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Yields of Gamma Rays Emitted Following Capture of Negative Muons by ^{28}Si and ^{24}Mg†

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We have measured the yields of specific final states excited in the capture of negative muons by ^{24}Mg and ^{28}Si. The yields are compared with the cross sections for excitation of the analog states by 180° electron scattering and with the relative populations of levels produced by the decay of the giant-dipole-resonance states.

I. INTRODUCTION

Negative muons brought to rest in matter are first slowed down to thermal velocities by ionizing collisions with electrons and are subsequently captured in outer atomic orbits. The atomically captured muon cascades in $\sim 10^{-13}$ sec by Auger and radiative transitions to the 1s atomic state. From this state the muon can either decay in 2×10^{-6} sec or be captured by the nucleus in the weak-interaction process

$$\mu^- + p \to n + \nu_\mu .$$

The capture occurs approximately in a time 10^{-7} $(82/Z)$ sec and for $Z>12$ dominates over the free decay. For capture by a complex nucleus, reactions of the type

$$\mu^- + (A,Z) \to [A-(x+y), Z-(x+1)]^* + \nu_\mu + xp + yn ,$$
$$x, y = 0, 1, 2, 3, \ldots$$

can occur. The resulting nucleus can be left in either an excited state or in the ground state. We present here results of experiments in which negative muons were captured by ^{24}Mg and ^{28}Si and the resulting nuclear γ rays observed. Comparisons are made with analogous (γ, p) and (γ, n) photodisintegration experiments and (e, e') electron excitation experiments.

The probability that muon-capture results in a nuclear transition of the type

$$|T=0,\ J^\pi = 0^+\rangle \to |T=1,\ J^\pi = 1^+\rangle$$

can be written approximately as[1]

$$\Lambda_{\mu c}(0^+ \to 1^+) = \frac{(Z\alpha m_\mu)^3}{\pi} \frac{1}{1+m_\mu/AM} R\frac{\nu^2}{2\pi}\frac{1}{1+\nu/AM}\left[|G_A|^2 + \tfrac{1}{3}(|G_p|^2 - 2G_pG_A)\right]\left|\left(1^+\left\|\sum_{i=1}^{A}\tau_i^{(-)} j_0(\nu x_i)\sigma(i)\right\|0^+\right)\right|^2 .$$

Similarly, for 180° electron excitation of the analog states, the cross section[1] can be written as

$$\frac{d\sigma}{d\Omega}(180°) = \frac{\pi\alpha^2}{k_1^2}\frac{1}{1+(k_1+k_2)/AM}\,|(1^+\|T_1^{\mathrm{Mag}}(k_1+k_2)\|0^+)|^2 ,$$

with

$$|(1^+\|T_1^{\mathrm{Mag}}(q)\|0^+)|^2 = \frac{1}{12\pi}\left(\frac{q}{2M}\right)^2\left|\left(1^+\left\|\sum_{i=1}^{A}\frac{\tau_i^3}{\sqrt{2}}\left[l(i)j_0(qx_i) + (\lambda_p-\lambda_n)j_0(qx_i)\sigma(i)\right]\right\|0^+\right)\right|^2 .$$

One can use our measured $\Lambda_{\mu c}$ for excitation of 1^+ levels in the $(A, Z-1)$ nuclei to obtain $|\int\sigma|^2$ and then relate this information to the measured $d\sigma/d\Omega(180°)$ for the analog states in order to infer the relative size of $|\int l|^2$. This procedure has been applied many times to the analogous β^- and γ decays of analog states.[2-4]

The participation of giant-dipole-resonance states in muon capture has long been under discussion.[5] It was originally introduced to account for total capture-rate measurements, but its importance has been uncertain until recently. One might hope to ascertain the extent to which 1^- giant-resonance states in the $(A, Z-1)$ nucleus participate in muon capture by the (A, Z) nucleus by making use of the deexcitation schemes of the known 1^- levels in the (A, Z) nucleus. If the analogs of these known 1^- states participate in muon capture, then the deexcitation schemes might be expected to be similar. A detailed comparison by the Louvain group[6] of the deexcitation schemes produced by the isobaric analogs excited in the weak and electromagnetic interactions in ^{40}Ca has given very strong evidence for the participation of giant-resonance levels in muon capture. This same comparison of the yields of states produced by $(\mu^-, \nu n)$ reactions can be made with recent (γ, p) and (γ, n) experiments. This comparison is illustrated in Fig. 1.

II. EXPERIMENTAL TECHNIQUE AND DATA ANALYSIS

The data were collected at the National Aeronautics and Space Administration Space Radiation Effects Laboratory (SREL) in Newport News, Virginia using the 105-MeV/c (backward) muon beam from the muon channel. A standard scintillation counter array was employed to define a stopping muon. Electronic logic requirements insured that events were analyzed only when muon stop signatures were separated by more than three capture lifetimes. Isotopically pure targets of $^{28}SiO_2$ and ^{24}MgO were used to avoid confusion between reactions of the types:

$$\mu^- + (A, Z) \rightarrow (A, Z-1)^* + \nu_\mu$$

and

$$\mu^- + (A+1, Z) \rightarrow (A, Z-1)^* + \nu_\mu + n \, .$$

The muonic x rays and nuclear γ rays were detected in a 50-cm^3 Ge(Li) detector having an instrumental resolution of 2.5 keV full width at half maximum at 1.3 MeV under running conditions. On-line analysis with the SREL IBM 360/44 data-acquisition system permitted separate storage of γ-ray events whose signals were prompt or delayed in time with respect to the stopping muon.

The yields of the γ rays were determined by using an experimental relative efficiency curve corrected for self-absorption in the target and by assuming a 100% yield for the K series muonic x rays. The yields of selected γ rays were also measured by an absolute efficiency technique in which use was made of a muonic x ray whose energy was near that of the photon of interest.[7] Corrections were applied for the finite observation time with respect to the muon-capture lifetime and for that fraction of muons which undergo decay rather than capture. The resultant yields are expressed in terms of the intensity of a given γ-ray transition per captured muon, and thus do not involve uncertainties due to branching-ratio information. Identification of the transitions was based on energy, presence of associated cascades, and the consistency of the yields for different experimental geometries. In both targets, γ rays could be observed with yields of 0.001 but whose sources were unidentifiable. The total rates to all ^{28}Al and ^{24}Na states were determined by an activation technique in which the muonic x rays and the γ rays emitted following β^- decay were detected in the same geometry with the same detector. The γ rays following β^- decay were observed with the beam off.

Background events were induced by neutron excitation of the levels of interest in both the target

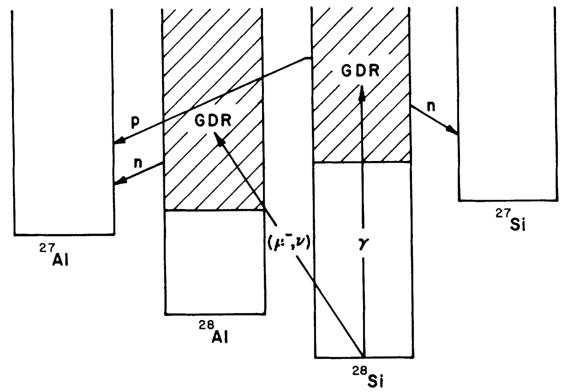

FIG. 1. A schematic representation of the comparison between $(\mu^-, \nu n)$, (γ, p), and (γ, n) reactions in ^{28}Si assuming each proceeds through the electric dipole giant-resonance (GDR) states.

and nearby materials such as the Al cap on the detector. Corrections for these neutron-induced γ-ray lines were determined from measurements taken when muons were stopped in a Cu absorber immediately upstream of the target and when muons were stopped in different targets. A total correction of $(15 \pm 2)\%$ was applied to the ^{28}Al activation measurements of which 2% was due to neutron interactions in the target itself. The time distribution of neutron-induced γ rays was identical to that of muon-capture γ rays, indicating that neutrons emitted following muon capture were responsible for the background events. Thus, the possibility of a simple subtraction of out-of-time background was excluded as a means of correcting the raw data.

The data presented here represent 1×10^{11} stopped muons. Approximately 7×10^{10} muons were stopped in $^{28}SiO_2$ and 3×10^{10} muons were stopped in ^{24}MgO.

III. RESULTS AND CONCLUSIONS

Tables I and II are a listing of the measured yields for ^{24}Mg and ^{28}Si. Comparisons with other experimental data have been made where possible. The results are consistent with recent $(\mu^-, \nu p)$ activation experiments, and experiments involving the observation of charged particles and neutron multiplicities following muon capture,[8-11] but we are unable to confirm the results of these experiments exactly because of our inability to measure capture to the ground states in the pertinent nuclei or to distinguish between emission of a d or of an np pair. Table III lists typical background radiation induced in extraneous materials.

Several comments may be made about the yields themselves. In the two cases where we have measured the total rate to all bound states (^{24}Na and ^{28}Al), capture to the excited states accounts for almost all the rate. Capture to the ground state in each has a yield of <0.06. We should point out that this is not too surprising when one considers the spin changes of 4 and 3, respectively. The 974-keV level in ^{28}Al is known[12] to be a 0^+ level. Direct capture to this level from ^{28}Si would be a pure Fermi transition. Using the branching ratios determined by Boerma[12] and correcting for cascades from higher levels we find the yield of direct capture to this level to be

$$Y_{\mu c}(974\text{ keV}) = 0.0005 \pm 0.0030 .$$

A calculation[13] of the yield indicates a rate of this order. Although we detect a relatively large amount of capture to a state at 7.7 MeV in ^{28}Al, the major contribution to bound-state captures does not seem to reside principally in this level as suggested by Bunatyan *et al.*[14] We find a fairly uniform population of all the low-lying 1^+ states in ^{28}Al (1.373, 1.620, 2.202 MeV).[12] Of course, unobserved cascades in ^{28}Al might tend to populate the lower states, but no such cascades were observed.

In Table IV we list the electroexcitation cross sections calculated using the measured muon-capture yields to the analog 1^+ states and compare them with the experimental cross sections[15, 16] for ^{28}Si and ^{24}Mg at a similar momentum transfer. For these calculations, the branching ratios in ^{28}Al obtained by Boerma[12] have been used to determine the state populations. The levels in ^{24}Mg are assumed to have only one branch. The cross sec-

TABLE I. Observed γ-ray transitions from μ^- capture in ^{24}MgO. Yield is the number of photons, not the number of transitions to a specific state, per captured muon. Energies are in keV.

Nucleus	Transition	Yield	Comments
^{24}Na	Total	0.228 ± 0.022	
	$472 \to 0$	0.167 ± 0.012	
	$1341 \to 472$	0.036 ± 0.004	
	$1347 \to 472$	0.040 ± 0.004	
	$1846 \to 472$	0.039 ± 0.004	
^{23}Na	$440 \to 0$	0.295 ± 0.012	
	$2078 \to 440$	0.039 ± 0.004	
	$2391 \to 440$	0.023 ± 0.002	
	$2391 \to 0$	0.021 ± 0.002	
	$2639 \to 0$	0.052 ± 0.006	
	$2705 \to 2078$	0.002 ± 0.001	
^{22}Na	$583 \to 0$	0.018 ± 0.001	
	$891 \to 0$	0.002 ± 0.0005	
	$1950 \to 580$	0.037 ± 0.004	Mixed with ^{24}Mg $1368 \to 0$
	$1528 \to 0$	0.002 ± 0.0005	
	$2970 \to 1955$	0.010 ± 0.002 [a]	
^{23}Ne	$980 \to 0$	0.002 ± 0.0005 [a]	
	$1770 \to 0$	0.005 ± 0.001	
^{22}Ne	$1247 \to 0$	0.044 ± 0.006	
^{21}Ne	$350 \to 0$	0.025 ± 0.003	
^{21}F	$1100 \to 0$	0.001 ± 0.0005	
^{20}F	$650 \to 0$	0.004 ± 0.001	
^{19}Ne	$1510 \to 0$	0.007 ± 0.001	
^{19}F	$109.9 \to 0$	0.005 ± 0.001	
	$197 \to 0$	0.020 ± 0.002	
	$1346 \to 0$	0.002 ± 0.001	
	$1460 \to 0$	0.007 ± 0.001	
^{18}Ne	$1880 \to 0$	0.004 ± 0.001	
^{18}O	$1979 \to 0$	0.019 ± 0.010	

[a] Corrections have been made for the excitation of levels of the same energy due to inelastic neutron scattering in the ^{27}Al detector cryostat cover.

tions $(d\sigma/d\Omega)_{\mu c}$ are calculated using $|\int\sigma|^2$ as determined from muon capture assuming $|\int l|^2=0$. Comparison shows that in general we cannot neglect that part of the electron cross section due to $|\int l|^2$. The actual size of $|\int l|^2$ cannot be determined because of a lack of knowledge of the σ-l relative phase, but the results are in agreement with β^--γ comparisons in the $2s$-$1d$ shell.[4] An apparent discrepancy exists in the case of the 1.373-MeV level in ^{28}Al. An inclusion of the second-order terms in $\Lambda_{\mu c}$ would reduce the values we calculate for the electroexcitation cross section, but these terms are expected to be small. If the population of the 1.373-MeV level were due primarily to cascades, the calculated electroexcitation cross sections would also be lowered. No such cascades were seen in the energy range below 7 MeV. A large value of $\int l$ with opposite phase from $\int\sigma$ could also account for the discrepancy.

Figure 2 shows a comparison of the relative yields of final states produced by the reactions ^{28}Si$(\mu^-, \nu n\gamma')^{27}$Al, ^{28}Si$(\gamma, p\gamma')^{27}$Al, and ^{28}Si$(\gamma, n\gamma')$-^{27}Si. The data from the $(\gamma, p\gamma')$ and $(\gamma, n\gamma')$ experiments are due to Thompson *et al.*[17] and represent the integral of the cross section for incident photon energies from 0–28 MeV. These (γ, p), (γ, n) experiments would populate the seven 1^-, $T=1$ and two 1^-, $T=0$ states as predicted[18] by the particle-hole shell model and as measured by Caldwell *et al.*[19] As indicated by Farris and Eisenberg,[18] the 1^-, $T=1$ states at 19.5, 21.8, and 26.3 MeV have the greatest γ-ray absorption strength. These states are the analogs of the 1^- states in ^{28}Al whose participation in muon capture is being investigated. We are thus exploring the contribution of electric dipole (first-forbidden muon-cap-

TABLE II. Observed γ-ray transitions from μ^- capture in $^{28}SiO_2$. Yield is the number of photons, not the number of transitions to a specific state, per captured muon. Energies are in keV.

Nucleus	Transition	Yield	Comments	Other measurements
^{28}Al	Total	0.26 ±0.03		0.28 ±0.04 [a]
	30→0	0.131 ±0.013		
	974→30	0.020 ±0.003		0.012±0.010 [b]
	1373→30	0.017 ±0.002		0.015±0.024 [b]
	1620→30	0.017 ±0.003		
	1620→0	0.018 ±0.003		
	2202→30	0.046 ±0.003		
	2202→974	0.011 ±0.002		
	7725→0	0.054 ±0.40		
^{27}Al	842→0	0.114 ±0.008 [c]		0.078±0.014 [b]
	1013→0	0.103 ±0.008 [c]		0.055±0.014 [b]
	2213→0	0.018 ±0.010 [c,d]	Mixed with $H(n, \gamma)D$	0.060±0.050 [b]
	2732→1013	0.008 ±0.007		0.020±0.030 [b]
	2979→0	0.026 ±0.008		
	3677→843	0.006 ±0.002		
^{27}Mg	984→0	0.019 ±0.002 [c]		0.004±0.010 [b]
^{26}Mg	1808→0	0.10 ±0.01 [c]		
	2940→1808	0.032 ±0.005 [c]		0.027±0.018 [b]
	3942→2940	0.0009±0.0006		
^{26}Al	229→0	0.007 ±0.002		
	418→0	0.009 ±0.002		
^{25}Mg	585→0	0.006 ±0.003	Mixed with ^{22}Na 583→0	
	975→0	0.008 ±0.003		
	1614→0	0.009 ±0.005		
^{24}Mg	1368→0	0.009 ±0.005		
^{22}Ne	1274→0	0.009 ±0.005		

[a] G. G. Bunatyan *et al.*, Ref. 21.
[b] T. A. E. C. Pratt, Ref. 7.
[c] Corrections have been made for the excitation of these levels due to inelastic neutron scattering in the ^{27}Al detector cryostat cover.
[d] This measurement comes from an experiment in Si (natural) which had significantly less contamination from $H(n, \gamma)D$.

TABLE III. Some background lines induced in extraneous materials for the targets ^{24}MgO and $^{28}SiO_2$.

Energy (keV)	Yield/Stopped μ	Identification
197	0.01	$^{19}F^*$
346	0.05	μK_α Al
296	0.003	μK_α Mg
476	0.20	$^{10}B(n, \alpha)^7Li^*$
511	0.45	β^+
596	0.02	^{74}Ge
693	0.01	^{72}Ge
700	0.07	^{74}Ge
803	0.003	^{206}Pb
835	0.02	^{72}Ge
842	0.01	^{27}Al
846	0.005	^{56}Fe
898	0.003	^{207}Pb
984	0.001	^{27}Mg
1013	0.001	^{27}Al
1172	0.007	^{60}Ni
1332	0.007	^{60}Ni
1808	0.007	^{26}Mg
2223	0.165	$H(n, \gamma)D$
2502	0.004	μL Pb
2642	0.004	μL Pb
5269	0.02	^{15}N
5298	0.06	^{15}N

ture) terms. The relative populations of the states as determined from the three experiments are in good agreement within the experimental errors. The yield of the 2.213-MeV state in ^{27}Al, which shows the largest discrepancy, is poorly determined in this experiment because of its Doppler-broadened character and a confusion with the strong 2.223-MeV line from $H(n,\gamma)D$ reactions occurring in shielding material. Capture to these excited states in ^{27}Al accounts for approximately 25% of the total muon-capture rate. Comparison with the neutron multiplicity experiments of MacDonald *et al.*[11] indicates that capture to the ground state in ^{27}Al occurs 20% of the time. The production of bound states in ^{27}Al thus accounts for 45% of the total capture rate in ^{28}Si. The good agreement between the deexcitation schemes of known 1^- giant-resonance states and the yields of states in ^{27}Al indicates that it is the 1^- giant-resonance states in ^{28}Al which are responsible for the production of ^{27}Al in muon capture.

If one were to adopt a direct-reaction model rather than a two-step giant-resonance model to account for the production of the ^{27}Al states, one might expect to see a different relative population of the excited states in ^{27}Al. The reaction $^{28}Si(d, {}^3He)^{27}Al$ is of a direct type,[20] and is similar to the reaction $^{28}Si(\mu^-, \nu n)^{27}Al$. Table V shows the relative population of states in ^{27}Al from the reactions $(\mu^-, \nu n)$ and $(d, {}^3He)$ on ^{28}Si. The two sets of results show little correlation. This comparison indicates that the states in ^{27}Al populated by muon capture have a distinct character similar to that seen in giant-resonance deexcitation and distinguishable from the distribution of states excited by a direct reaction.

Approximately 74% of the total muon-capture rate in ^{28}Si occurs to states other than the bound states in ^{28}Al. Figure 3 shows the ground-state energies of all nuclei observed to be excited by muon capture in ^{28}Si. The solid lines represent removal of particles one at a time, while the dashed lines represent the removal of bound clusters (eg., $^{26}Mg+d$, $^{25}Mg+t$, $^{24}Na+\alpha$) from ^{28}Al. If we adopt the giant-resonance mechanism for muon capture, comparison with Table II shows that between 5–20% of the total muon-capture rate is to states energetically inaccessible to decay from the strong 1^-, $T=1$ states in ^{28}Al predicted[18] by the particle-hole shell model. These popula-

TABLE IV. Comparison of 180° experimental inelastic electron scattering cross sections with the values predicted by muon-capture measurements. $E_{\mu c}$ and $E_{e,e'}$ are the 1^+ energy levels excited in muon capture and electroexcitation, respectively; $q_{\mu c}$ and $q_{e,e'}$ are the respective momentum transfers for the reactions. The cross section $(d\sigma/d\Omega)_{\mu c}$ is calculated using the measured muon-capture yields and assuming $|\int l|=0$.

Nucleus	$E_{\mu c}$ (MeV)	$q_{\mu c}$ (MeV)	$E_{e,e'}$ (MeV)	$q_{e,e'}$ (MeV)	$(d\sigma/d\Omega)_{\mu c}$ (10^{-32} cm²/sr)	$(d\sigma/d\Omega)_{e,e'}$ (10^{-32} cm²/sr)
^{28}Si	1.373	99.963	10.48	101.32	0.53 ± 0.05	0.10 ± 0.03 [a]
	1.620	99.716	10.86	100.94	0.37 ± 0.04	0.60 ± 0.05 [a]
	2.202	99.134	11.41	100.39	1.01 ± 0.10	2.50 ± 0.14 [a]
^{24}Mg	0.473	99.671	9.94	101.86	0.78 ± 0.08	1.04 ± 0.05 [b]
	1.3414	98.803	10.70	101.10	0.56 ± 0.06 } 1.2 ± 0.2	1.94 ± 0.07 [b]
	1.3469	98.797			0.64 ± 0.07 }	

[a] L. W. Fagg *et al.*, Ref. 15.

[b] L. W. Fagg *et al.*, Ref. 16.

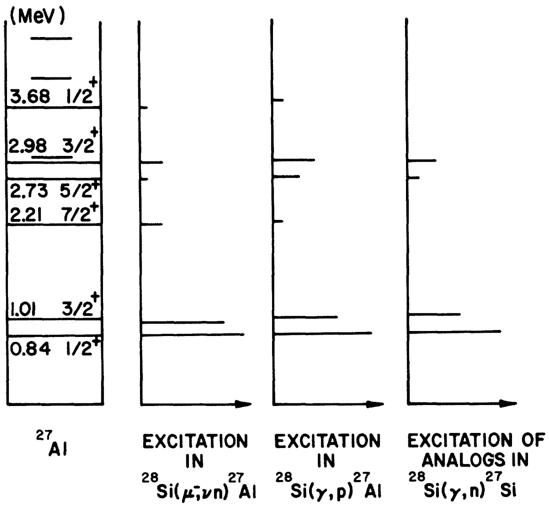

FIG. 2. Comparison of the relative yields of states populated by $(\mu^-, \nu n)$, (γ,p), and (γ,n) reactions in ^{28}Si. The (γ,p) and (γ,n) data are the result of observations of final nuclear γ rays and represent the integral of the cross section from 0–28-MeV incident photon energy.

TABLE V. Relative populations of levels in ^{27}Al from the reactions ^{28}Si$(\mu^-, \nu n)^{27}$Al and ^{28}Si$(d, {}^3\text{He})^{27}$Al. The results of the muon-capture experiment reflect the branching ratios determined by DeVoigt *et al.* (Ref. 22).

Level energy (MeV)	J^π	Relative yield from ^{28}Si$(\mu^-, n)^{27}$Al	Relative yield from ^{28}Si$(d, {}^3\text{He})^{27}$Al [a]
0	$\frac{5}{2}^+$	20.0 [b]	3.12
0.843	$\frac{1}{2}^+$	10.6	0.79
1.013	$\frac{3}{2}^+$	9.5	0.75
2.213	$\frac{7}{2}^+$	1.8	
2.732	$\frac{5}{2}^+$	1.0	0.75
2.980	$\frac{3}{2}^+$	2.6	≤0.24
3.001	$\frac{9}{2}^+$		
3.668	$\frac{1}{2}^+$	0.9	
4.410	$(\frac{5}{2}^+)$		0.35

[a] H. E. Gove *et al.*, Ref. 20.

[b] This yield is calculated from the data obtained in the present experiment and the single-neutron-emission probability observed by MacDonald *et al.*, Ref. 11.

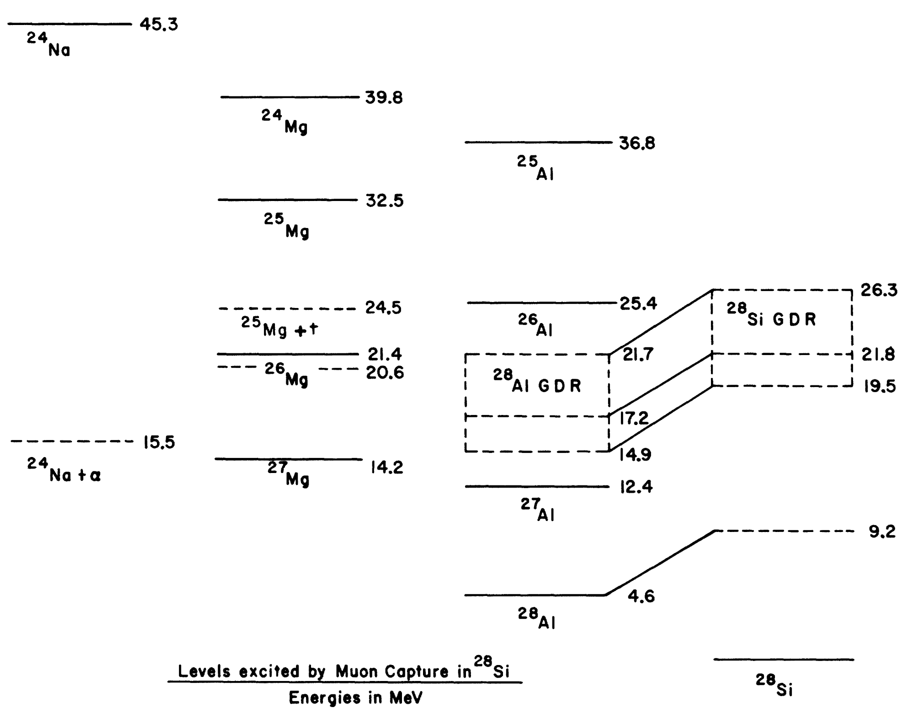

FIG. 3. An energy-level diagram showing the ground states of all nuclei observed to be excited by muon capture in ^{28}Si. Also included are the energies of the strong 1^-, $T=1$ giant-resonance states. The solid lines represent removal of particles one at a time, while the dashed lines represent removal of groups of particles from ^{28}Al.

tions could be due to axial vector (A) states accessible in muon capture but not in photoexcitation as suggested by the Louvain group[6] or it could be due to weak vector (V) states. The data of Caldwell *et al.*,[19] for instance, certainly show a nonnegligible contribution to the total photon cross section from energies above 30 MeV.

The significantly higher yield of *pn* states (^{26}Mg) vs *nn* states (^{26}Al) can also be explained in terms of the giant-resonance mechanism for muon capture. Figure 3 shows that the low-lying states in ^{26}Mg are energetically accessible to decay from some of the strong 1^-, $T=1$ giant-resonance states in ^{28}Al, while the ^{26}Al states are not.

The capture of muons by a cluster within the nucleus would be difficult to interpret with the present experimental technique. It can be pointed out, however, that the production of large numbers of the nuclei which would result from the emission of all the particles of a cluster after capture (*nn* or *pnn*) is not observed.

IV. ACKNOWLEDGMENTS

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