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Energy Levels in Na^{23} from the $Ne^{22}(p,\gamma)Na^{23}$ Reaction[*]

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The gamma-ray excitation function for the $Ne^{22}(p,\gamma)$ reaction has been investigated in the energy range of 600 kev to 1800 kev. Eleven resonances could definitely be identified to result from this reaction. The cascades leading to the ground state of Na^{23} were determined and found to proceed for the most part through well-known lower lying states, although no gamma rays corresponding to transitions through the 2.08 Mev and 2.39 Mev were observed at any of the resonances investigated.

INTRODUCTION

THE excited states of Na^{23} have been studied by means of several different reactions.[1] Relatively little is known to date about the properties of all but the first excited state at 439 kev whose spin and parity appear to be $\frac{5}{2}+$.[2,3] It is well known that this nucleus cannot be described by a single-particle configuration. The configuration $(d_{\frac{5}{2}})^3$ explains the experimental value of the spins of both the ground state and first excited state but fails to account for the observed level spacings. Theoretical calculations have recently been made[4] to account for the observed level structure using the rotational model. Spin assignments made on this basis may be verified by observing gamma-ray cascades, through these levels, originating from the compound states of the nucleus. The $Ne^{22}(p,\gamma)Na^{23}$ reaction is ideally suited for this purpose. Several resonances originating from this process have been reported,[5,6] but the gamma-ray spectra have been observed only at one of these resonances. In the present experiments we have studied this reaction for a 1.5-Mev range of proton energies observing the gamma-ray spectra at the most prominent resonances.

EXPERIMENTAL PROCEDURE

Thin isotopic targets[7] of Ne^{22} were bombarded with the proton beam of one microampere from the University of Kansas Van de Graaff generator. The targets were mounted in a special target chamber that allowed good thermal contact between the target backing and the walls of the chamber to minimize heating by the beam. Experience showed that with such precautions the targets withstood several hours of bombardment without appreciable target depreciation. The gamma rays produced by the reaction were detected by a 3-in.×3-in. NaI(Tl) crystal mounted on a Dumont 6263 photomultiplier tube. Because of the low cross section of the reaction the geometry was arranged to permit the crystal to subtend a solid angle of nearly 2π radians. The pulses, after suitable amplification, were displayed on a 256-channel RCL pulse-height analyzer. Simultaneously the total number of gamma rays of energy greater than 1.5 Mev were recorded by a conventional scaler.

The excitation curve was obtained for proton energies ranging between 600 kev and 1800 kev. This interval was covered in 2.5-kev steps except in those regions at which a resonance structure was observed. In these instances the observations were repeated at 1.25 kev and for considerably longer preiods to improve the statistics. Pulse-height spectra were obtained at the most prominent resonances. These were analyzed by comparing the pulse-height distribution with the following standard pulse profiles: the 9.18-Mev γ ray

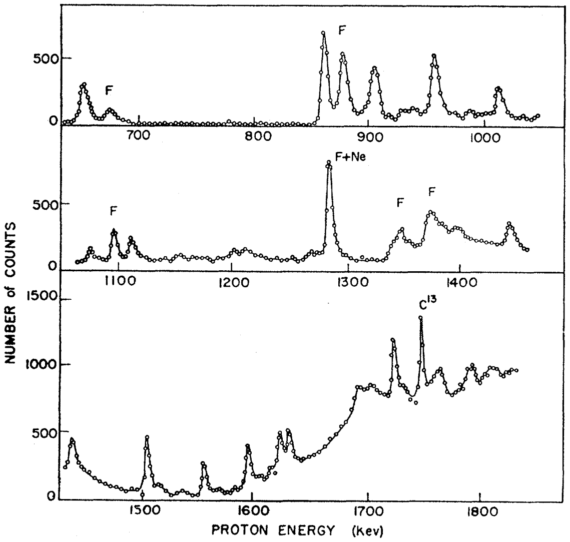

FIG. 1. Excitation curve for the $Ne^{22}(p,\gamma)Na^{23}$ reaction. Those resonances marked F are due to fluorine contamination. The sharp resonance at 1743 kev is a result of the $C^{13}(p,\gamma)$ reaction. The general increase in gamma-ray background for proton energies above 1600 kev is not quantitatively reproducible as it presumably arises from a reaction in carbon built up on the target.

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[1] P. M. Endt and C. M. Braams, Revs. Modern Phys. **29**, 683 (1957).

[2] W. G. Read and R. W. Krone, Phys. Rev. **104**, 1018 (1956).

[3] Berenbaum, Towle, and Matthews, Proc. Phys. Soc. (London) **A69**, 858 (1956).

[4] E. B. Paul and J. H. Montague, Nuclear Phys. **4**, 375 (1957).

[5] Broström, Huus, and Koch, Nature **160**, 498 (1947).

[6] Thornton, Meads, and Collie, Phys. Rev. **109**, 480 (1958).

[7] The targets were supplied by the Atomic Energy Research Establishment, Harwell, England.

resulting from the $C^{13}(p,\gamma)$ reaction, the 6.13-Mev γ ray from the $F^{19}(p,\alpha\gamma)$ reactions, the 4.43-Mev γ ray from the $B^{11}(p,\gamma)$ reaction, and the 1.28-Mev γ ray from Na^{22}.

EXPERIMENTAL RESULTS

Figure 1 shows the excitation curve for the $Ne^{22}(p,\gamma)$ reaction. Because of the very limited supply of target material, no attempt could be made to assure that all the structure observed is due to the above reaction. In the energy range investigated, eleven resonances could definitely be ascribed to the Ne^{22} process. Others are most certainly due to fluorine which could readily be ascertained by studying the pulse-height spectra. The strong resonance at $E_p = 1280$ kev, although coinciding very closely with a fluorine resonance, is in part at least due to the neon reaction and, to a lesser degree, this is probably also true for the resonance observed at $E_p = 873$ kev. Above 1.6 Mev the structure becomes considerably more complicated. Of the two most prominent resonances in this region, the one at 1721 kev is due to Ne^{22}; the one at 1744 kev results almost certainly from the $C^{13}(p,\gamma)$ reaction. The remaining resonances in this region were too weak and not sufficiently isolated to study their gamma-ray spectrum with profit.

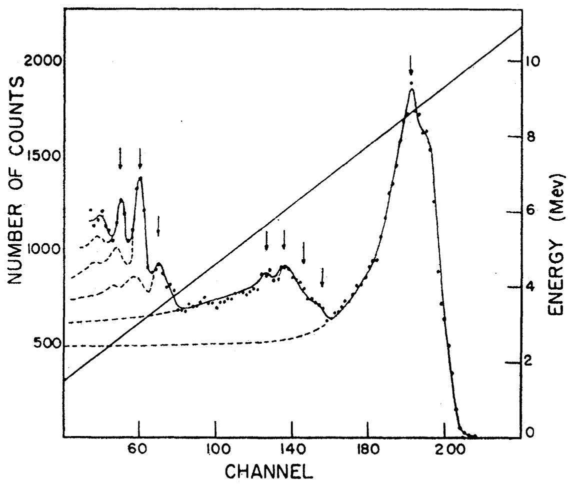

FIG. 2. Pulse-height spectrum observed at $E_p = 634$ kev. Aside from the strong high-energy peak corresponding to the ground-state transition, three low-energy gamma rays are clearly visible. These are parts of cascades through the 3.85, 2.98, and 2.60-Mev states.

A typical pulse-height spectrum is shown in Fig. 2. The solid curve indicates the observed distribution. The dashed lines serve to indicate how the spectrum is analyzed in terms of the shapes of typical single-calibration gamma rays of appropriate energy. Table I and Fig. 3 summarize the results obtained at eleven different resonances. All of these show alternate cascades of varying intensities. The most conspicuous feature of the spectra is the disappearance of the ground-state transition for proton energies above 1 Mev and the apparent absence of any cascades through the second and third excited states at 2.08 and 2.39 Mev. Transitions to either the 2.64- or 2.71-Mev level occur at all except the 1.50- and 1.55-Mev resonances. These two levels are too close to be resolved but may perhaps be distinguished by the two alternate modes of decay that are observed. Experimentally one finds a ground-state transition corresponding to a 2.55-Mev gamma ray and an alternate transition to the first excited state corresponding to a 2.15-Mev gamma ray. The difference in energy is 40 kev less than the energy difference between the ground-state and first excited state, supporting the hypothesis that two different intermediate levels are involved. It should be noted however that the observed energy of both states is consistently lower (by about 90 kev) than that reported by Buechner *et al.*[8] Transitions to the 2.98-Mev state are observed at various resonances notably at 1280 and 1443 kev. This level decays predominantly to the ground state although a very weak transition to the 439-kev state cannot be ruled out. The same holds true for the 3.92-Mev level which is excited appreciably at $E_p = 859$

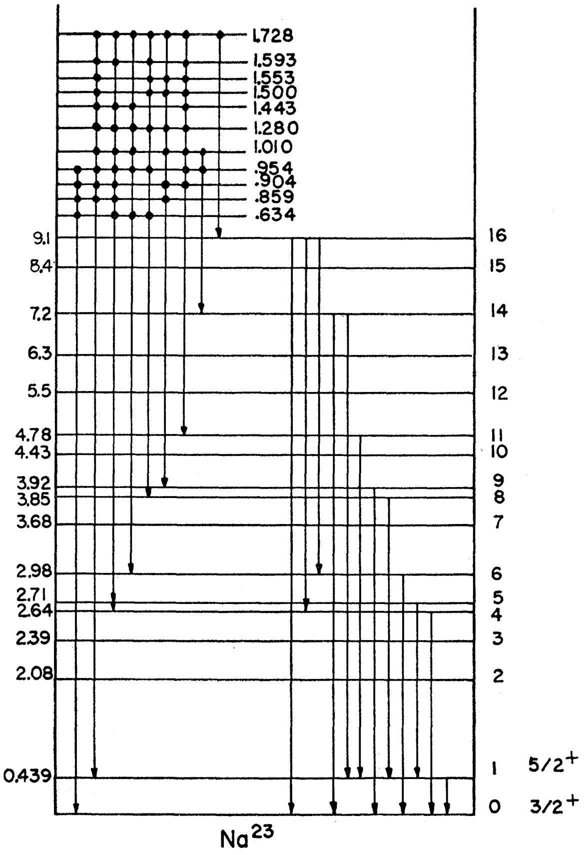

FIG. 3. Energy level diagram of Na^{23}. The energies of the 16 reported levels are those given by Endt and Braams.[1] The cascades shown summarize the results of this experiment.

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[8] W. W. Buechner and A. Sperduto, Phys. Rev. **106**, 1008 (1957).

TABLE I. Summary of gamma-ray cascades observed at 11 resonances in $Ne^{22}(p,\gamma)Na^{23}$. All the levels reported previously in Na^{23} have been listed. The numbers (0 to 16) identify the various levels. They correspond to the numbers found on the right of the energy level diagram. The relative intensities listed are the observed values. They are considered accurate within 10%. An asterisk shows whenever serious discrepancies occur in the intensities of different members of a cascade. The intensities of transitions to the levels No. 4, 5, 6, 8, 9, and 10 are the upper limits. This is due to the complication caused by contaminant reaction in fluorine.

Transition	Final state energy (Mev) \ E_p (kev) Q value (Mev)	634 9.40	859 9.61	904 9.65	954 9.70	1010 9.75	1280 10.125	1443 10.160	1500 10.228	1553 10.278	1593 10.317	1721 10.438
Res. to 0	0	85	50	56	60							
Res. to 1	0.439		18	27	19	24	23	22	62	35	47	17
Res. to 2	2.08											
Res. to 3	2.39											
Res. to 4 } Res. to 5	2.64 2.71	6	9	7	6	27	18	36			25	7
Res. to 6	2.98	4			5	5	30	28(?)			?	13(?)
Res. to 7	3.68											
Res. to 8	3.85	4			4		8		9	18	13	17
Res. to 9	3.92		23	3		5	14		18	27		7
Res. to 10	4.43											
Res. to 11	4.78			8	2	5	8	14	14	18	12	7
Res. to 12	5.50											
Res. to 13	6.30											
Res. to 14	7.20				4	33						
Res. to 15	8.40											
Res. to 16	9.10						?	?				33
16 to 0							?	?				18
16 to 4+5							?	?				12
16 to 6							?	?				12
14 to 0					1	8						
14 to 1					4	24						
11 to 1				16*	2	5	9	14	14	19	12	7
9 to 0			18	5		5	14		18	27	?	7
8 to 1		4			4		7		9	18	13	16
6 to 0		3			5	4	33	39*				25*
6 to 1 } 4 to 0		7	11	5	8	23	17	39			25	13
5 to 0		2	7	3	3	11	6	19			13	5
1 to 0		5	21	30	35	61	51	78	84	72	84	50

kev. The 3.85-Mev level again is distinguishable from the former only by its alternate mode of decay. The presence of a fairly intense 4.40-Mev gamma ray at a number of resonances without a feeder gamma ray of comparable intensity suggests a possible cascade through the 4.8-Mev and 439-kev states. At $E_p = 1010$ kev the intensity of the 2.60-Mev gamma ray is too large compared with that of the gamma ray arising from a transition between the resonance level and the 2.60-Mev level. A possible explanation is an alternate decay from the resonance level through the 7.20-Mev state which in turn decays to the 439-kev state or the ground state in the ratio 3:1.

At the 1720-kev resonance one observes for the first time an intense 1.30-Mev gamma ray which cannot readily be fitted into the level scheme so far discussed. Such a gamma ray could arise from a transition to a 9.1-Mev level which is probably the 9.01 Mev level previously reported[1]; this state in turn would then decay to either the ground state, the 2.60-Mev state, or the 2.98-Mev state in the ratio 2:3:3.[9] To check this hypothesis a search was made for a resonance in $Ne^{22}(p,\gamma)$ at approximately 350 kev proton energy. Although there was a faint indication of a resonance at approximately the right bombarding energy, the results were inconclusive because of the very low cross section and the proximity of a $F^{19}(p,\alpha\gamma)$ resonance.

In order to check some of the more questionable decay modes, an attempt was made to obtain coincidences between gamma rays belonging to a given cascade. Figure 4 shows the target assembly used. This particular arrangement was chosen because of the very low gamma-ray yield of the reaction. The coincidence spectrum is obtained by recording on the 256-channel analyzer only those gamma rays originating from counter 1 which are in coincidence with gamma rays of a given energy originating from counter 2. The coincidence circuit with a resolving time of approximately 2.5 microsecond is part of the pulse-height analyzer.

At the 859-kev resonance the 5.68-Mev gamma ray appears to be in coincidence with 3.92-Mev gamma ray as expected. At the 904-kev resonance the pulse-height spectrum shows two strong peaks corresponding to 3.92 and 4.40 Mev. Their relative intensity and the abnormal broadness of the former strongly suggest that they result from two different gamma-ray cascades,

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[9] Part of the 1.30-Mev gamma ray may be due to the $Ne^{22}(p,p')$ reaction leading to the first excited state at 1.28 Mev. That the 1.30-Mev gamma ray is not entirely due to inelastic scattering is apparent from the relative intensities of the 2.60- and 3.00-Mev gamma rays compared with those of their respective feeder gamma rays.

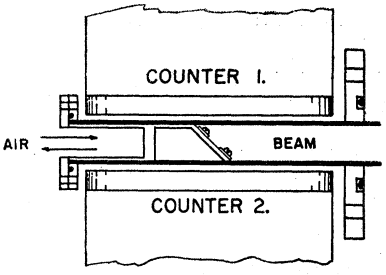

FIG. 4. Target chamber assembly used for coincidence measurements. The target chamber is constructed of a $\frac{1}{2}$-in. diameter tube of German silver, 0.008 in. thick. The insert onto which the target is clamped is made of aluminum.

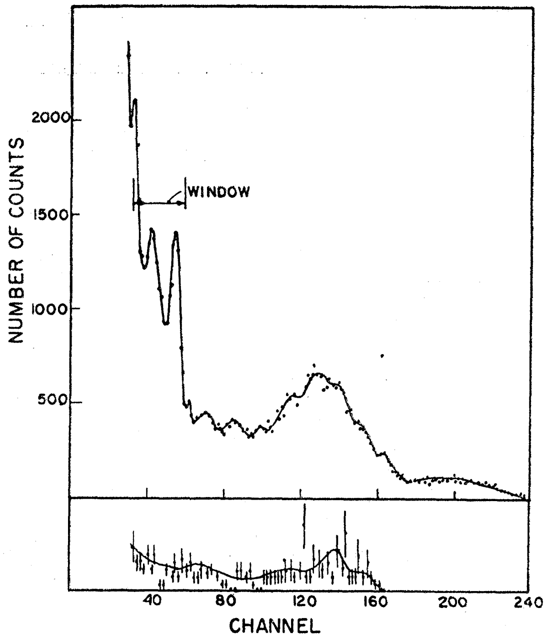

FIG. 5. Pulse-height spectrum and coincidence spectrum at $E_p = 1010$ kev. The window is set to pass gamma rays having energies between 1.90 and 2.80 Mev.

one through the 4.80-Mev state, the other through the 3.92-Mev state. On this hypothesis the coincidence spectrum is expected to show a 4.85- and 5.75-Mev gamma ray. The measurements, although not altogether clear, show that coincidences do occur at these two energies. At the 1010-kev resonance a cascade through the 7.2-Mev state requires a gamma ray of 6.78 Mev in coincidence with a gamma ray of energy 2.56 Mev. Figure 5 shows the coincidence spectrum. Even with the obviously poor statistics the measurements confirm the existence of a gamma ray of the appropriate energy. The ordinary pulse-height spectrum plotted above shows virtually no indication of this gamma ray as it is completely masked by the strong distribution resulting from the always-present fluorine contamination.

DISCUSSION

Recent success of the Bohr-Mottelson rotational model in explaining the nuclear spectra of medium light nuclei prompts one to apply this model to Na^{23}. This nucleus contains 7 nucleons in the $1d_{\frac{5}{2}}$ subshell. Of these, only one proton and two neutrons are likely to contribute to low-energy level formation. For a deformation of the order suggested by the nuclear quadrupole moment and the cross section of the Coulomb excitation of the first excited state one finds that levels with $\Omega = K = \frac{1}{2}$ or $\frac{5}{2}$ are almost degenerate and lie considerably above levels for which $K = \frac{3}{2}$. Accordingly the ground state should belong to $I = \Omega = K = \frac{3}{2}$. At higher energies one may expect interference between the states of different K as a result of rotation-particle coupling.[10] Calculations by Paul *et al.*[4] have yielded a level scheme that bears strong resemblance to the low-lying states experimentally observed. Accordingly it is expected that the spins of the five states between 2 Mev and 3 Mev be $\frac{7}{2}^+$, $\frac{1}{2}^+$, $\frac{5}{2}^+$, $\frac{3}{2}^+$, and $9/2^+$, respectively. It is difficult to reconcile the $9/2^+$ assignment ascribed to the 2.98-Mev state with the observation that it decays almost exclusively to the ground state ($\frac{3}{2}^+$), nor do these assignments help to explain the failure of observing cascades through either the 2.08- or 2.39-Mev states.

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[10] A. K. Kerman, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **30**, No. 15 (1956).