in which the intermediate radiation is unobserved. In this case the inelastically scattered protons need not be detected and the angular distribution of the 440-kev gamma radiation may be measured relative to the incident proton beam. Even though the above procedure is much simpler experimentally than an angular correlation measurement between the inelastically scattered protons and the subsequent gamma radiation, such a correlation experiment, using coincidence techniques, would have the inherent advantage that fewer adjustable parameters would enter into the interpretation of the results. Any parameter, for example, required for describing the formation of the compound nucleus Mg^{24} would be irrelevant in a proton-gamma correlation study. This disadvantage of a triple correlation measurement is offset, however, by using wherever possible those parameters which have previously been used in the interpretation of related experiments.

EXPERIMENTAL PROCEDURE

The experimental arrangement and the method used for these measurements have been described in detail by Prosser *et al.*[1] One important improvement in the technique consisted in recording the gamma rays from the movable counter with a 10-channel discriminator. This procedure offers the advantage that the angular distribution of the low-energy 440-kev gamma radiation may readily be obtained in the presence of low-intensity, high-energy gamma rays resulting from competing reactions. Observations were made at various angles and the yields of the 440-kev gamma ray were taken as the area under the appropriate peak of the pulse-height distribution. Due precautions were taken to compute this yield by means of a consistent procedure, as the counting rate usually did not drop to zero on the low-energy side of the peak. The angular distribution was then determined by comparing the yield at the appropriate angular positions[2] with that of the fixed monitor counter.

RESULTS

The results of the measurements of the 440-kev gamma-ray angular distribution for proton energies of 1.288 and 1.460 Mev are shown in Fig. 1. The indicated errors are the probable ones arising only from the statistics. Calculations of a least-squares fit of the experimental points are indicated by the solid curves. Only those terms in the least-squares fit which were outside the probable errors are shown. Because of the smallness of the coefficients and the geometry of the experimental arrangement, no correction was made for the finite solid angle subtended by the counters. Calculations indicate that the solid-angle correction factors differ from unity by a negligible amount.[3]

The form of the experimental distributions may be interpreted by using the theory developed by Bieden-

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[1] Prosser, Baumann, Read, Brice, and Krone, Phys. Rev. **104**, 369 (1956).
[2] P. C. Price, Phil. Mag. **45**, 237 (1954).
[3] M. E. Rose, Phys. Rev. **91**, 610 (1953).

harn and Rose.[4] A useful modification, particularly adaptable to the triple correlation process, has recently been given Sharp *et al.*[5] To apply this formalism to the present problem, specific assumptions must be made with regard to the relative contributions of the channel spins and the orbital angular momenta of the incoming and outgoing particles, as well as the multipole order of the gamma radiation emitted. Because of the low-energy of the 440-kev radiation, the intensity of $E2$ radiation should be smaller by several orders of magnitude to that of $M1$ radiation. For the bombarding energies used it also appears reasonable to assume that at least the outgoing (inelastically scattered) protons contain only the lowest partial wave consistent with conservation of momentum and parity. Although these specific assumptions reduce the possible number of theoretical fits of the angular distribution considerably, these assumptions alone are not sufficient to give a unique assignment of the spin and the parity of the excited state of Na^{23}. The various possibilities are discussed below for two resonances which decay predominantly by inelastic scattering, and for which the spin and the parity have been independently determined.

One of the resonances chosen for this investigation (at $E_p=1.288$ Mev) is ideally suited for these measurements. Aside from having the largest cross section for the inelastic scattering process in this range of proton bombarding energies, it decays strongly by elastically scattered protons and by the emission of alpha particles to the ground state of Ne^{20} as well. This permits the determination of the spin and parity of the compound state by two entirely independent experiments. The elastic proton scattering experiments have been reported by Baumann *et al.*[6] who have given an assignment of $1-$ for this compound state. This result is in agreement with the earlier results of Stelson[7] based upon the angular distribution of alpha particles from the $Na^{23}(p,\alpha)Ne^{20}$ reaction. It is of interest to note that the experimental angular distribution of the alpha particles could be fitted only by assuming that the compound state was formed primarily by channel spin 2 and with a large admixture of f-wave protons, which for these proton energies cannot be justified by penetrability arguments alone. Assuming the validity of these assumptions on the basis of the agreement with the elastic scattering data, one should expect that these same parameters should be used in the description of the inelastic scattering process. The inclusion of these parameters, in addition to those assumed above, allows one to determine uniquely the angular distribution of the 440-kev gamma radiation for various values of the spin of the excited state. It may indeed be shown that the experimental distribution $W(\theta)=1-0.074P_2(\cos\theta)$ may be fitted precisely by assuming that the first excited state of Na^{23} is $5/2+$, that the ratio of channel spins $s_1(2)/s_1(1)=2$ and that the ratio of the intensities of f-wave protons to p-wave protons is 0.03. This corresponds to a ratio for the reduced widths for the formation of the compound nucleus $[\gamma_3{}^2/\gamma_1{}^2]^{\frac{1}{2}}=4$ which is nearly the same as the value assumed by Stelson.

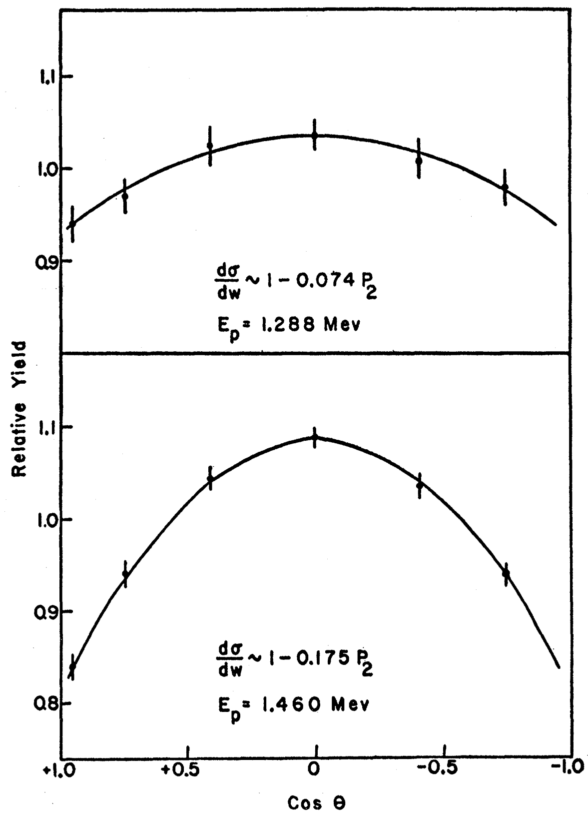

FIG. 1. Angular distributions of the gamma rays for proton bombarding energies $E_p=1.288$ Mev and $E_p=1.460$ Mev.

It should be emphasized that the experimental distribution may be fitted by assuming $J=\frac{3}{2}+$, and indeed for $J=\frac{3}{2}$ or $5/2$ and parity odd. This may be achieved, however, only by making less plausible assumptions about the parameters involved. The anisotropy of the distribution definitely rules out the possibility of $J=\frac{1}{2}$ for the excited state. This is in agreement with recent experiments by Mooring and Monahan[8] who observed a marked anisotropy in the angular yield of the 440-kev gamma rays resulting from the $Na^{23}(n,n')Na^{23}$ reaction.

The second resonance at which measurements were made occurs at proton energy $E_p=1.460$ Mev. For this resonance there exist again two independent determinations of spin and parity which, however, are not in agreement with each other. The elastic scattering experiments[6] have given an assignment of $3-$ whereas

[4] L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. **25**, 729 (1953).

[5] Sharp, Kennedy, Sears, and Hoyle, Chalk River Laboratory Report CRT-556 (unpublished).

[6] Baumann, Prosser, Read, and Krone, Phys. Rev. **104**, 376 (1956).

[7] P. H. Stelson, Phys. Rev. **96**, 1584 (1954).

[8] F. P. Mooring and J. E. Monahan (private communication).

an earlier report by Newton[9] has suggested an assignment of 2− for this state. The experimental distribution $W(\theta)=1-0.175P_2(\cos\theta)$ may be fitted for either of the above assignments, but for the latter assignment only if one assumes that the compound state (2−) is formed exclusively by channel spin 2. Neither the 2− assignment nor this mode of formation can be reconciled with the elastic scattering data which require approximately equal contributions of the two entrance channels. An assignment of 5/2+ for the first excited state of Na^{23} is again in agreement with these parameters. This internal consistency leads one to suspect not only that the compound state at $E_p=1.460$ Mev is indeed a 3− state, but also that the 5/2+ assignment for Na^{23*} is certainly the most plausible of those suggested.

[9] J. O. Newton, Phys. Rev. **96**, 241 (1954).

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Beta Decay of Tb^{161}†

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The radiations emitted in the beta decay of 7-day Tb^{161} have been studied with a 180°, 40-cm radius of curvature, shaped magnetic field spectrometer and a scintillation counter. Gamma-gamma coincidence measurements have also been made. The following transitions with multipolarities indicated were observed (energies in kev): 25.5($E1$), 48.9($M1$), 56.9($E1$, tentative), and 74.6($E1$). The following beta groups were also observed (energies in kev): 571, 522, 496, and 439. A level scheme incorporating these data is presented.

I. INTRODUCTION

Terbium-161 is a β^- emitter with a half-life of 7 days. The spin of Dy^{161}, the daughter, was determined to be 5/2 by Cooke and Park.[1] The end point of the beta spectrum was determined to be 0.5 Mev by absorption measurement.[2] Scharff-Goldhaber *et al.*[3] made a probable assignment of a 26-kev gamma ray to Tb^{161} based on proportional chamber results. Cork *et al.*[4] reported a single 49.0-kev gamma ray which was converted mainly in the L_I electron subshell and from this fact assigned an $M1$ multipolarity to the transition. This group postulated that the beta decay went to an excited state 49.0 kev above the ground state and was followed by an $M1$ transition to ground. The energy of this gamma ray was given as 48.8 kev by Jaffe[5] from curved crystal spectrometer measurements.

Recently, Barloutaud and Ballini[6] studied the decay of Tb^{161} using a scintillation spectrograph and coincidence techniques. They reported a gamma ray at ~75 kev, 45–45 kev γ-γ coincidences, and 45–75 kev γ-γ coincidences. The total β-spectrum end point was determined to be 550±10 kev, and the β spectrum in coincidence with the 75-kev gamma ray was reported to have the same "shape" and end point as the total β spectrum. This group also found coincidences between a β group and a 47–48 kev gamma ray. They proposed a level scheme in which two beta groups populate the first and second excited states, 75 kev and 125 kev above the ground state of Dy^{161}, respectively, with no beta decay directly to the ground state.

Temmer and Heydenburg have examined the levels observed from Coulomb excitation in natural dysprosium.[7] They feel that the first excited state, spin =7/2, of the Bohr and Mottelson unified model[8] rotational band of Dy^{161} and Dy^{163} lies ~76 kev above ground, and that the second rotational level, spin =9/2, lies ~166 kev above the ground state.

It seemed to be of interest to re-examine the decay of Tb^{161} since neither of the reported level schemes incorporated all of the experimental data.

II. EXPERIMENTAL PROCEDURE

The beta spectrum and conversion lines were measured in a high-resolution, 40-cm radius of curvature, 180°, shaped magnetic field spectrometer.[9] A specially designed end-window, loop-anode counter[10] was used for electron detection. This counter has a plateau of over 100 volts at a threshold of 950 volts with a slope of 1.5% rise per 100 volts increase. A thin Zapon window (cutoff=1.7 kev), supported on 56% trans-

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[1] A. H. Cooke and J. G. Park, Proc. Phys. Soc. (London) **A435**, 282 (1956).
[2] R. E. Hein and A. F. Voigt, Phys. Rev. **79**, 783 (1950).
[3] Scharff-Goldhaber, der Mateosian, McKeown, and Sunyar, Phys. Rev. **78**, 325 (1950) (A).
[4] Cork, LeBlanc, Nester, and Stumpf, Phys. Rev. **88**, 685 (1952).
[5] H. Jaffe, University of California Radiation Laboratory Report UCRL-2537, 1954 (unpublished).
[6] R. Barloutaud and R. Ballini, Compt. rend. **241**, 389 (1955).
[7] G. M. Temmer and N. P. Heydenburg (private communication, June, 1956).
[8] A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **27**, No. 16 (1953).
[9] L. M. Langer and C. S. Cook, Rev. Sci. Instr. **19**, 249 (1948).
[10] E. A. Plassman and L. M. Langer, Phys. Rev. **96**, 1593 (1954).