Because the usual $M1$ matrix element vanishes in the denominator of λ for such transitions, this form of λ is not readily amenable to calculation. For l-forbidden transitions the numerator reduces to

$$-\sum_m \boldsymbol{\varepsilon}_m \cdot \langle \mu \mathbf{r}(\boldsymbol{\sigma}\cdot \mathbf{r})/R^2\rangle \tag{9}$$

and λ may be rewritten as $\lambda=\alpha\delta\lambda'$. The first factor is

$$\alpha=[5/(2\pi^{\frac{1}{2}})](\hbar c/R)^2(2Mc^2E)^{-1}, \tag{10}$$

where E is the gamma-ray energy and R is the nuclear radius ($R=1.2\times10^{-13}A^{\frac{1}{3}}$ cm). The second factor, δ, is the $E2/M1$ mixture ratio obtained from the experimental γ-γ angular correlation, and the third factor is

$$\lambda'=\sum_m \boldsymbol{\varepsilon}_m\cdot\langle \mu \mathbf{r}(\boldsymbol{\sigma}\cdot\mathbf{r})\rangle/\sum_m r^2 Y_2{}^m. \tag{11}$$

This factorization is independent of the form of the $M1$ matrix element which may in actuality contain spin-orbit and exchange operators. λ' does not contain l-forbidden matrix elements and is independent of the nuclear radial matrix elements. Thus the use of δ, the experimental mixture ratio, may serve as an aid to the computation of λ.

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Nuclear Levels in Si^{28} and P^{31}†

P. M. Endt, *Fysisch Laboratorium der Rijksuniversiteit, Utrecht, The Netherlands*

AND

C. H. Paris, *Physics Department and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts*

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Lead-phosphate targets have been bombarded with protons accelerated by an electrostatic generator to energies of 6.5 and 7.0 Mev. Charged reaction products (alpha particles and elastically and inelastically scattered protons) were observed at 50, 90, and 130 degrees to the proton beam with a high-resolution magnetic analyzer.

The ground-state Q-value of the $P^{31}(p,\alpha)Si^{28}$ reaction has been measured as 1.909 ± 0.010 Mev. Levels were observed in Si^{28} at 1.771 and 4.617 Mev and in P^{31} at 1.267, 2.234, 3:133, 3.293, 3.414, 3.505, 4.188, 4.257, 4.430, 4.590, 4.633, 4.784, and 5.012 Mev.

I. INTRODUCTION

The reaction $Si^{30}(p,\gamma)P^{31}$ is being investigated at present in Chalk River,[1] Liverpool, and Utrecht, in order to determine spins and parities of nuclear levels in P^{31}. For the analysis of the complicated gamma-ray spectra observed in this reaction, it is extremely helpful if the excitation energies of levels in the final nucleus are known with good precision. The present high-resolution magnetic analysis of the $P^{31}(p,p')P^{31}$ reaction was started to provide such data. The photoplates used to record the elastically and inelastically scattered protons also showed alpha-particle groups from which new information was obtained on the $P^{31}(p,\alpha)Si^{28}$ reaction.

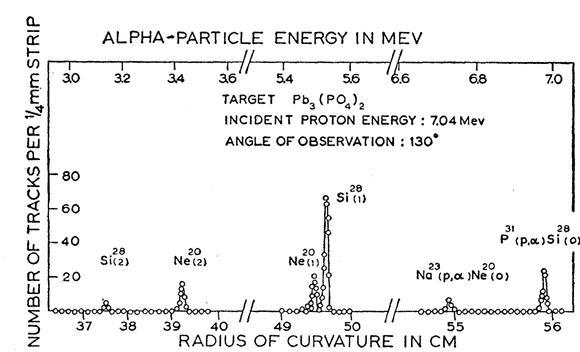

Fig. 1. Energy spectrum of alpha particles observed from the proton bombardment of a lead-phosphate target.

Prior to this work, only the first level in both Si^{28} and P^{31} had been observed from high-resolution (p,p') magnetic analysis,[2,3] while higher levels had been reported from (d,n) and (p,γ) experiments.[4]

II. EXPERIMENTAL PROCEDURE

Protons accelerated with the MIT–ONR electrostatic generator[5] were used to bombard thin lead-

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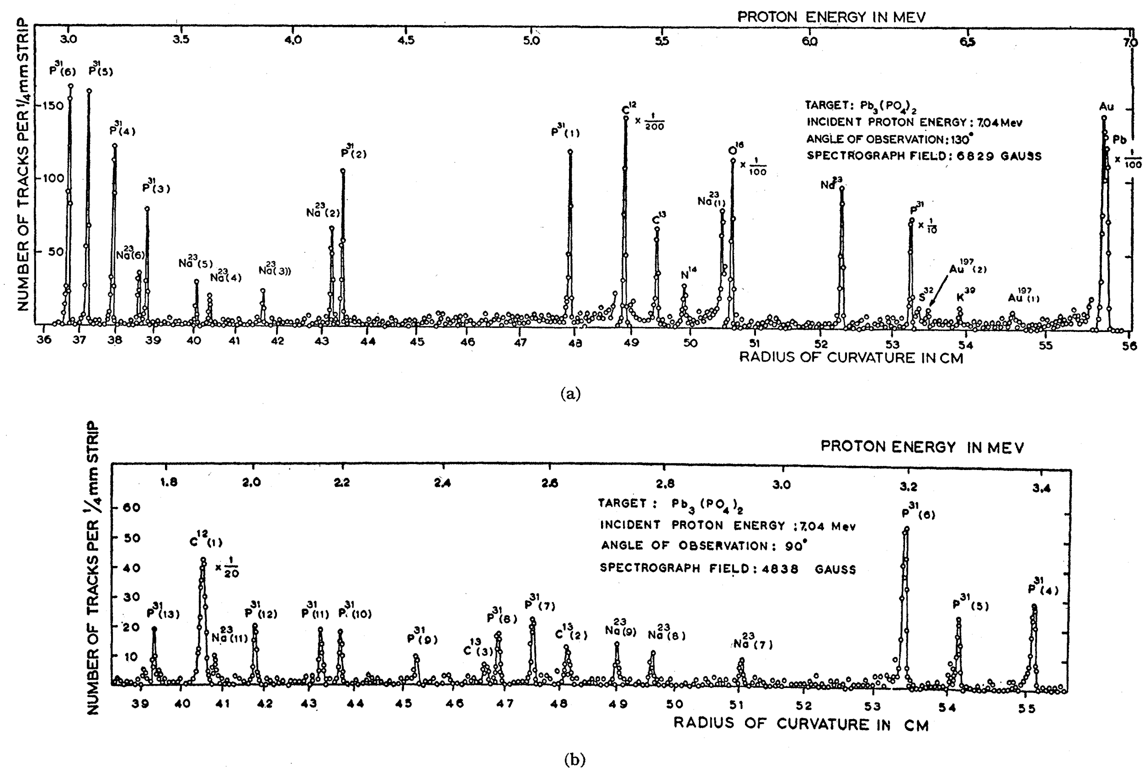

FIG. 2. Energy spectra of protons observed at two different spectrograph field settings and at different angles from the proton bombardment of a lead-phosphate target. The spectra overlap to a certain extent.

phosphate targets obtained by evaporation onto Formvar films strengthened by a thin evaporated gold layer. Energies of charged reaction products emitted from the target at angles of 50, 90, or 130 degrees to the proton beam were determined with a broad-range magnetic spectrograph.[6]

Four different bombardments were performed at an incident proton energy of 7.037 Mev. Both at $\theta=90$ degrees and at $\theta=130$ degrees, exposures were made at two different spectrograph field settings so as to focus either the high-energy (3.0 to 7.0 Mev) or the low-energy (1.5 to 3.5 Mev) part of the secondary-particle energy spectrum on the nuclear emulsion serving for particle detection. Two additional exposures of the low-energy spectrum were obtained at an incident proton energy of 6.513 Mev and at angles of $\theta=50$ degrees and $\theta=90$ degrees.

III. RESULTS

The alpha-particle spectrum obtained from the $E_p=7.037$ Mev, $\theta=130$ degree, bombardment is shown in Fig. 1. From comparison with the $E_p=7.037$ Mev, $\theta=90$ degrees, exposure it could be concluded that, of the six observed groups, three have to be assigned to the $P^{31}(p,\alpha)Si^{28}$ reaction and three to the $Na^{23}(p,\alpha)Ne^{20}$ reaction. The presence of such an unexpectedly large amount of sodium in the target was confirmed by the observation of the corresponding elastically and inelastically scattered proton groups (see Fig. 2). The Q values computed for the three $Na^{23}(p,\alpha)$ groups agree well within the experimental error with those reported by Sperduto and Buechner.[7] The three $P^{31}(p,\alpha)Si^{28}$ groups correspond to a ground-state Q value of 1.909 ± 0.010 Mev, and to excited states in Si^{28} at 1.771 ± 0.008 and 4.617 ± 0.008 Mev. Although the group leading to level (2) is of low intensity, both in the 90- and 130-degree exposure, it is very sharp; furthermore, the background in this energy region is completely negligible.

The proton spectra observed from the 7.037 Mev, $\theta=130$ degrees, bombardment at high spectrograph field settings and from the 7.037 Mev, $\theta=90$ degrees, bombardment at low field setting are shown in Fig. 2. Proton groups are found from elastic scattering by Pb, Au, K^{39}, S^{32}, P^{31}, Na^{23}, O^{16}, N^{14}, C^{13}, and C^{12}. Two weak groups, also observed by others[8] in analogous experiments with the same apparatus, were ascribed to inelastic scattering by Au^{197}. Contaminant groups arising from inelastic scattering were observed from

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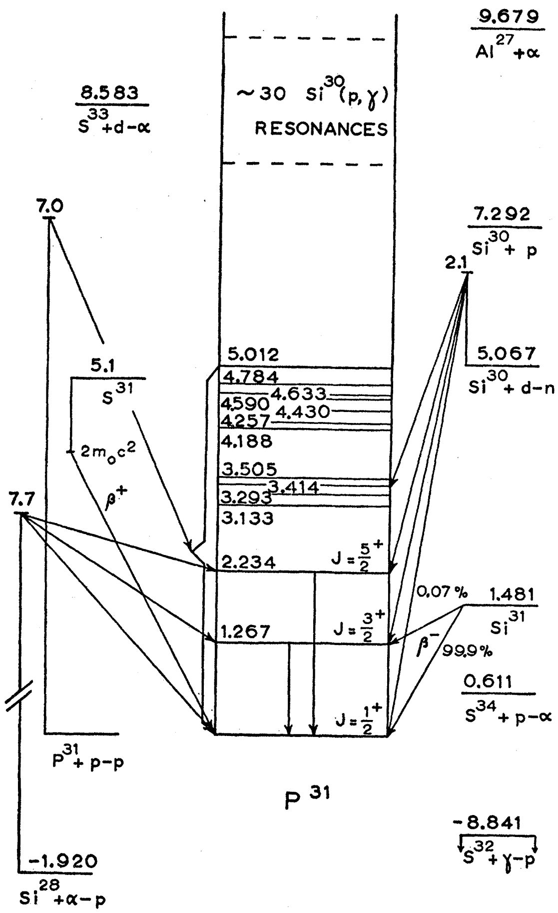

FIG. 3. Level diagram of P^{31}.

C^{12}, C^{13}, and, notably, from Na^{23}. The excitation energies of Na^{23} levels obtained in this work agreed well with those measured by Sperduto and Buechner.[7] The remaining groups were assigned to P^{31} because they could not be attributed to any of the contaminants known to be present and because they showed the expected energy shift as a function of angle and bombarding energy. They correspond to levels at 1.267, 2.234, 3.133, 3.293, 3.414, 3.505, 4.188, 4.257, 4.430, 4.590, 4.633, 4.784, and 5.012 Mev, all ±0.005 Mev.

IV. DISCUSSION

The ground-state Q value of 1.909±0.010 Mev found for the $P^{31}(p,\alpha)Si^{28}$ reaction is in exact agreement with an earlier MIT value of 1.909±0.010 Mev[9] and in very good agreement with a recent measurement at the Bartol Research Foundation of 1.911±0.005 Mev.[2]

The excitation energy of the first level in Si^{28}, which was found to be 1.771±0.008 Mev, is also in fair agreement with the values of 1.777 Mev reported from the $Si^{28}(p,p')Si^{28}$ reaction[3] and 1.782±0.010 from the $Al^{28}(\beta^-)Si^{28}$ reaction.[10] With low-resolution methods, this level has been observed from many reactions.

The second level at 4.617±0.008 Mev has also been given as 4.47±0.10 Mev[11] and as 4.54±0.2 Mev[12] from the $Al^{27}(d,n)Si^{28}$ reaction and as 4.6±0.3 Mev from the $Si^{28}(p,p')Si^{28}$ reaction.[13] This level probably decays with a 2.8-Mev gamma ray to the Si^{28} first level.[14]

The first level in P^{31}, here observed at 1.267±0.005 Mev, has also been reported from magnetic analysis of the $P^{31}(p,p')P^{31}$ reaction at 1.264±0.004 Mev.[2] Scintillation spectrometer measurements yield 1.26 Mev from the $Si^{31}(\beta^-)P^{31}$ decay,[15] 1.26±0.015 Mev from the $P^{31}(p,p')P^{31}$ reaction,[16] and 1.26 Mev from the $Si^{30}(p,\gamma)P^{31}$ reaction.[1] A level at 2.23 Mev has also been observed from the latter reaction.[1] A level at 3.4 Mev may have been observed from the $Si^{30}(d,n)P^{31}$ reaction.

The present information on the P^{31} level scheme, along with older data, is presented in Fig. 3.

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