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Coulomb Excitation with Ne^{20} Ions*

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Neon ions with energies ranging from 8 to 15 MeV have been obtained by the acceleration of doubly and triply charged ions in a 5.5-MV Van de Graaff. These projectiles have been used to study Coulomb excitation in 18 nuclei ranging from Li^7 to Th^{232}. In particular, the levels of Ti^{47}, V^{51}, Fe^{57}, Ni^{61}, Zn^{67}, Ge^{73}, and As^{75} were investigated. The spin of the 320-keV state of V^{51} is uniquely assigned as 5/2 and the mixing ratio, $\delta=(E2/M1)^{1/2}$, is $0.52\pm.07$. Strong evidence is found against previous assignments of 5/2 for the spin of the 184-keV state in Zn^{67}. The yields and angular distributions of the gamma rays require spin assignments of 3/2 and 1/2 for the 184- and 93-keV states, respectively, in Zn^{67}.

I. INTRODUCTION

THE accuracy of the theoretical description of the electromagnetic excitation of low-lying nuclear levels can be exploited if nuclear force interactions, proper, are avoided. Heavy-ion projectiles are an aid in this respect, especially with lighter target nuclei. Previous work[1,2] with neon ions of 9 to 11 MeV demonstrated that these projectiles gave useful intensities of pure Coulomb excitation of states in Li^7, F^{19}, and Na^{23}. It was found that oxide targets could be used without the complication of oxygen reactions which occur with lighter projectiles.

The previous work also indicated that for somewhat heavier nuclei it would be very desirable to have neon ions with somewhat higher energies. Therefore, a PIG (Phillips ion gauge) type ion source was developed[3] for installation in the 5.5-MV Van de Graaff. With this ion source there was an enhanced output of doubly and triply charged ions. Useful beams of neon ions up to 15.4 MeV were obtained.

This article reports the results of some Coulomb excitation yields and angular distribution measurements made on 18 nuclei ranging from Li^7 to Th^{232}. Especial emphasis was placed on the study of the Coulomb excitation of levels in Ti^{47}, V^{51}, Fe^{57}, Ni^{61}, Zn^{67}, Ge^{73}, and As^{75}.

II. EXPERIMENTAL METHOD

Thick target γ-ray yields and angular distributions were observed in this work. A 3-×3-in. NaI(Tl) cylindrical crystal was used to detect the γ rays. For the yield measurements, the detector was usually located 5 cm from the target, and at 235° with respect to the incident direction of the beam. Distances of 10 or 15 cm, and angles of 0° and 90° were used for the angular distribution (anisotropy) measurements. (The A_4 coefficients appear to be very small in the transitions studied, so more complete distributions were usually not measured.) A 256-channel pulse-height analyzer recorded the spectra.

Many of the details of the γ-ray yield analysis are similar to those reported previously.[4] The interference from bremsstrahlung was negligible. The errors in the determination of the yield are 5 to 7%.

In the anisotropy measurements, the values of R [defined as $W(0°)/W(90°)$] were normalized by comparing them with measurements of Mn^{55}, which is known to have an essentially isotropic angular distribution [anisotropy $=-(0.005\pm0.006)$].[2]

The neon ions could not be bent sufficiently, in the charge state in which they were accelerated, by the 90° analyzing magnet. Therefore a gas stripper[2] was used. From among the various stripped components, one accelerated as Ne^{2+} and stripped to Ne^{5+} was selected. Similarly, ions accelerated as Ne^{3+} were obtained at the target with a charge of 6. Currents up to 1.5 μA of Ne^{5+} and 0.04 μA of Ne^{6+} were obtained at the targets. These upper limits were set partly by the ion source output and partly by the characteristics of the accelerating system.

A large, movable lead shield surrounded the detector.[2] With this in place, the low-energy γ-ray background (below 200 keV) counting rate was reduced, with the Van de Graaff running, by a factor of about 1000, so that small yields could be measured.

III. EXTRACTION OF $B(E2)_{\rm ex}$

The method for obtaining $\epsilon B(E2)_{\rm ex}$ from the thick-target yields is similar to that previously reported.[4] With the neon ions at the energies used, the classical value of the cross section (and also of the angular distribution particle parameter a_ν) is estimated to be sufficiently accurate for the intended results. The form of the equation which was used for extracting $\epsilon B(E2)_{\rm ex}$

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[1] P. H. Stelson and F. K. McGowan, Nuclear Phys. **16**, 92 (1960).

[2] P. H. Stelson and F. K. McGowan, *Reactions Between Complex Nuclei* (John Wiley & Sons, Inc., New York, 1960), p. 47.

[3] R. C. Ritter and P. H. Stelson (to be published); R. C. Ritter, thesis (unpublished).

[4] P. H. Stelson and F. K. McGowan, Phys. Rev. **110**, 489 (1958).

is

$$\epsilon B(E2)_{\mathrm{ex}}=\frac{436.9A_2{}'Z_2{}^2}{A_1n\eta K^2}I'\bigg/\int_0^E\frac{E'g(\xi)dE}{dE/d\rho x}. \tag{1}$$

As used here, ϵ is defined as the ratio of the observed γ-ray yield to the total de-excitation of the state; $A_2{}'$ is the molecular weight of the target; n is the number of target nuclei per molecule and η is the isotopic fraction of the desired nuclei. Z_2e is the nuclear charge of the target, and A_1 is the projectile mass number. The factor $K=A_2/(A_1+A_2)$ accounts for center-of-mass corrections, where A_2 is the target mass number; $B(E2)_{\mathrm{ex}}$ is the (upward) reduced transition probability in the conventional units, $e^2\times10^{-48}$ cm^4; and I' is the observed yield in γ rays per incident particle. The integral is in units of MeV-mg/cm^2. $E'=E-\Delta E'$ is the outgoing projectile energy, in MeV, where $\Delta E=K\Delta E'$ is the excitation energy in MeV; $dE/d\rho x$ is the stopping power in keV-cm^2/mg; and $g(\xi)=1.2665f_{E2}(\xi)$ is the classical "excitation function."[5]

The integral was calculated numerically for each nuclear state of interest. Its dependence on the projectile energy is shown in Fig. 1 for 3 states in Fe^{57}. It normally contributes the largest error to the estimation of $\epsilon B(E2)_{\mathrm{ex}}$, primarily because of the uncertainty in $dE/d\rho x$. Curves of $dE/d\rho x$ versus neon energy were obtained for each target material, by converting proton stopping power data by the method of Papineau.[6]

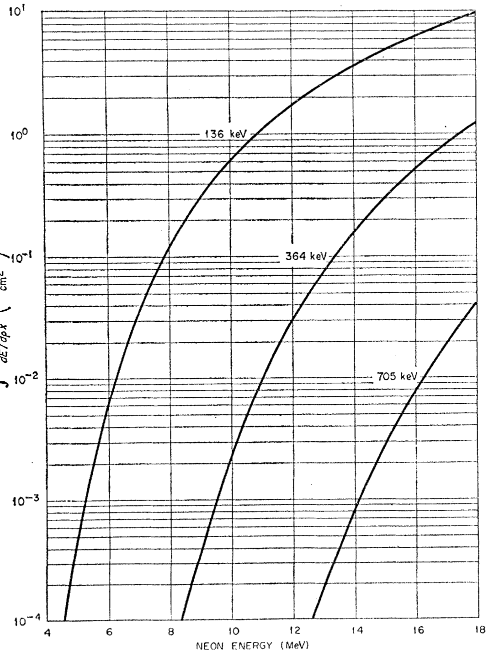

FIG. 1. Coulomb excitation thick target integrals for neon ions on an $(Fe^{57})_2O_3$ target.

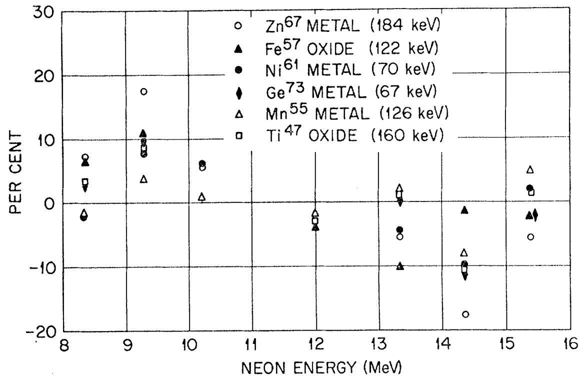

FIG. 2. Variation of experimental $\epsilon B(E2)$ with neon ion incident energy.

The particular form of the curve used for Z_{eff} (the effective ionic charge of the projectile) as a function of the "characteristic velocity," $v/Z_1{}^{2/3}$, is that of Heckman *et al.*[7] (Z_1e is the projectile nuclear charge.) From the data of Heckman *et al.*, and the limited amount of other available data[8,9] for the measured stopping power for heavy ions in a suitable energy range, this method is estimated to have an error with a standard deviation of 8 to 10%.

From this error, and the estimated uncertainty in I', an error of ±15% (for one standard deviation) is assigned to the $\epsilon B(E2)_{\mathrm{ex}}$ results. Part of this error is also attributed to an observed energy dependence of the $\epsilon B(E2)_{\mathrm{ex}}$. This is depicted for several targets in Fig. 2. A systematic error in our $dE/d\rho x$ curves would probably be in the wrong direction to explain this trend. In these curves $dE/d\rho x$ falls with decreasing energy, but some experimenters[8,10] treat $dE/d\rho x$ as a constant in the region of interest here. Alternatively, an energy-dependent error in the recorded number of projectiles striking the target (i.e., in the interpretation of the integrated current) could arise from charge exchange in the beam between the analyzing magnet and the target. An estimate of the upper limit of this effect[11] would correspond to a total $\epsilon B(E2)$ variation of about 7%. A possible surface layer on metallic targets would have an effect opposite to that observed.

IV. THE EXPERIMENTAL RESULTS

A survey of the neon-ion Coulomb excitation was made on 18 nuclei from Li^7 to Th^{232}. Table I lists the

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[5] See, e.g., the review by K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Revs. Modern Phys. **28**, 432 (1956).

[6] M. A. Papineau, Compt. rend. **242**, 2933 (1956).

[7] H. H. Heckman, B. L. Perkins, W. G. Simon, F. M. Smith, and W. H. Barkas, Phys. Rev. **117**, 544 (1960).

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[9] W. Whaling, *Encyclopedia of Physics*, XXXIV, edited S. Flügge (Springer-Verlag, Berlin, 1956), Vol. 34, p. 194.

[10] D. G. Alkhazov, A. P. Grinberg, G. M. Gusinskiĭ, K. I. Erokhina, and I. Kh. Lemberg, Soviet Phys.—JETP **10**, 1086 (1960).

[11] Data and a discussion of charge exchange have been reported by E. L. Hubbard and E. J. Lauer, Phys. Rev. **98**, 1814 (1955); R. L. Gluckstern, Phys. Rev. **98**, 1817 (1955).

TABLE I. Summary of yield and angular distribution results. Column 1 lists the nucleus. Column 2 lists the energies of the levels excited. The values were taken from reference 14. The target compound and enrichment, respectively, are given in columns 3 and 4. Column 5 lists the $\epsilon B(E2)_{\mathrm{ex}}$ obtained using Eq. (1). Where several values were determined for a given transition, the average is given. In column 6, $\epsilon B(E2)_{\mathrm{ex}}$ values by other experimenters are listed for comparison. Column 7 lists the average coefficient, A_2, measured for each transition, as calculated from Eq. (2). An error of ±15% is assigned to $\epsilon B(E2)_{\mathrm{ex}}$ except for Mn^{55}.

(1) Nucleus	(2) Level (keV)	(3) Target compound	(4) Target enrichment	(5) $\epsilon B(E2)_{\mathrm{ex}}$ ($e^2\times10^{-48}$ cm^4)	(6) Other $\epsilon B(E2)_{\mathrm{ex}}$ values	(7) A_2
Li^7	478	Li_2CO_3	nat.	0.00076	0.00073[a]	· · ·
F^{19}	197	CaF_2	nat.	0.005	0.005[a]; 0.003[b]; 0.002[b]	· · ·
Na^{23}	438	NaCl	nat.	0.015	0.013[b]; 0.011[a]; 0.0095[c]	-0.015 ± 0.018[d]
Ti^{47}	160	TiO_2	0.856	0.028	0.040[b]	-0.035 ± 0.012
V^{51}	320	V_2O_5	nat.	0.013	0.013[c]; 0.012[e]; 0.0056[b]	$+0.239\pm0.015$
Cr^{53}	155	Metal	0.953	<0.00005	0.015[b]; <0.0001[f]	· · ·
Mn^{55}	126	Metal	nat.	(0.031)[g]	0.087[b]; 0.075[b]; 0.057[h]	· · ·
Fe^{57}	136	Fe_2O_3	0.838	0.037[i]	0.043[j]; 0.050[k]; 0.044[h]	-0.036 ± 0.025
Fe^{57}	364	Fe_2O_3	0.838	0.037	0.033[k]	$+0.125\pm0.03$
Ni^{61}	67	Metal	0.744	0.00064	0.00038[l]	-0.010 ± 0.021
Ni^{61}	282	Metal	0.744	0.0012	0.00090[l]	· · ·
Zn^{67}	93	Metal	0.924	0.00011[m]	· · ·	· · ·
Zn^{67}	184	Metal	0.924	0.018	0.032[l]	$+0.227\pm0.015$
Ge^{73}	67	Metal	0.861	0.046	0.085[l]	$+0.036\pm0.015$
As^{75}	199	As_2O_3	nat.	0.015	0.016[b]; 0.025[b]	-0.006 ± 0.022
As^{75}	280	As_2O_3	nat.	0.052	0.050[b]; 0.071[b]	-0.197 ± 0.026
Ru^{101}	127	Metal	0.911	0.028	0.061[b]	$+0.114\pm0.022$
Pd^{110}	374	Metal	0.914	0.91	1.04[b]; 0.95[b]; 0.26[b]	n
Pr^{141}	145	Pr_6O_{11}	nat.	<0.003	0.0036[o]	· · ·
$Hf^{177,179}$	112	Metal	nat.	0.46[i]	0.59[b]; 0.37[p]; 0.84[q]	· · ·
Ta^{181}	136	Metal	nat.	0.74	1.04[l]; 0.83[r]; 0.81[l]; 0.68[l] 0.64[r]; 0.59[l]; 0.52[l]	· ·
Th^{232}	53	Metal	nat.	0.023	0.057[b]; 0.0096[b]; 0.020[s] 0.036[t]; 0.027[u]; 0.031[v]	· · ·

[a] See reference 1.
[b] See the review article, reference 5.
[c] H. E. Gove and C. Broude, *Reactions Between Complex Nuclei* (John Wiley & Sons, Inc., New York, 1960), p. 57.
[d] The (small) Doppler effect was not included in the calculation.
[e] B. M. Adams, D. Eccleshall, and M. J. L. Yates, *Reactions Between Complex Nuclei* (John Wiley & Sons, Inc., New York, 1960), p. 95.
[f] See reference 10.
[g] This value is suspect, because of possible surface layers.
[h] T. Huus, J. H. Bjerregard, and B. Elbek, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **30**, No. 17 (1956).
[i] The measured γ rays were unresolved ones from two transitions.
[j] See reference 24.
[k] See reference 25.
[l] See reference 14.
[m] Corrected for cascade γ rays.
[n] Both A_2 and A_4 are significant. See the discussion.
[o] See reference 34.
[p] Data of Huus *et al.*, as quoted in reference 14 was combined. See the discussion.
[q] Data of Heydenburg and Temmer, as quoted in reference 14, was combined. See the discussion.
[r] See reference 35.
[s] See reference 36.
[t] D. H. Rester, M. S. Moore, F. E. Durham, and C. M. Class, Nuclear Phys. **22**, 104 (1961).
[u] R. E. Bell, S. Bjornholm, and J. C. Severiens, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd **32**, No. 12 (1960).
[v] E. Skurnik, B. Elbek, and M. C. Oleson, quoted in reference u.

results of the survey, and the "best" values for transitions studied in more detail. The method for obtaining A_2 has been reported previously,[12] but one difference here is that angular distribution measurements were only taken at the two angles 0° and 90°. The experimental value, R (defined above), provided the coefficient A_2 from the equation

$$A_2=\frac{2}{a_2g_2}\left(\frac{R-1}{R+2}\right), \tag{2}$$

where a_2 is the thick target particle parameter,[12] and g_2 is a correction for the finite solid angle subtended by the detector.[13] Corrections for the coefficient A_4 were not found to be significant, except for Pd^{110}.

Some of the nuclear states, particularly those in the nuclei from Ti^{47} to As^{75}, were studied in more detail. Tables II and III contain the individual results for these excitations.

V. REMARKS ON INDIVIDUAL NUCLEI

Li^7

The only measurement on this nucleus was made with 15.4-MeV neon ions. The observed value of 1.41×10^{-8} γ rays per incident particle for the 478-keV yield corresponds to $\epsilon B(E2)_{\mathrm{ex}}=0.00076$, in units of $e^2\times10^{-48}$ cm^4. The agreement with earlier results[1] for neon ions at 9–11 MeV is good. This suggests that even though the spectrum (Fig. 3) shows some reaction peaks, the electromagnetic process is dominant for the excitation of the 478-keV state. This result is of particular interest in that the calculated (classical) distance of closest approach[5] is less than that for any of the other nuclei studied. (The 15.4-MeV projectile energy

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[12] See, e.g., F. K. McGowan and P. H. Stelson, Phys. Rev. **106**, 522 (1957).
[13] M. E. Rose, Phys. Rev. **91**, 610 (1953).

TABLE II. Detailed γ-ray yield results. Column 1 lists the nucleus and the energy, in kev, of the level excited. In column 2 the neon incident energy is given. Columns 3 and 4 give the measured yield and the calculated integral, respectively. In column 5 the $\epsilon B(E2)_{ex}$, as calculated from Eq. (1), is listed.

(1) Nucleus and level (keV)	(2) Neon energy (MeV)	(3) Yield, I' (γ-rays/inc. particle)	(4) Integral (MeV mg cm^{-2})	(5) $\epsilon B(E2)_{ex}$ ($e^2\times10^{-48}$ cm^4)
Ti^{47} (160)	8.34	1.70×10^{-9}	0.121	0.0281
	9.29	4.25×10^{-9}	0.280	0.0305
	12.01	19.0×10^{-9}	1.40	0.0272
	13.38	34.2×10^{-9}	2.42	0.0283
	14.36	41.8×10^{-9}	3.36	0.0250
	15.38	63.9×10^{-9}	4.52	0.0284
V^{51} (320)	15.38	4.87×10^{-9}	0.784	0.0127
Mn^{55} (126)	8.34	6.84×10^{-9}	0.309	0.0309
	9.29	15.0×10^{-9}	0.641	0.0326
	10.21	25.7×10^{-9}	1.13	0.0317
	12.01	58.4×10^{-9}	2.63	0.0309
	13.38	98.6×10^{-9}	4.30	0.0320
	14.36	119×10^{-9}	5.77	0.0289
	15.38	178×10^{-9}	7.54	0.0329
Fe^{57} (136)	8.34	2.56×10^{-9}	0.164	0.0401
	9.29	5.96×10^{-9}	0.367	0.0417
	12.01	24.5×10^{-9}	1.73	0.0362
	13.38	38.8×10^{-9}	2.95	0.0340
(136) [a]	14.36	58.7×10^{-9}	4.06	0.0372
(350)		2.96×10^{-9}	0.197	0.0386
(136) [a]	15.38	73.8×10^{-9}	5.41	0.0350
(228)		0.382×10^{-9}	...	...
(350)		4.89×10^{-9}	0.367	0.0342
(228) [b]	15.38	8.44×10^{-11}	...	...
Ni^{61} (67)	8.34	3.90×10^{-10}	1.49	0.000623
	9.29	6.89×10^{-10}	2.39	0.000686
	10.21	9.89×10^{-10}	3.49	0.000676
	13.38	22.1×10^{-10}	8.66	0.000609
	14.36	26.0×10^{-10}	10.8	0.000574
	15.38	36.0×10^{-10}	13.2	0.000651
(282)	15.38	5.26×10^{-10}	1.02	0.00122
Zn^{67} (184) [a]	8.34	2.17×10^{-10}	0.0279	0.0180
(93+91)		8.21×10^{-11}	...	...
(184) [a]	9.29	7.51×10^{-10}	0.0873	0.0199
(93+91)		23.0×10^{-11}	...	...
(184) [a]	10.21	17.0×10^{-10}	0.208	0.0189
(93+91)		45.8×10^{-11}	...	...
(184) [a]	13.38	106×10^{-10}	1.52	0.0161
(93×91)		292×10^{-11}	...	...
(184) [a]	14.36	149×10^{-10}	2.32	0.0148
(93+91)		350×10^{-11}	...	...
(184) [a]	15.38	250×10^{-10}	3.40	0.0170
(93+91)		611×10^{-11}	...	...
Ge^{73} (67)	8.34	1.97×10^{-8}	1.32	0.0473
	9.29	3.53×10^{-8}	2.21	0.0508
	13.38	13.0×10^{-8}	8.96	0.0461
	14.36	14.5×10^{-8}	11.2	0.0410
	15.38	19.5×10^{-8}	13.8	0.0449
As^{75} (199) [a]	15.38	8.29×10^{-10}	2.06	0.0152
(280)		8.80×10^{-10}	0.647	0.0515
Ru^{101} (127)	14.36	1.36×10^{-8}	3.60	0.0254
	15.38	2.37×10^{-8}	5.15	0.0310
Pd^{110} (374)	13.38	0.774×10^{-9}	0.00634	0.921
	14.36	2.17×10^{-9}	0.0182	0.897
	15.38	5.50×10^{-9}	0.0460	0.900

[a] Simultaneous measurements.

[b] In coincidence with the 122-keV gamma ray. The total efficiency of the 122-keV counter was 0.241. This corresponds (considering the internal conversion coefficient) to a singles yield of 3.6×10^{-10} γ rays/incident particle for the 228-keV gamma ray.

TABLE III. Gamma-ray angular distributions. Column 1 lists the nucleus and the energy, in keV, of the level excited. The incident neon ion energy is given in column 2. The measured value of R is listed in column 3. Column 4 gives the detector distance h at which the angular distribution was measured. In column 5, the thick-target particle parameter $\bar{a}_2$ is given.

(1) Nucleus and level (keV)	(2) Neon energy (MeV)	(3) R	(4) h (cm)	(5) $\bar{a}_2$
Ti^{47} (160)	10.21	0.960 ± 0.014	15	0.793
V^{51} (320)	15.38	1.308 ± 0.022	10	0.826
Fe^{57} (136)	10.21	0.952 ± 0.030	15	0.747
(136)	15.38	0.971 ± 0.015	10	0.593
(350)	15.38	1.16 ± 0.04	10	0.882
Ni^{61} (67)	10.21	0.991 ± 0.018	10	0.592
Zn^{67} (184)	10.21	1.312 ± 0.015	10	0.891
(184)	15.38	1.238 ± 0.024	15	0.722
(91+93)	10.21	1.126 ± 0.022	10	0.891
(91+93)	15.38	1.100 ± 0.035	15	0.722
Ge^{73} (67)	8.34	1.041 ± 0.011	10	0.730
(67)	10.21	1.029 ± 0.011	15	0.616
As^{75} (199)	15.38	0.994 ± 0.023	10	0.762
(280)	15.38	0.782 ± 0.026	10	0.858
Ru^{101} (127)	10.21	1.136 ± 0.020	15	0.887
	15.38	1.094 ± 0.030	10	0.698
	15.38	1.208 ± 0.040	15	0.698
Pd^{110} (374)	15.38	1.585 ± 0.035	10	0.987[a]

[a] $\bar{a}_4=-0.112$.

corresponds to about 2/3 the Coulomb barrier[5] for neon ions on Li^7. Both the projectile and target nuclear radii were considered in this estimate.) The increase in complexity of the spectrum from that with 11-MeV neon ions is considerable. (See Fig. 3 of reference 1.)

F^{19}

The yield of the 197-keV state of F^{19} was measured as 3.70×10^{-8} γ rays per incident particle, with 11.9-

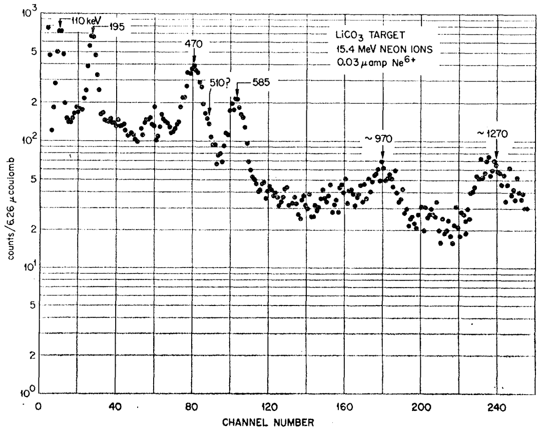

FIG. 3. Scintillation pulse-height spectrum produced by bombardment of a $LiCO_3$ target with neon ions.

MeV neon ions. The value of $\epsilon B(E2)_{\text{ex}}$ was calculated from this to be 0.005, in agreement with the results of reference 1. The de-excitation of this state appears to be pure $E2$, so that values of the measured mean lifetime τ can be directly compared to the present $\epsilon B(E2)$. Three values listed[14] for τ are very near 1.25×10^{-8} sec, which corresponds to $\epsilon B(E2)_{\text{ex}} = 0.0066$. Within the probable errors, this and the Coulomb excitation results agree.

The 110-keV odd-parity[14] state was also excited. It is expected to be an $E1$ excitation, the only one known in this work. From the measured yield of 3.34×10^{-9} γ rays per incident particle a value $\epsilon B(E1)_{\text{ex}} = 3.6e^2 \times 10^{-30}$ cm^2 was calculated. (A 15% correction was assumed[1] for backscattering from the 197-keV gamma rays.) In reference 1, a value nearly twice as large, $6.3e^2 \times 10^{-30}$ cm^2, was reported. That result contained an omission[15] of a factor of 1/2. When corrected, it agrees with the present value.

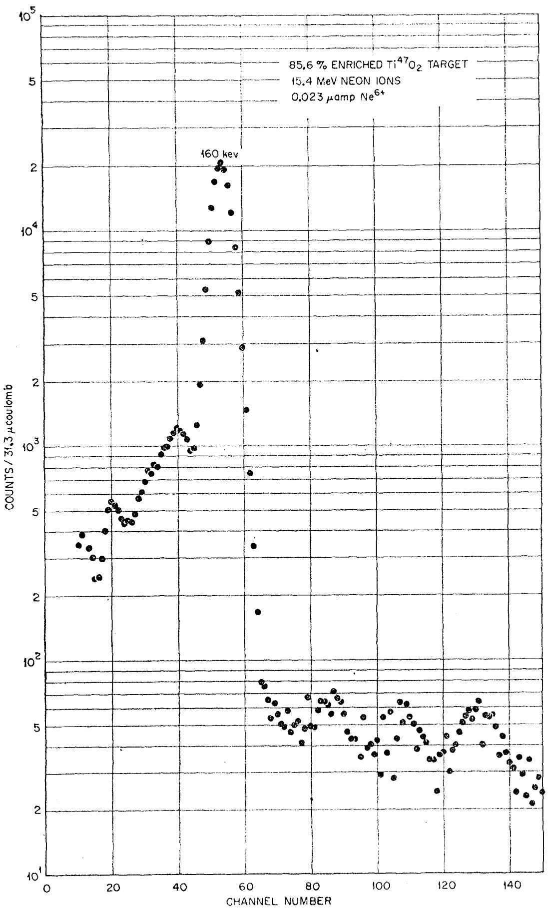

FIG. 4. Scintillation pulse-height spectrum produced by bombardment of a Ti^{47}O$_2$ target with neon ions.

A spectrum from 15.4-MeV ions was taken with a low amplifier gain. There were no measurable peaks above 197 keV in the spectrum, which extended to about 2.8 MeV.

Na^{23}

Both the yield and angular distribution of the 438-keV state in Na^{23} were measured, with 15.4-MeV neon ions. The yield, 3.27×10^{-8} γ rays per incident particle, corresponds to $\epsilon B(E2)_{\text{ex}} = 0.015$, which is in reasonable agreement with other reported values.

A single set of angular distributions at 10 cm gave a value $R = 0.984 \pm 0.019$, from which it is estimated that $A_2 = -0.015 \pm 0.018$, if relativistic effects[2] are not considered. There is a disagreement[2] between the lifetime of this state measured by resonance fluorescence and the lifetime deduced from Coulomb excitation (angular distribution and yield of gamma-rays from Coulomb excitation).

Ti^{47}

The pulse-height spectrum of a Ti^{47}O$_2$ target, bombarded by 15.4-MeV neon ions, is shown in Fig. 4. Only the 160-keV state appears to have been appreciably excited. The $E2$ character of the excitation of this state has been confirmed by Bromley *et al.*[16] with He^3- and He^4-induced Coulomb excitation. The nearly constant value of $\epsilon B(E2)_{\text{ex}}$ with changing projectile energy, as shown in Table II, supports this.

In the further analysis of this transition, our measured value of A_2 was too near zero to permit a sensitive prediction of the multipole mixture δ^2. Table IV lists the pertinent quantities of the analysis. The listed value of δ^2 for Ti^{47} was determined from the lifetime and our $B(E2)$. Holland and Lynch,[17] using their measured lifetime, a theoretical value for the internal conversion coefficient α_T, and $\epsilon B(E2)_{\text{ex}} = 0.040$, calculated δ^2 to be 0.013. They used 7/2 as the spin of the excited state.

The $5/2^-$ spin of the ground state of Ti^{47} has been measured,[14] but the $(7/2^-)$ assignment is not based on very strong experimental evidence. Our results are not able to bear on this. Our measured value of A_2 for this transition (-0.035 ± 0.012) is consistent with the tabulated value of δ^2 (0.0086 ± 0.0030) for an excited state spin of either $3/2^-$ or $7/2^-$. The possibility of correlation attenuation would in addition allow an assignment of $5/2^-$. The $B(E2)$ enhancement factor of about 16, over a single-particle estimate,[18] makes it appear questionable to use single-particle shell-model predictions as part of the evidence for a spin assignment.

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[14] See, e.g., *Nuclear Data Sheets*, National Academy of Sciences, National Research Council (U. S. Government Printing Office, Washington, D. C., 1960).

[15] P. H. Stelson (private communication).

[16] D. A. Bromley, J. A. Kuehner, and E. Almqvist, Phys. Rev. **115**, 586 (1959).

[17] R. E. Holland and F. J. Lynch, Phys. Rev. **121**, 1464 (1961).

[18] See the discussion of Sec. VI for the single-particle estimate used here.

TABLE IV. Transition properties for levels in medium-light odd-A nuclei. Column 1 lists the nucleus. The transition energy is given in column 2. The ground and excited state spins are given in columns 3 and 4, respectively. Column 5 gives the value used for the total internal conversion coefficient. In column 6 the factor ϵ, defined in the text, is listed. Column 7 lists the decay $B(E2)$ from our results. In column 8 the $E2$ enhancement factor, $B(E2)_{\mathrm{dec}}/B(E2)_{\mathrm{s.p.}}$, is given. Equation (4) defines the $B(E2)_{\mathrm{s.p.}}$ used. A measured mean lifetime value is given in column 9. In column 10 the ratio of the $E2$ to M1 intensity in the γ-ray decay is given. The method of calculation, in each case, is given in the text. Column 11 lists the $B(M1)_{\mathrm{dec}}$ calculated from $B(E2)_{\mathrm{dec}}$ δ^2 and α_T. In column 12 the enhancement (reciprocal inhibition) factor for $B(M1)$ is listed. It is calculated as the ratio $B(M1)_{\mathrm{dec}}/B(M1)_{\mathrm{s.p.}}$. For $B(M1)_{\mathrm{s.p.}}$ we used the estimate in reference 37, with the free-particle values for μ_p and μ_n. Values for F and F' have been rounded off.

(1) Nucleus	(2) Transition (keV)	(3) j_g	(4) j_e	(5) α_T	(6) ϵ	(7) $B(E2)_{\mathrm{dec}}$ ($e^2\times10^{-48}$ cm^4)	(8) F	(9) τ (10^{-9} sec)	(10) δ^2	(11) $B(M1)_{\mathrm{dec}}$ $(e\hbar/2M_c)^2$	(12) F'
Ti^{47}	160	$5/2^-$	$(7/2^-)$	0.0036	0.99	0.021	16	0.32±0.10[a]	0.0086 ±0.003	0.0438	1/35
V^{51}	320	$7/2^-$	$5/2^-$	0	1.0	0.017	9	0.31±0.08[b]	0.269 ±0.09	0.0045	1/640
Mn^{55}	126	$5/2^-$	$(7/2^-,3/2^-)$	0.016	0.98	(0.023)	(14)	0.34±0.10[a]	0.0084[a]	(0.0305)	(1/70)
Fe^{57}	136	$1/2^-$	$5/2^-$	0.11	0.98	0.013	10	12.7 ±0.5[a]	[c]	[c]	[c]
Fe^{57}	364	$1/2^-$	$(3/2^-)$	0	0.92	0.020	15	...	(0.0071 or 34.7)	...	...
Fe^{57}	122[d]	$3/2^-$	$5/2^-$[d]	0.016	...	0.0072[e]	5	...	0.036 ±0.008[f]	0.00209	1/670
Ni^{61}	67	$3/2^-$	$(5/2^-)$	0.12	0.89	0.00048	0.3	7.5 ±0.5[g]	0.000067±0.000015	0.0227	1/60
Ni^{61}	282	$3/2^-$	...	0	0.99	(0.0012)[h]	(0.8)[h]	...	...	...	...
Zn^{67}	93	$5/2^-$	$1/2^-$	0.84	0.54[e]	0.00061[e]	0.1	13,700±1,400[i]	[c]	[c]	[c]
Zn^{67}	184	$5/2^-$	$3/2^-$	0.014	0.88	0.031	11	1.45±0.15[a]	0.26 ±0.08	0.00342	1/490
Zn^{67}	91[d]	$1/2^-$[d]	$3/2^-$	0.063	...	≤0.006	≤4.2	...	≤0.005	0.0065	1/150
Ge^{73}	67	$9/2^+$	$(7/2^+,11/2^+)$	0.229	0.80	0.072	24	2.33±0.20[a]	0.0036	0.0632	1/30
As^{75}	199	$3/2^-$	$(1/2^-)$	0.02	0.98	0.031	8	1.30±0.15[j]	0.189 ±0.08	0.00462	1/720
As^{75}	280	$3/2^-$	$5/2^-$	0.008	0.97	0.036	16	0.4 ±0.2[j]	~0.27	~0.0085	~1/240

[a] See reference 17.
[b] N. N. Delyagin and M. Preiss, Soviet Phys.—JETP **9**, 1127 (1959).
[c] Pure $E2$ decay.
[d] Upper cascade γ rays.
[e] These values were obtained indirectly. See the text.
[f] G. R. Bishop, M. A. Grace, C. E. Johnson, A. C. Knipper H. R. Lemmer, J. Perezy Jorba, G. R. Surlock, Phil. Mag **46**, 951 (1955).
[g] R. E. Holland, F. J. Lynch, and E. N. Shipley, Bull. Am. Phys. Soc. **5**, 424 (1960).
[h] j_e is not known, so the statistical factor is omitted.
[i] W. E. Meyerhof, L. G. Mann, and H. I. West, Jr., Phys. Rev. **92**, 758 (1953).
See reference 31.

V^{51}

The spectrum resulting from 15.4-MeV neon ion bombardment of a vanadium oxide target is shown in Fig. 5.

The large measured anisotropy ($A_2=0.239\pm0.015$) allowed a unique spin assignment of $5/2^-$ for the 320-keV excited state. It also predicts two possible values of δ. The lower one, $+0.52\pm0.07$, in conjunction with the measured mean life of the state as listed in Table IV, $(0.31\pm0.08)\times10^{-9}$ sec, predicts an $\epsilon B(E2)_{\mathrm{ex}}$ value of 0.0127 ± 0.0036, in good agreement with our measurement. Other measured values of the mean lifetime which have been reported are $(0.42\pm0.06)\times10^{-9}$ sec,[19] $(0.28\pm0.05)\times10^{-9}$ sec,[20] $(0.28\pm0.03)\times10^{-9}$ sec,[21] and $(0.15\pm0.03)\times10^{-9}$ sec.[22]

Cr^{53}

A possible 155-keV state has been reported from proton bombardment of this nucleus.[23] However, its existence has been doubted by other experimenters.[10] In the present investigation a search was made for this state, but the yield spectra showed no measurable peak at 155 keV. A yield of only 0.977×10^{-10} γ rays per incident particle would have been noticeable at this position on the 13.4-MeV neon ion spectrum. This corresponds to an $\epsilon B(E2)_{\mathrm{ex}}$ of about 0.00005. It is concluded that either: (1) the state doesn't exist, (2) it has an $\epsilon B(B2)_{\mathrm{ex}}$ smaller than 0.00005, or (3) its spin and/or parity will not allow $E2$ Coulomb excitation.

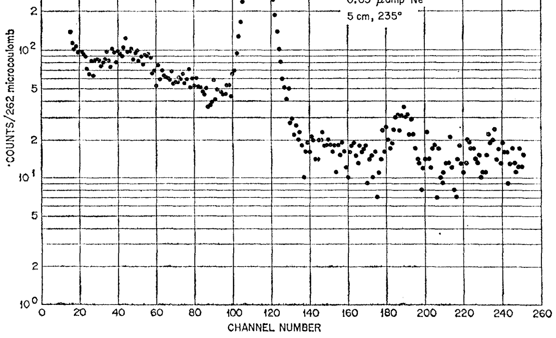

FIG. 5. Scintillation pulse-height spectrum produced by bombardment of a V_2O_5 target with neon ions.

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[19] T. D. Nainan, Bull. Am. Phys. Soc. **5**, 239 (1960).

[20] F. J. Lynch and R. E. Holland, Bull. Am. Phys. Soc. 4, 404 (1959).

[21] A. W. Sunyar, *Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1959), Vol. 14, p. 347.

[22] H. Schopper, Z. Physik 144, 476 (1956).

[23] H. Mark, C. McClelland, and C. Goodman, Phys. Rev. 98, 1245 (1955).

Spectra taken with 14.4-MeV neon ions did not show any significant peaks up to about 1 MeV.

Mn^{55}

The surface of this metallic target appears to form compounds very quickly in air. These would be expected to alter the stopping power, especially for heavy ions, and result in erroneously low values for the calculated $\epsilon B(E2)_{ex}$. Nevertheless, the results for excitation of the 126-keV state are given in the tables. The angular distribution was measured, but with poor absolute accuracy. It generally confirmed the more extensive measurements reported in reference 2. The nearly isotropic distribution and strong yield were suitable for normalization of the angular distribution measurements of other nuclei.

In Table IV the factors listed for Mn^{55} were calculated from the present $\epsilon B(E2)_{ex}$ and the measured lifetime. The parentheses represent our particular uncertainty about the results.

A spectrum of Mn^{55}, bombarded by 15.4-MeV neon ions, is shown in Fig. 6.

Fe^{57}

Figure 7 shows a spectrum of the 15.4-MeV neon ion bombardment of an enriched $(Fe^{57})_2O_3$ target. In our arrangement the 14-keV γ rays could not be observed. The 122- and 136-keV γ rays were not resolved. The ϵ of Table IV includes both of these γ rays as the observed component of the de-excitation of the 126-keV state. A value of 8.6±0.2 has been reported[24] for the ratio of the intensities of the 122- and 136-keV γ rays, the 122-keV γ rays being dominant.

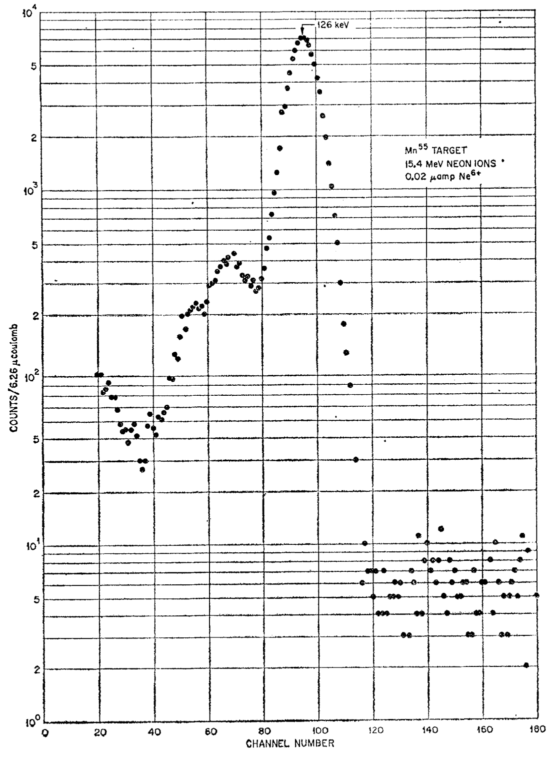

FIG. 6. Scintillation pulse-height spectrum produced by bombardment of a manganese target with neon ions.

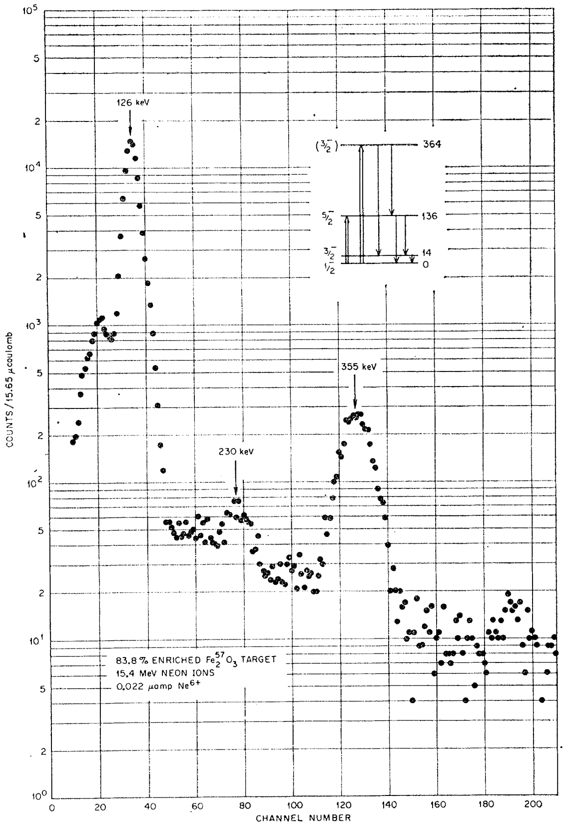

FIG. 7. Scintillation pulse-height spectrum produced by bombardment of a $(Fe^{57})_2O_3$ target with neon ions. The energies shown at the peaks were measured, but they are not expected to be as accurate as those in reference 14.

At the two highest bombarding energies the 364-keV state was excited sufficiently for quantitative measurements. The decay is mostly to the 14-keV state. A branching ratio could not be estimated, and apparently none has been reported.

The 364-keV state also cascades through the 136-keV state. The yield of the 228-keV cascade γ ray was measured directly and also in coincidence with the 122-keV γ ray. The two resulting values for the γ-ray cascade-to-crossover ratio agreed within about 6%. A best value is taken to be 0.075±0.011. This agrees with a reported value of 0.075, obtained from helium ion Coulomb excitation.[25]

With Hg^{203} and Be^7 radioisotopes for the energy calibrations the two principle γ rays were measured to

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[24] A. T. G. Ferguson, M. A. Grace, and J. O. Newton, Nuclear Phys. **17**, 9 (1960).

[25] G. F. Pieper and N. P. Heydenburg, Phys. Rev. **107**, 1300 (1957).

be 355±4 keV and 126±4 keV. These are used in Fig. 7, although the accepted values of reference 14 are expected to be better.

The $\epsilon B(E2)_{\text{ex}}$ for the 136-keV state is consistent with the mean lifetime and δ^2 values listed in Table IV. Since the lifetime of the 136-keV state is long, extranuclear effects[24] prevent the use of our measured A_2 value in the analysis of the 122-keV transition.

Our measured coefficient, $A_2=0.125\pm0.030$, for the 350-keV γ ray is consistent with a spin of $3/2^-$ or $5/2^-$ for the 364-keV state. The assignment $3/2^-$ was given recently,[26] and, therefore, it was used in the present analyses. The lifetime of this state has not been measured, so that a choice could not be made between the two possible values of δ^2. The smaller value for δ^2 gives an estimated $B(M1)$ relative to $B(M1)_{\text{s.p.}}$ of $F'=1/2.8$ which would be the largest in Table IV. The larger value for δ^2 implies $F'=1/1750$, which would be the smallest value in the Table. Mean lives of 2.8×10^{-12} sec and 3.8×10^{-10} sec, respectively, would be predicted from these values for δ^2 and the $B(E2)$. The larger value for δ^2 predicts such a long lifetime that the possibility of extranuclear attenuation effects could make conclusions based on this value of δ^2 uncertain.

Ni^{61}

Figure 8 shows the relatively weak excitation of the 67- and 282-keV levels in Ni^{61}. Although the 215-keV cascade gamma ray is not clearly discernible, the evidence for or against its existence is not strong.

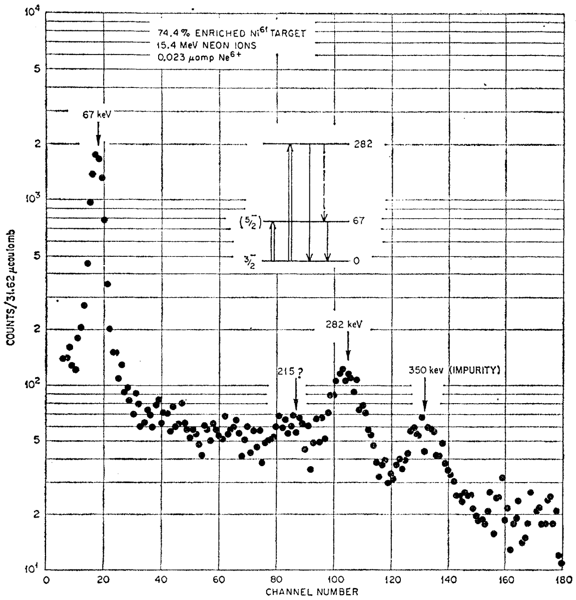

FIG. 8. Scintillation pulse-height spectrum produced by bombardment of a Ni^{61} target with neon ions.

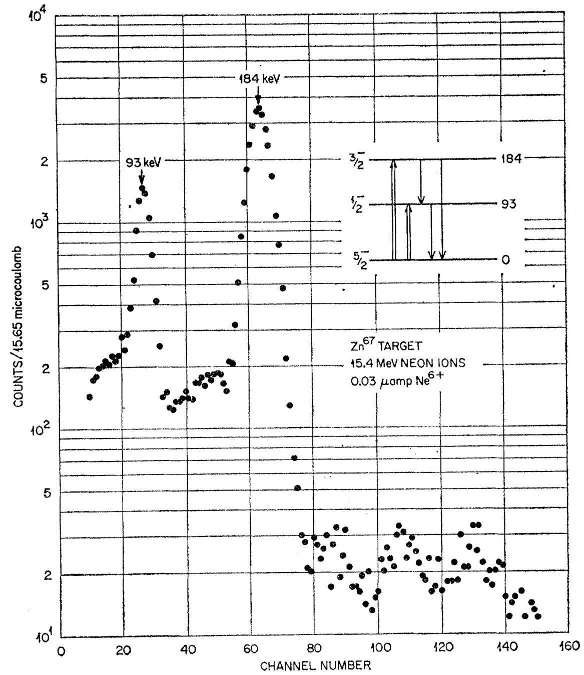

FIG. 9. Scintillation pulse-height spectrum produced by bombardment of Zn^{67} with neon ions.

Angular distribution measurements were made, but the poor statistics prevented any significant analysis for the 282-keV state. A nearly isotropic distribution was observed for the 67-keV state. From the lifetime and $\epsilon B(E2)_{\text{ex}}$ a value, $|\delta|=0.0082\pm0.0018$ is calculated, if the spin of the excited state is $5/2^-$, as seems likely.[14] This corresponds to $A_2=(-0.07\pm$a negligible error), so that such a spin assignment would imply that correlation attenuation has affected our A_2 value. A magnetic moment comparable to that for the ground state (0.3 nm)[14] would, in the magnetic field reported for metallic nickel at the nucleus (170 000 G),[27] provide such attenuation. A spin of $3/2^-$ or $1/2^-$ would require an isotropic distribution, as the ground-state spin is $3/2^-$. Thus, the present result cannot provide a choice among the three spins which are consistent with an $M1$ component in the decay.

Zn^{67}

A strong 184-keV γ ray and a composite (91+93)-keV γ-ray peak are observed in the Zn^{67} spectrum (Fig. 9). These γ rays mainly result from the strong excitation of a state at 184 keV which decays both by crossover and by cascade to a 93-keV state.

A large anisotropy, $A_2=+0.227\pm0.015$, was observed for the angular distribution of the 184-keV γ rays. This makes possible a unique spin assignment of $3/2^-$ for the 184-keV state. Previously, Rietjens and

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[26] V. F. Vervier and G. A. Bartholomew, *Proceedings of the International Conference on Nuclear Structure, Kingston* (University of Toronto Press, Toronto, 1960), p. 650.

[27] L. Bruner, J. Budnick, and R. Blume, Phys. Rev. **121**, 83 (1961).

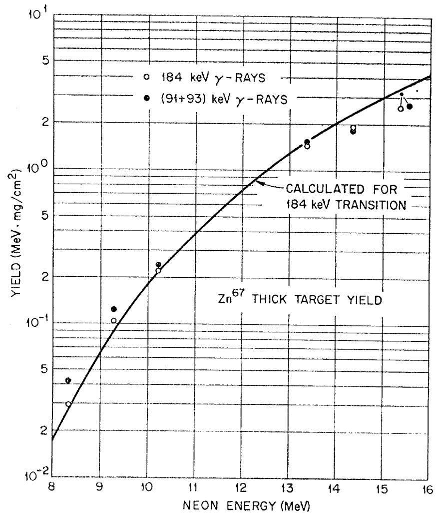

FIG. 10. Energy dependence of 184 keV and (93 keV+91 keV) thick target γ-ray yields of Zn^{67}. The 184-keV experimental points are normalized to the average $\epsilon B(E2)_{\text{ex}}$. The (93 keV+91 keV) points are normalized to agree with the 184-keV yield at 15.4-MeV neon ion energy.

Van den Bold[28] had assigned a spin of $5/2^-$ to the 184-keV state on the basis of γ-γ angular correlations resulting from the β decay of Ga^{67}. However, their analysis was based on the assumption that the 184-keV γ ray is pure $M1$. This is crudely supported by the measured internal conversion coefficient. A $5/2^-$ spin assignment for the 184-keV state is clearly inconsistent with our measured angular distribution since spin 5/2 can have, at most, an A_2 value of $+0.09$.

With the spin assignment of $3/2^-$, our A_2 measurement predicts two possible values for δ; $+(0.51\pm0.07)$ and $+(3.1\pm0.1)$. The internal conversion coefficient and the measured lifetime indicate that $+(0.51\pm0.07)$ is the correct choice for δ. This value of δ is still sufficiently large to invalidate the analysis of Rietjens and Van den Bold based on the assumption of pure $M1$ for the 184-keV transition.

The mean life of the 184-keV state can be calculated from the following quantities obtained in this work: $\epsilon B(E2)_{\text{ex}}=(0.018\pm0.003)$, $\delta=+(0.51\pm0.07)$, and R(184-keV state) = cascade transitions/crossover transitions = 0.15 ± 0.03. The calculated mean life is 2.2 ± 0.7 nsec and this is to be compared with the direct measurement of Holland and Lynch[17] of (1.45 ± 0.15) nsec.

The mean life of the 93-keV state is known; the measurements give 13 μsec.[14] Furthermore, the internal conversion coefficient indicates that the γ-ray transition is predominantly $E2$. Assuming as much as 30% $M1$, one still finds that the $B(M1)$ for decay is a factor of 10^6 smaller than the single-particle estimate. Therefore, invoking a strong plausibility argument, we can assume that the spin of the 93-keV state is such as to not allow decay by $M1$ radiation. The two possible spin values are, therefore, $1/2^-$ and $9/2^-$. However, the $9/2^-$ can be eliminated because the 184-keV state, which certainly has spin 3/2, decays by a 91-keV transition to the 93-keV state by radiation which is predominantly $M1$ as indicated by the internal conversion coefficient.

Contrary to a previous report,[29] the present results show a weak direct Coulomb excitation of the 93-keV state. Figure 10 shows the deviation of the combined 91- and 93-keV γ-ray yield curve from both the theoretical and experimental 184-keV curves. (The difference between the two experimental yields is the most significant because it avoids most of the error associated with deviations from the theoretical curves.) The $B(E2)$ obtained for direct excitation of the 93-keV state is consistent with the observed mean life if it is assumed that the state has spin $1/2^-$ and therefore decays by pure $E2$ radiation. It is interesting to note that the $B(E2)_{\text{ex}}$ for the 93-keV state is about 160 times smaller than that for the 184-keV state.

There is good evidence, cited above, for an assignment of $1/2^-$ to the 93-keV state. If the spin is $1/2^-$, then the 93-keV γ rays from both cascade and direct excitation are isotropic. Even if the spin assignment were in error, it is still likely that the 93-keV γ rays are isotropic because of the 13 μsec mean life. By correcting the observed angular distribution of the composite (91- and 93-keV) peak for the isotropic component resulting from the 93-keV γ rays, we have obtained a value $+0.184\pm0.03$ for A_2 for the 91-keV γ rays.

The value $A_2=+0.184\pm0.03$ agrees quite well with the spin sequence $\frac{5}{2}(E2)\frac{3}{2}(E2+M1)\frac{1}{2}$ with $|\delta|\leq0.07$. The observed internal conversion coefficient also indicates that the 91-keV transition is predominantly $M1$. The observed A_2 can also be obtained with spin assignments of 3/2 or 5/2 for the 93-keV state. However, the resultant values for δ require a sufficiently large amount of $E2$ to give poor agreement with the observed internal conversion coefficient.

Taking the Holland and Lynch value for the mean life of the 184-keV state, the transition branching ratio of 0.15 for cascades/crossovers, and $|\delta|\leq0.07$ for the 91-keV transition, we can calculate the $B(M1)_d$ and $B(E2)_d$ for the 91-keV γ ray. The values obtained are $B(M1)_d=0.0065$ and $B(E2)_d\leq0.006$.

Ge^{73}

Of the low-lying states in Ge^{73}, only the excitation of the 67.0-keV state is clearly evident in the spectrum, which is shown in Fig. 11. The existence of a cascade γ ray to the 13.5-keV state could not be determined from this spectrum. The analysis is not sensitive to this, as the backscatter peak from the 67-keV γ ray falls at about 53 keV.

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[28] L. H. Th. Rietjens and H. J. Van den Bold, Physica 21, 701 (1955).

[29] G. M. Temmer and N. P. Heydenburg, Phys. Rev. 96, 426 (1954).

The measured angular distributions provided the value $+0.036\pm0.015$ for A_2. This does not permit an accurate determination of δ, so the measured lifetime and our $\epsilon B(E2)_{\rm ex}$ were used. A value based on theoretical $E2$ and $M1$ conversion coefficients, 0.229, is also inferred for α_T in this calculation. A spin assignment of ($9/2^+$) or ($11/2^+$) has been suggested[14] for the 67.0-keV state. For our $\epsilon B(E2)_{\rm ex}$ and the measured lifetime listed in Table IV, a spin of 9/2 would imply that $A_2=-0.12\pm0.01$. Similarly, a spin of 11/2 would set $A_2=+0.0056\pm0.007$ or $A_2+=0.0033\pm0.0006$. A spin of 7/2, which also appears possible, would infer that $A_2=+0.064\pm0.008$ or $A_2=+0.028\pm0.01$. Thus, our measured A_2 would favor a spin of 7/2, but it would also permit 11/2. The possibility of a large correlation attenuation of the measured A_2 and the inclusion of an error of two standard deviations would also permit 9/2, but this seems less likely. We have used 7/2 in our analyses.

As^{75}

The excitation of the 199- and 280-keV levels in As^{75} appears in the spectrum in Fig. 12. Evidence for a reported[14] 1.3% 81-keV cascade γ ray is not clear in this spectrum. We have, however, used that value in the analysis. To test for possible excitation of the 265-keV state, an energy calibration was made, based on Hg^{203}, and the shape and width of the apparent 280-keV peak of As^{75} was carefully studied. It is estimated that if there were 265-keV γ rays in the spectrum, their yield was less than 10% of the 280-keV γ-ray yield.

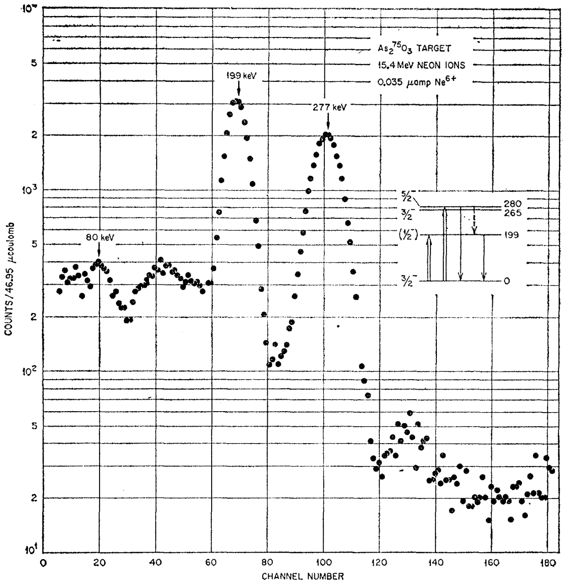

FIG. 12. Scintillation pulse-height spectrum produced by bombardment of an As$_2$O$_3$ target with neon ions.

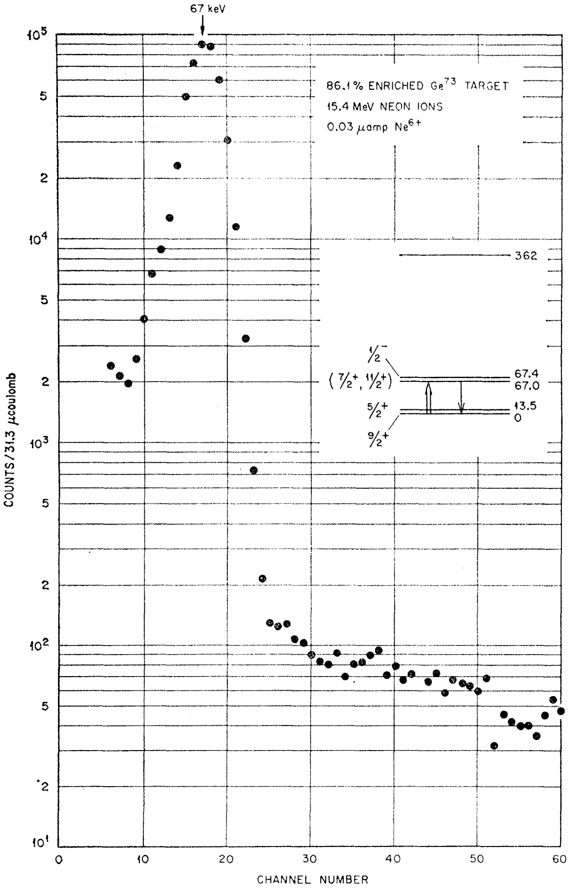

FIG. 11. Scintillation pulse-height spectrum resulting from bombardment of Ge^{73} with neon ions.

The large measured value for A_2 uniquely predicts a spin assignment of $5/2^-$ for the 280-keV state. This confirms the listed value,[14] which was based on the comparative γ-ray lifetime from a $9/2^+$ state above. Two possible values, -0.52 or -1.03, are inferred for δ from the present measurement of A_2. But A_2 is near the peak of the curve, and the assigned experimental errors would permit any value of δ from -0.34 up to -1.40. A measured mean lifetime of $(7.8\pm0.7)\times10^{-10}$ seconds has been reported for this state.[30] With our $\epsilon B(E2)_{\rm ex}$, this value implies that $|\delta|=1.22\pm0.14$. Another mean lifetime measurement[31] has been given, but with relatively large quoted errors.

Several measurements of δ from angular correlations[14] have been published. Metzger and Todd,[32] guided by their internal conversion electron data, combined the various angular correlation data to obtain a value of $\delta=-0.42\pm0.05$ which was judged to reconcile both sets of experiments. A value of $\delta=-0.75$ has been obtained from a measurement of the polarization

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[30] J. Varma and M. A. Eswaran, Phys. Rev. **125**, 656 (1962).

[31] E. N. Shipley, F. J. Lynch, and R. E. Holland, Bull. Am. Phys. Soc. 4, 404 (1959).

[32] F. R. Metzger and W. B. Todd, Nuclear Phys. **10**, 220 (1959).

direction correlation.[33] The lower present value, -0.52, was therefore used in our analysis. With our $B(E2)$, this value of δ would imply a mean lifetime of 3.0×10^{-10} sec, which agrees with one of the measured values.[31] Metzger and Todd predicted a mean lifetime of 2.4×10^{-10} sec from their data, using the same method.

For the 199-keV state, the small measured A_2 coefficient could not be used to determine δ accurately. From the measured lifetime[31] and our $B(E2)$, a value of δ was calculated. It is consistent with the measured value of A_2, and a spin of $1/2^-$, $3/2^-$, or $5/2^-$ for the 199-keV state. (The latter value fits the analysis the least.) For the analysis leading to other quantities in Table IV, the listed[14] probable spin, $(1/2^-)$, was used.

Ru^{101}

The results for excitation of the 127-keV state in Ru^{101} are given in Tables I, II, and III. No explanation has been found for the relatively large ($\sim$20%) difference in the $\epsilon B(E2)_{\mathrm{ex}}$ values at the two bombarding energies, or for the disagreement with the other value listed in Table I. The lifetime of the excited state has apparently not been reported. The present value of A_2, with the $B(E2)$, would predict a mean lifetime of 1.33×10^{-9} sec or 4.25×10^{-8} sec, assuming that there was no correlation attenuation. This also assumes that the excited state spin is $(3/2^+)$.[14]

Pd^{110}

The excitation of the 374-keV state in this nucleus was convenient as a test of the γ-ray angular distribution from heavy-ion Coulomb excitation. There is an apparently unattenuated strong anisotropy associated with this 0–2–0 spin sequence.[12] With measurements at only two angles, it was possible only to determine the preservation of the anisotropy, as the relatively large value of A_4 prevented a unique determination of the coefficients. The large measured value of R, 1.585 ± 0.035, differs by 1.4 standard deviation from the theoretically predicted value (1.535).

Pr^{141}

A 145-keV state has been reported for Pr^{141}, but it was not measurably excited in this work. It has also been stated that this level was not excited with 6-MeV helium ions.[5] By a method similar to that for Cr^{53}, the present results would predict an upper limit of 1.9×10^{-10} γ rays per incident particle for the yield of such a transition when 14.4-MeV neon ions were used. This corresponds to $\epsilon B(E2)_{\mathrm{ex}}=0.003$. Previously assigned spins and parities[14] of the ground and 145-keV states would allow $E2$ Coulomb excitation. A value, $\epsilon B(E2)_{\mathrm{ex}}=0.0036\pm0.00072$, has been published for heavy-ion excitation of this state.[34]

Hf

A natural hafnium target was used to test the neon ion Coulomb excitation in the region $A\approx180$. Gamma rays from the 112-keV state in Hf^{177} and the 122-keV state in Hf^{179} were not resolved. The combined yield, 2.22×10^{-8} γ rays per incident particle, was used to find an effective value of $\epsilon B(E2)_{\mathrm{ex}}=0.46$. This agrees with a result obtained similarly from proton bombardment of a natural Hf target.[35] Comparison with others' results for separated isotopes is made possible by combining them according to the natural isotopic abundances. Ignoring the mass and γ-ray energy differences, the formula for combining the Hf^{177} and Hf^{199} results is

$$\epsilon B(E2)_{\mathrm{ex}}{}^{177+179}=0.43\epsilon B(E2)_{\mathrm{ex}}{}^{179}+0.57\epsilon B(E2)_{\mathrm{ex}}{}^{177}. \quad (3)$$

For this the natural isotopic abundances $\eta^{177}=0.185$ and $\eta^{179}=0.138$ were used. The two combined $\epsilon B(E2)_{\mathrm{ex}}$ values obtained this way, and listed in Table I, bracket the present result.

Ta^{181}

A number of values for $\epsilon B(E2)_{\mathrm{ex}}$ have been given[14] for the 136-keV transition in Ta^{181}, all for proton or helium ion bombardment. The present value 0.74 was obtained from 11.8-MeV neon ion bombardment which gave a yield of 4.82×10^{-9} γ rays per incident particle. It falls centrally among the other values quoted in Table I.

Th^{232}

One yield measurement with 15.4-MeV neon ions was made for the 53-keV transition in Th^{232}. The results were 5.09×10^{-9} γ rays per incident particle, for which $\epsilon B(E2)_{\mathrm{ex}}=0.0232$. This agrees, within about 15%, with a recent result obtained with 4-MeV helium ions.[36] It is among the other values quoted in Table I.

VI. DISCUSSION

In the survey of γ-ray yields we did not find any consistent evidence for the departure of the neon ion Coulomb excitation process from expectations. There were a few cases in which our $\epsilon B(E2)_{\mathrm{ex}}$ values deviated from reported values for light ions by more than the quoted errors. We were able to test part of these by the use of helium ions and the values obtained were in agreement with the neon values.

In more detailed discussion we consider only the odd-A nuclei from Ti^{47} to As^{75}. These nuclei are in a region where the even-even neighbors exhibit near-

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[33] H. J. Van den Bold, J. Van de Geijn, and P. M. Endt, Physica **24**, 23 (1958).

[34] I. Kh. Lemberg, *Reactions Between Complex Nuclei* (John Wiley & Sons, Inc., New York, 1960), p. 112.

[35] P. H. Stelson and F. K. McGowan, Phys. Rev. **99**, 112 (1955).

[36] F. K. McGowan and P. H. Stelson, Phys. Rev. **120**, 1803 (1960).

harmonic vibrational spectra. From Table IV one sees that of the 14 transitions studied in these nuclei, 9 have an estimated enhancement factor for $B(E2)$ of about 10 or larger. On the other hand, 3 transitions are inhibited. For the single-particle decay transition we have used the estimate[37]

$$B(E2)_{\text{s.p.}}=\frac{1}{4\pi}\left(\frac{3}{5}R_0^2\right)^2 C(j_>,j_<)\frac{2j_f+1}{2j_<+1}, \tag{4}$$

where $R_0=1.20\times A^{1/2}$ F.

Odd-A nuclei, such as these, have been treated by a model which assumes a coupling of intrinsic nucleon states to collective oscillations.[5,38,39] A parameter q which is used to characterize the strength of this coupling, is calculated from the phonon vibrational properties of the adjacent even-even nuclei. Table V lists q and other relevant quantities for these nuclei. In calculating q, and the surface tension parameter C, we found it convenient to use the following equations:

$$q=(\langle\beta^2\rangle_{\text{av}}/8\pi)^{1/2}(k/\hbar\omega_2), \tag{5}$$

and

$$C=\tfrac{5}{2}\hbar\omega_2/\langle\beta^2\rangle_{\text{av}}. \tag{6}$$

Here $\langle\beta^2\rangle_{\text{av}}$ is the square of the rms value of the deformation parameter; k is a coupling parameter taken to be 40 MeV; and $\hbar\omega_2$ is the energy of the first 2^+ collective excited state in the adjacent even-even nucleus.

The values of q in Table V suggest an intermediate coupling situation.

The two nuclei with the smallest values for q are Ni^{61} and V^{51}, both of which are single-closed-shell (s.c.s.) nuclei. Kisslinger and Sorensen[40] have considered a pairing plus P_2 force model for s.c.s. nuclei. A general result of this model is that the low-lying excited states of such nuclei are expected to be quasi-particle states which exhibit inhibited $E2$ transitions. The small $B(E2)$'s for excitation of the 67- and 282-keV states in Ni^{61} are in agreement with this prediction. For Ni^{61}, Sorensen[41] has also considered the coupling of the quasi-particle states to the first and second phonon states. He predicts that the first excited state to have an appreciable amount of one-phonon amplitude occurs at 1.28 MeV. However, the reported $B(E2)$ for excitation of the 0.66-MeV state[42] indicates that this state contains a large amount of one-phonon amplitude.

TABLE V. Vibrational parameters for medium-light odd-A nuclei. Column 1 lists the nucleus. Column 2 lists the adjacent even-even nuclei which were used in the calculation. Where 2 nuclei are listed, the average of their properties was used. Column 3 gives the estimated rms value of the deformation parameter β. In column 4 the energy of the first excited 2^+ collective level in the even-even nucleus is given. Column 5 gives the surface tension parameter, as calculated from Eq. (6). In column 6 the coupling parameter q is given, as calculated from Eq. (5).

(1) Nucleus	(2) Adjacent nuclei	(3) $\bar{\beta}_{\text{rms}}$[a]	(4) $\hbar\bar{\omega}_2$[b] (MeV)	(5) $\bar{C}$ (MeV)	(6) q
${}_{22}Ti_{25}^{47}$	${}_{22}Ti_{24}^{46}$, ${}_{22}Ti_{26}^{48}$	0.265	0.94	34	2.2
${}_{23}V_{28}^{51}$	${}_{24}Cr_{28}^{52}$	0.255	1.43	55	1.4
${}_{25}Mn_{30}^{55}$	${}_{26}Fe_{30}^{56}$	0.255	0.84	33	2.4
${}_{26}Fe_{31}^{57}$	${}_{26}Fe_{30}^{56}$	0.255	0.84	33	2.4
${}_{28}Ni_{33}^{61}$	${}_{28}Ni_{32}^{60}$, ${}_{28}Ni_{34}^{62}$	0.19	1.25	82	1.2
${}_{30}Zn_{37}^{67}$	${}_{30}Zn_{36}^{66}$, ${}_{30}Zn_{38}^{68}$	0.22	1.06	55	1.7
${}_{32}Ge_{41}^{73}$	${}_{32}Ge_{40}^{72}$, ${}_{32}Ge_{42}^{74}$	0.275	0.72	24	3.0
${}_{33}As_{42}^{75}$	${}_{32}Ge_{42}^{74}$, ${}_{34}Se_{42}^{76}$	0.31	0.58	15	4.3

[a] P. H. Stelson, *Proceedings of the International Conference on Nuclear Structure*, Kingston (University of Toronto Press, Toronto, 1960), p. 791.
[b] See reference 14.

The large $B(E2)$ observed for excitation of the 320-keV state in the s.c.s. nucleus V^{51} is in strong disagreement with an interpretation of this state as a $5/2^+$ quasi-particle state. The model of de-Shalit[43] which interprets the low-lying states to be the result of coupling the core excitation to a single shell-model state seems to be much more appropriate for the low-lying levels of V^{51}.

The remaining nuclei, Ti^{47}, Fe^{57}, Zn^{67}, Ge^{73}, and As^{75}, are not s.c.s. nuclei and their spectra are generally more complex. Perhaps the most interesting feature is the comparatively large $E2$ enhancements observed for the excitation of levels which are relatively low-lying compared to the 2^+ states of adjacent even-even nuclei. These enhancements indicate that the levels cannot be thought of as pure quasi-particle states. The coupling between nucleon states and phonon vibrations is sufficiently strong to introduce into these states a considerable phonon amplitude. The 93- and 184-keV states in Zn^{67} are particularly interesting. The $B(E2)$ for excitation of the 184-keV state is comparable to those observed for excitation of even-even Zn nuclei which have 2^+ states with energies of approximately 1 MeV. On the other hand, the $B(E2)$ for excitation of the 93-keV state is inhibited and has a $B(E2)$ about 1/100 of that for the 184-keV transition. A similar situation exists for the 265- and 280-keV states in As^{75}; the $B(E2)$ for exciting the 265-keV state is at least 10 times less than that for the 280-keV state.

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[38] D. C. Choudhury, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **28**, No. 4 (1954).

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[42] L. W. Fagg, E. H. Geer, and E. A. Wolicki, Phys. Rev. **104**, 1073 (1956).

[43] A. de-Shalit, Phys. Rev. **122**, 1530 (1961).