Low-Lying Excited States of Na^{22}†

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Using the singly and doubly ionized helium beams as well as a He^3 beam from our electrostatic generator, we have studied the low-lying level structure of Na^{22} in the $F^{19}(\alpha,n\gamma)Na^{22}$ and $Ne^{20}(He^3,p\gamma)Na^{22}$ reactions, respectively. We found one excited state at 666±4 kev in addition to most other states previously discovered in the self-conjugate reaction $Mg^{24}(d,\alpha)Na^{22}$ which presumably yields only states having $T=0$. We believe this state to be the 0^+ analog of the ground states of the two neighboring even-even nuclei forming the $T=1$ triplet at $A=22$. By various coincidence experiments, this state is found to decay by a 73-kev transition, having a probable half-life of 0.014 μsec, to the first-excited state of Na^{22} at 593 kev, which in turn decays to the 3^+ ground state with a half-life of 0.266±0.010 μsec. With the plausible assignment of 1^+ for the 593-kev state (0^+ being completely ruled out by the half-life) this would represent a pure $M1$—pure $E2$ cascade, whose strengths would be 0.0045 and 0.0077 single-particle units, respectively. The location of the first $T=1$ state occurs exactly as expected from a systematic study of the $A=4n+2$ series Coulomb-energy differences, lending additional support to the $I=0^+$, $T=1$ assignment.

We observed proton groups to most previously known states, and one new one at 3.75 Mev. A number of higher energy gamma rays were found in coincidence with those already mentioned which we can interpret within the framework of known excited states.

A. INTRODUCTION

IN view of the self-conjugate nature of the odd-odd nucleus Na^{22}, it is natural to inquire as to which of its excited states might be analogs of those of its two even-even neighbors, Ne^{22} and Mg^{22}. In particular, the lowest of these $T=1$ states, corresponding to the spin zero ground states of the neighbors, had not been located in Na^{22}, but is rather well identified in all other members of the $A=4n+2$ family of light nuclei having $N=Z$. As was pointed out some time ago,[1,2] the energy difference between the members of an isobaric triplet, having different values of T_z can be properly interpreted as a Coulomb energy difference and can lead to the determination of nuclear radii as in true odd-A mirror nuclei.

Some years ago we discovered a gamma-ray transition of 593 kev when bombarding F^{19} with alpha particles, and were able to assign this transition to the first-excited state of Na^{22} on the basis of neutron and gamma-ray threshold measurements in the $F^{19}(\alpha,n\gamma)Na^{22}$ reaction.[3] Since 600 kev was not too far below the value predicted for the first $T=1$ state by the systematics, we tried to find out whether $I=0^+$ was a possible spin assignment for this state. Isotropy is of course a necessary but not a sufficient condition. However, if this state be the first above the ground state—which is known to have character 3^+—the de-excitation would have to take place by an $M3$ transition, for which the single-particle lifetime estimate is about 0.1 second, and the "systematic" lifetime undoubtedly much longer. We were able to place an upper limit of 0.01 second upon this lifetime, which in effect ruled out a $M3$ isomerism and hence a spin 0^+, $T=1$ assignment. Subsequently, Browne and Cobb studied the level structure of Na^{22} by the self-conjugate reaction[4,5] $Mg^{24}(d,\alpha)Na^{22}$ and found a number of excited states, among which was one coincident in energy within the experimental uncertainties with the 593-kev state (see Fig. 7). Since only $T=0$ states should be appreciably excited in their reaction, the first $T=1$ state remained unknown. Our further attempts to identify this state form the substance of the present investigation.

B. EXPERIMENTAL DETAIL

We have tried to reach possible $T=1$ states by using the reactions (I) $F^{19}(\alpha,n\gamma)Na^{22}$ and (II) $Ne^{20}(He^3,p\gamma)Na^{22}$. In both cases we studied coincident events by means of an 80-channel quartz memory pulse-height analyzer[6] gated by a single channel in a modified "slow-fast"[7] time-compensated[8] coincidence system having $2\tau\sim30$ millimicroseconds.

In reaction (I) we used a moderately thin (~100 kev) target of CaF_2. The gamma rays were detected by one 1 in. ×1 in. and one 2 in. ×2 in. NaI(Tl) crystal placed very close to the target but shielded from each other by one-eighth inch lead to minimize Compton coincidences. We used both our singly charged He^+ beam up to 3.7 Mev, and our doubly charged He^{++} beam at about 6 Mev from the Department of Terrestrial Magnetism electrostatic generator. The slow-fast system allowed us to monitor the

† Preliminary results presented at the 1958 Spring Meeting of the American Physical Society [G. M. Temmer and N. P. Heydenburg, Bull. Am. Phys. Soc. Ser. II, **3**, 200 (1958)].

[1] O. Kofoed-Hansen, Phys. Rev. **92**, 1075 (1953).

[2] P. Stähelin, Phys. Rev. **92**, 1076 (1953).

[3] N. P. Heydenburg and G. M. Temmer, Phys. Rev. **94**, 1254 (1954).

[4] C. P. Browne and W. C. Cobb, Phys. Rev. **99**, 644(A) (1955).

[5] C. P. Browne, Laboratory of Nuclear Science, Massachusetts Institute of Technology, Progress Report, May 31, 1955 (unpublished).

[6] Schultz, Pieper, and Rosler, Rev. Sci. Instr. **27**, 437 (1956).

[7] G. S. Stanford and G. F. Pieper, Rev. Sci. Instr. **26**, 847 (1955).

[8] B. Johansson, Nuclear Instr. **1**, 274 (1957).

accidental coincidence rate simultaneously with the accidental plus true rate. The former was always below five percent of the true rate. This is important since the bombardment of F^{19} with alpha particles leads to several other reactions giving rise to abundant undesirable and even coincident gamma rays.[3] Delayed coincidences were observed by inserting appropriate lengths of tapped delay line or cable, depending upon the time ranges involved.

In reaction (II) we used a small gas cell containing ordinary neon at pressures up to one-fourth atmosphere, separated from the main vacuum by the thinnest reliable nickel window (0.05 mil, or 1.1 mg/cm^2), one quarter inch in diameter. At the bottom of the cell the beam was stopped in a niobium foil. A small window of one-mil aluminum on one side of the cell allowed protons to emerge and enter a 1-mm thick NaI(Tl) crystal, viewing the target at right angles to the He^{3+} beam. The beam energy at the target volume was usually about 2.5 Mev, and the effective gas target thickness was about 100 kev. For the detection of the 73-kev gamma transition we used a $\frac{1}{4}$-inch thick NaI crystal at right angles to the beam opposite the proton counter. The entire target assembly was insulated so that the beam current could be monitored; it had to be kept below 0.6 microampere to avoid burning the Ni window. Our ion source gas supply consisted of a 100-cc reservoir[9] of pure He^3. At the time of this writing we have been using the beam for about 50 hours from our rf ion source with no evidence of having depleted the gas supply appreciably.

C. BACKGROUND PROBLEMS

We found the He^3 beam to produce considerable prompt gamma-ray background as well as to induce copious amounts of various positron activities. Even at 2.5 Mev the thin nickel window was found to yield unpleasant amounts of Cu^{60} (24 min) activity. Other activities were minimized by lining all important collimating apertures with tantalum foil. A detectable amount of Na^{22} (2.6 years) activity was built up in both reactions (I) and (II) over a period of several months.

In the case of reaction (II) we could detect the presence of small amounts of air (nitrogen) by the prolific, high-Q reaction $N^{14}(He^3,p)O^{16}$, yielding up to 17 Mev protons at 90 degrees.

Since we used ordinary Ne targets (Ne^{20}, 91%; Ne^{21}, 0.26%; Ne^{22}, 8.8%) the possibility of reaction products originating from Ne^{22} must be considered. Fortunately the Q value for the (He^3,p) reaction on this isotope is some 2.3 Mev higher than for Ne^{20}, so that the proton transitions to the first six or seven states of Na^{24} would give groups at energies higher than the Na^{22} ground-state group. No appreciable amounts of such protons were observed. This does not rule out the possibility that some of the weaker groups we observed in single proton spectra (see Fig. 4) might be due to $Ne^{22}(He^3,p)Na^{22}$.

D. RESULTS

(I) $F^{19}(\alpha,n\gamma)Na^{22}$

Figure 1 shows various gamma rays belonging to the $F^{19}(\alpha,\alpha'\gamma)F^{19}$, $F^{19}(\alpha,p\gamma)Ne^{22}$, and $F^{19}(\alpha,n\gamma)Na^{22}$ reactions at 3.9 Mev bombarding energy. The lowest energy peak at 73 kev was a newcomer on the scene; we verified that it was *not* (a) a K x-ray of Pb, by removing all Pb shielding, and (b) a secondary effect due to one of the higher gamma rays, by seeing its intensity change relative to the other peaks upon varying the bombarding energy. It practically disappears at 3.2 Mev. The next two peaks are the well-known first two excited states of F^{19}, predominantly Coulomb-excited.[3,10] The 593-kev peak represents the first-

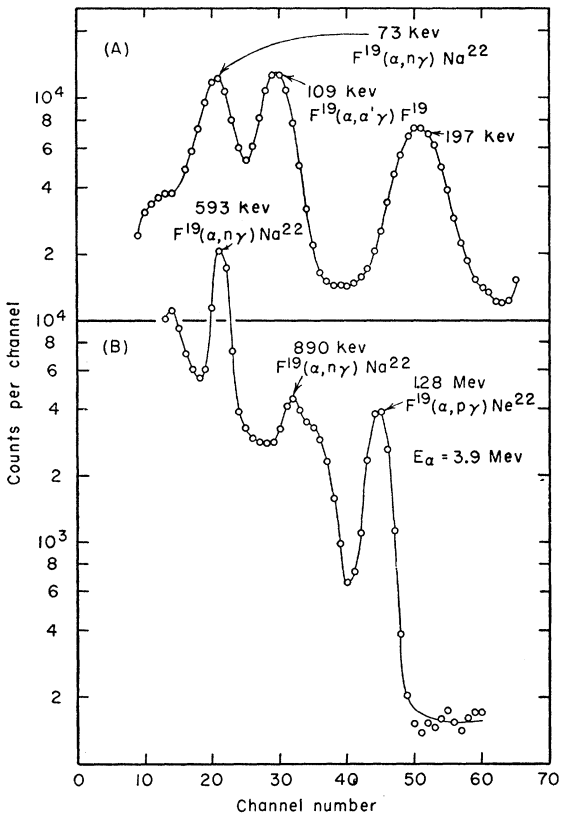

FIG. 1. Gamma-ray scintillation spectra obtained upon bombarding F^{19} with 3.9-Mev alpha particles. (a) Low-energy portion showing 73-kev peak representing cascade radiation between second- and first-excited states of Na^{22} following (α,n) reaction, and the two well-known peaks at 109 and 197 kev following inelastic (and Coulomb) excitation of F^{19}. (b) High-energy portion containing 593-kev and 890-kev lines representing ground-state transitions from first and third excited states of Na^{22}, respectively, and 1.28-Mev gamma following $F^{19}(\alpha,p)Ne^{22*}$ reaction. 1 in. $\times$1 in. NaI(Tl) crystal detector used.

[9] Obtained from Isotopes Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

[10] Sherr, Li, and Christy, Phys. Rev. **96**, 1258 (1954).

excited state transition in Na^{22} as previously reported.[3] It has since also been observed in the same reaction by the Duke group.[11] Next we see a peak at 890±10 kev which undoubtedly corresponds to the direct ground-state transition from the third-excited state of Na^{22}. Finally, we see the first-excited state transition of Ne^{22}, following the (α,p) reaction. Upon gating our coincidence system with the single channel at 593 kev, we observed the pulse-height distribution shown in Fig. 2(b) proving unequivocally that the 73-kev peak represents a real transition, in coincidence with the 593-kev radiation. Upon inserting delay in the 73-kev branch, we obtain the delayed coincidence curve shown in Fig. 1(a). This then yields the half-life of the 593-kev first-excited state of Na^{22} to be 0.266±0.010 microsecond. We obtained the same (but less reliable) value when bombarding at 5.7 Mev and gating the coincidence circuit with a gamma energy at about 1.3 Mev. When gating on the 73-kev peak, the coincidence spectrum we obtain at the higher bombarding energy is shown in Fig. 3. The gamma-ray energies indicated are those transitions from higher known states of Na^{22} which might be expected to feed the new 593+73 =666±4 kev second-excited state. All our data are compatible with the occurrence of cascades through the 666-kev and 593-kev states when Na^{22} decays from more highly excited states, although direct transitions to the 593-kev state (without 73-kev gamma ray) are not ruled out.

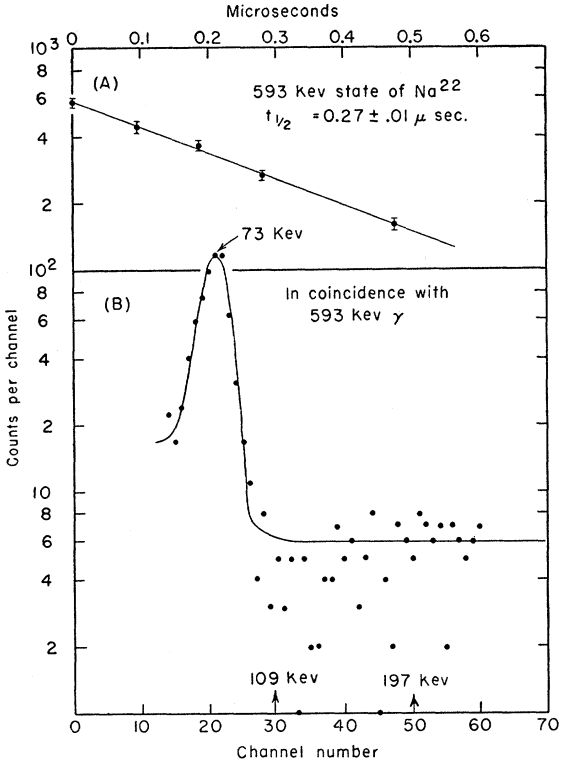

FIG. 2. Results of 73-kev—593-kev coincidence measurements at 3.9-Mev bombarding energy. (a) Decay of 593-kev state as a function of delay inserted in 73-kev channel (upper abscissa). (b) Coincident pulse-height spectrum obtained with single-channel gate on 593-kev peak. Compare with singles spectrum in Fig. 1(a).

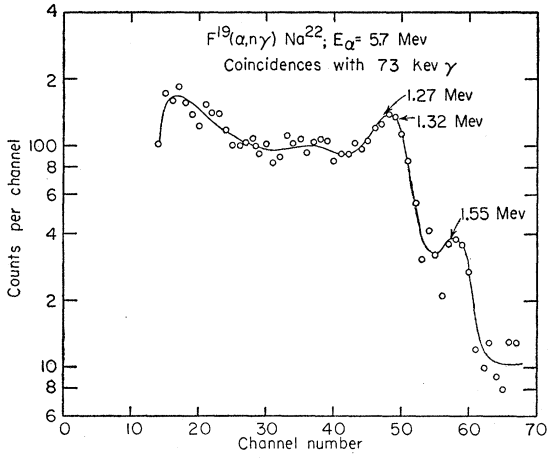

FIG. 3. High-energy portion of coincident gamma spectrum obtained at 5.7-Mev bombarding energy. Single-channel gate at 73-kev peak. Arrows indicate gamma cascades believed responsible for feeding 666-kev state (see level scheme in Fig. 7). 2 in. ×2 in. NaI(Tl) crystal detector used.

Incidental to this investigation, we also observed both the prompt and delayed coincidences expected from the $(\alpha,\alpha'\gamma)$ reaction on F^{19}, which had previously been observed only with inelastic proton excitation.[12] A half-life of 80±5 millimicroseconds was found for the 197-kev state of F^{19}, while an upper limit of 10 mμsec. could be set for the 109 kev state, both values being in good accord with previous determinations.[13] The former was fed by a gamma ray of about 1.35 Mev from a 1.55-Mev state, while the latter followed a ~1.25-Mev transition from a ~1.35-Mev state (for proton excitation, see reference 12).

Upon gating with gamma-ray energy above 1.25 Mev, we observe the 73-kev, 109-kev, and 197-kev peaks in prompt coincidence. When inserting delay in the gating channel, we see that the (essentially prompt) 109-kev peak falls off most rapidly, the 73-kev peak less rapidly, and the 197-kev peak hardly decreases in intensity, as is to be expected in view of its 80-millimicrosecond lifetime. The 109-kev falloff gives a measure of the "electronic" half-life of prompt radiation at that energy (9 mμsec). The fact that the 73-kev radiation decays more slowly can be blamed in part on its lower energy and hence its greater time jitter due to the decreased number of photoelectrons from the photocathode. However, the true half-life of the transi-

[11] R. M. Williamson and B. S. Burton, Bull. Am. Phys. Soc. Ser. II, 2, 182 (1957).

[12] Toppel, Wilkinson, and Alburger, Phys. Rev. **101**, 1485 (1956).

[13] Fiehrer, Lehmann, Lévêque, and Pick, Compt. rend. **241**, 1748 (1955).

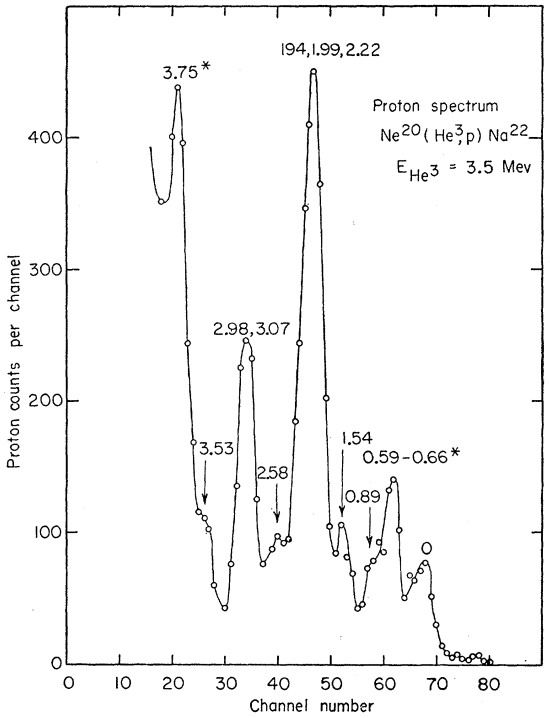

FIG. 4. Proton spectrum obtained under conditions of best resolution from the $Ne^{20}(He^3,p)Na^{22}$ reaction at 3.5-Mev bombarding energy at 90 degrees to the beam. Group labelled 0 coincides with calculated ground-state Q value within the errors. Other peaks are identified nominally with reference to Fig. 7. States marked with asterisk are new. 1-mm thick NaI(Tl) crystal detector.

tion is probably close to the observed value of 14 mμ sec.*

(II) $Ne^{20}(He^3,p\gamma)Na^{22}$

Figure 4 shows the proton spectrum obtained when bombarding neon with 3.5-Mev He^3 particles. Using the known ground-state Q value of 5.78 Mev for this reaction, and calibrating the crystal for proton energy by means of the $N^{14}(He^3,p)O^{16}$ reaction leading to the ground state and first four excited states of oxygen, we calculated the ground-state proton group of Na^{22} to lie within 100 kev of the peak marked (0) in Fig. 4. Using the known levels shown in Fig. 7 as a guide,[5] we have tentatively identified the excited-state groups of Na^{22} as shown. No pronounced additional peaks are seen to occur within the limited resolution possible in this work except for a state at 3.75 Mev which lies beyond the range covered in the previous investigations. Upon changing the bombarding energy, all peaks were observed to shift in the manner appropriate for this particular reaction. The spectrum of Fig. 7 was obtained under our best conditions, the counter being placed some 6 cm from the proton exit window. Because of the restriction in current intensity, the proton counting rate was rather low. Figures 5(a) and 5(b) show portions of the gamma singles spectrum obtained at 3.2-Mev He^3 bombardment. Again we see a pronounced 73-kev peak, and an indication of the 593-kev transition, partially obscured by the omnipresent annihilation radiation, mainly from the activated nickel foil. When gating with the 73-kev gamma ray, and relaxing our proton geometry conditions somewhat, we observe the coincident proton spectrum shown by a dashed curve in Fig. 6, to be compared with the single proton spectrum shown in full trace. The ground-state group is conspicuously absent, as it should be; the group leading to the states around 3.0 Mev also does not cascade through the 666-kev state. The coincidence rate was too low to attempt another check on the 73-kev lifetime by proton gating.

However, we were able to obtain gamma-gamma coincidences upon replacing the proton counter with a 2 in. ×2 in. NaI crystal, and gating the coincidence circuit with 73-kev radiation. The coincident spectrum showed a definite peak around 1.28 Mev (compare Fig. 3). Once again we obtained an apparent half-life of 14 mμ sec. for the 666-kev state of Na^{22} (see, however, reference *).

E. DISCUSSION

A summary of what is now known about the level structure of Na^{22} is given in Fig. 7. The circumstantial

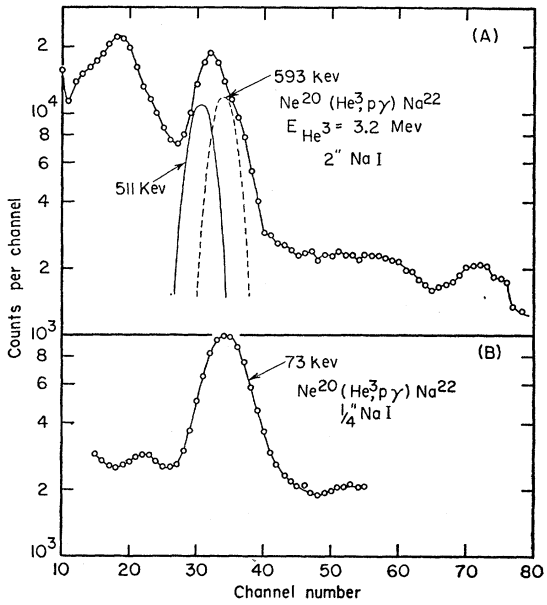

FIG. 5. Gamma-ray scintillation spectra obtained upon bombarding Ne^{20} with 3.2-Mev He^3 ions. (a) Higher energy portion showing composite peak of annihilation radiation (from Ni window positron activity) and 593-kev radiation from first-excited state of Na^{22}. 2 in. ×2 in. NaI(Tl) crystal. (b) Low-energy portion showing 73-kev cascade radiation from second excited state of Na^{22}. ¼ in. NaI(Tl) crystal.

* *Note added in proof.*—A recent measurement by R. E. Holland and F. J. Lynch using pulsed-beam techniques sets an upper limit for the 73-kev transition half-life of 0.35 msec. We are indebted to these authors for a private communication of their results.

evidence is strong for the new state at 666 kev to be the lowest $T=1$, $I=0^+$ state in Na^{22}. The lifetime of the 593-kev state completely rules out spin 0^+, since a pure $M3$ transition of this energy would have a lifetime of ~ 0.1 second or longer. Character 1^+ seems the most plausible assignment. In fact, a very recent study of the $Na^{23}(d,t)Na^{22}$ reaction and analysis in terms of a pickup mechanism[14] seems to lead unequivocally to $l_n=2$ angular distributions for the ground state, 593-kev, 893-kev, and 1.54-Mev triton groups, and hence insures *positive* parity and $I \leq 4$ for these states. It is puzzling that these authors did not observe the 666-kev state, although their resolution was definitely sufficient, and the reaction allows both $T=0$ and $T=1$ states to be excited.

Returning to the 1^+ assignment for the 593-kev state, this leads to pure $E2$ decay to the ground state, with a reduced transition probability of 0.0077 single-particle units (s.p.u.). The 0^+, $T=1$ state at 666 kev would then decay by a pure $M1$ transition of 73 kev, whose reduced transition probability amounts to 0.0045 s.p.u.‡ Both of these strengths are of the order of magnitude encountered in this region of nuclear masses. On the other hand, spin 2^+ for the 593-kev state would entail both an unlikely $E2$ decay of ~ 5000 s.p.u., and an inordinately slow 593-kev $M1$ decay of 5×10^{-7} s.p.u.

One expects on the basis of almost any nuclear model to find low-lying excited states having spins 0^+, 1^+, 2^+, and 3^+ for the configuration of $_{11}Na^{22}$. In particular, the predictions of the rotational model are quite explicit here.[15] Application of this model and its appropriate

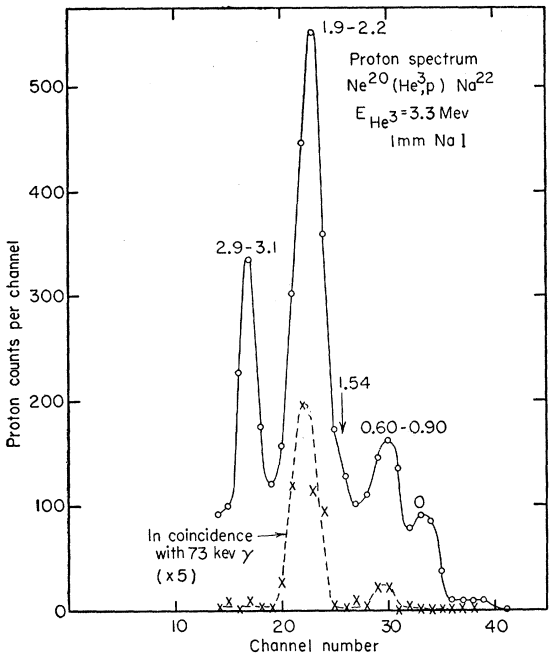

FIG. 6. Proton spectrum in poor resolution from $Ne^{20}(He^3,p)Na^{22}$ reaction at 3.3 Mev, $\theta=90°$. *Solid curve*: single spectrum of groups up to about 3-Mev excitation in Na^{22}. (Compare Fig. 4.) *Dashed curve*: coincident spectrum as gated by 73-kev gamma radiation. Note absence of ground state (0) and states at ~ 3.0 Mev.

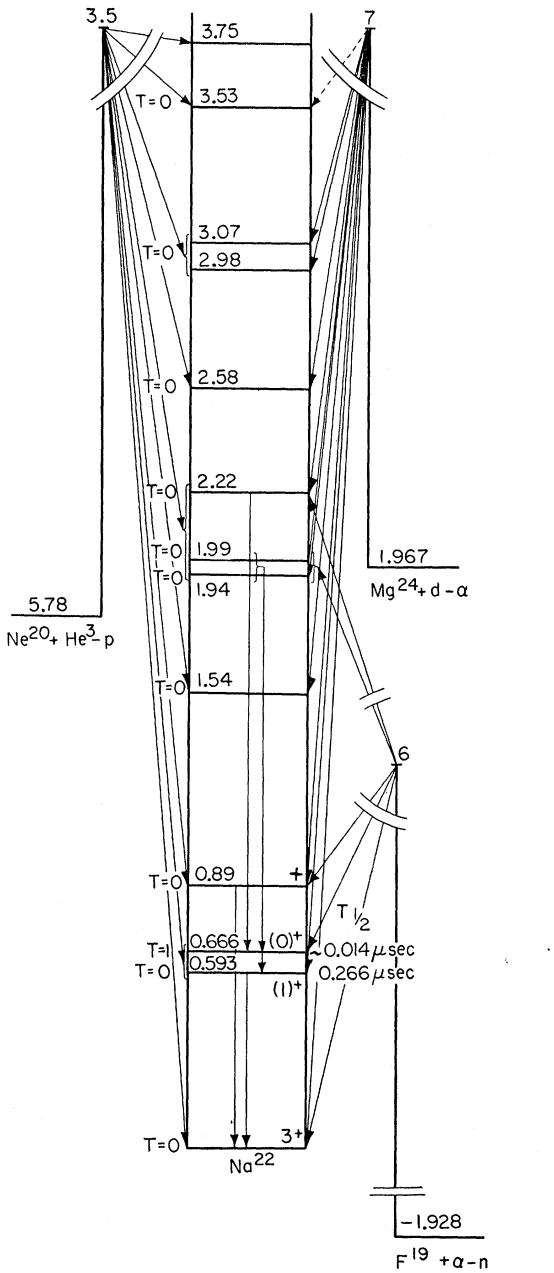

FIG. 7. Level scheme of Na^{22}. Reaction Q values and bombarding energies are shown on distorted scale, only levels of Na^{22} shown correctly. All states except 666 kev and 3.75 Mev were known from $Mg^{24}(d,\alpha)Na^{22}$ (see reference 5).

[14] W. F. Vogelsang and J. N. McGruer, Phys. Rev. **109**, 1663 (1958).

‡ *Note added in proof.*—In view of the upper limit added in proof above, the latter strength now amounts to *more* than 0.18 s.p.u. This fact lends strong support to the $\Delta T=1$ character of the transition, since $M1$ radiation in self-conjugate nuclei with $\Delta T=0$ should be inhibited about one-hundredfold, according to a recent theoretical study; see G. Morpurgo, Phys. Rev. **110**, 721 (1958).

[15] G. Rakavy, Nuclear Phys. **4**, 375 (1957).

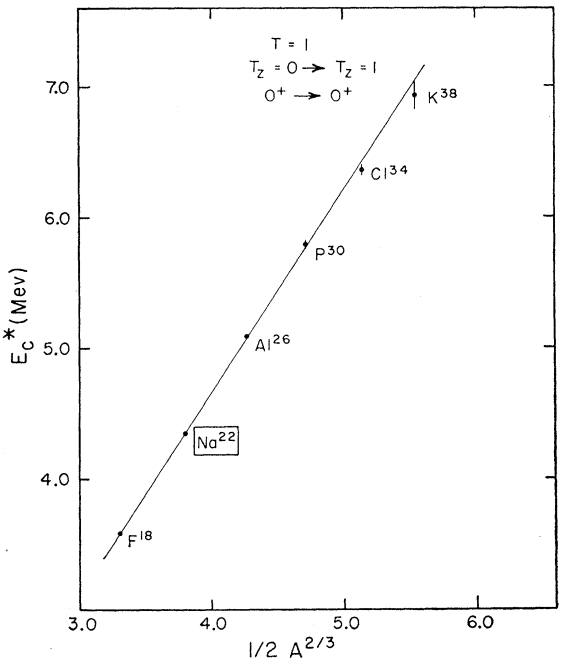

FIG. 8. Systematics of Coulomb energy differences for the $(4n+2)$-series of self-conjugate nuclei between major shells at 8 and 20. Energies are obtained from differences between $T_z=0$ and $T_z=1$ members of ground-state isobaric triplets (references 17 and 18), and size corrected to the nearest $(4n+1)$ mirror nuclei. They are plotted against $\frac{1}{2}A^{\frac{2}{3}}$ of the latter (reference 16). Na^{22} is seen to fall as expected. Straight line has no particular significance except to indicate trend for uniformly-charged sphere model with radius varying as $R=r_0A^{\frac{1}{3}}$, with $r_0=1.30\times10^{-13}$ cm.

wave functions[16] may well be justified in view of the fact that the calculated equilibrium deformations[15] for nuclei between $A=18$ and $A=24$ attain values comparable to those of the heavier nuclei exhibiting well-developed rotational bands. For Na^{22}, the intrinsic spin projections along the nuclear symmetry axis of protons and neutrons are $\Omega_p=\Omega_n=\frac{3}{2}$; three low-lying rotational bands are predicted as follows:

(a) $K=2\Omega=3$, $I=3^+, 4^+, 5^+\cdots$, $T=0$;

(b) $K=0$, $I=1^+, 3^+, 5^+\cdots$, $T=0$;

(c) $K=0$, $I=0^+, 2^+, 4^+\cdots$, $T=1$.

[16] S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **29**, No. 16 (1955).

The first state of band (a) should be the ground state under rather general assumptions, while no unique prediction exists for the relative positions of bands (b) and (c). No negative-parity states are available. The slowness of our 593-kev $E2$ transition would follow naturally because of $\Delta K=3$ (first K forbidden). The state at 890 kev might then have character 4^+ and be the next member of the ground-state band; the moment of inertia inferred from level spacings in neighboring Na^{23} leads to about this energy, and the observed predominant ground-state decay is to be expected. It is clear that considerably more information is needed to put these speculations on a firmer basis.

Browne, in a preliminary study of the $Mg^{25}(p,\alpha)Na^{22}$ reaction at a single energy and angle, finds some evidence for an alpha group to a level at $\sim$0.66 Mev,[17] the only group not also found in the self-conjugate reaction $Mg^{24}(d,\alpha)Na^{22}$.[5] This is very probably the same $T=1$ state.

If the state at 666 kev is the analog of the ground states of the even-even neighbors Ne^{22} and Mg^{22}, then we should find the next $T=1$ state at about 1.3 Mev (as in Ne^{22}) above the former, or at an excitation of about 2.0 Mev in Na^{22}. We cannot draw any conclusion concerning the presence or absence of such a state from our data.

Finally, it is interesting to examine the systematics of the Coulomb-energy differences for the $4n+2$ isobaric triplets in this region of masses. In Fig. 8 we have plotted the energy differences between the lowest $T=1$ states[18,19] corrected to the nearest $4n+1$ mirror nuclei, against $A^{\frac{2}{3}}$. We see that the Na^{22} point falls exactly where expected. We make no attempt here to refine these considerations beyond the uniformly charged sphere model, as has been done by Kofoed-Hansen,[20] and merely confine ourselves to nuclei between the major shells at 8 and 20 so as to obtain an approximate straight-line relationship. The straight line corresponds to a nuclear radius variation $R=r_0A^{\frac{1}{3}}$, with $r_0=1.30\times10^{-13}$ cm.

[17] C. P. Browne (private communication).

[18] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

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

[20] For a complete discussion of nuclear size determination from mirror nuclei, see, e.g., O. Kofoed-Hansen, Nuclear Phys. **2**, 441 (1956/57), and Revs. Modern Phys. **30**, 449 (1958).