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Neutron Groups from K(α,n)Sc†

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Neutron groups resulting from the alpha-particle bombardment of separated isotopes of potassium have been observed. Ground-state Q values of -3.42 ± 0.06 Mev for $K^{41}(\alpha,n)Sc^{44}$ and -7.16 ± 0.06 Mev for $K^{39}(\alpha,n)Sc^{42}$ were obtained. A large number of excited states or groupings of states were also observed. The presence of chlorine in one of the targets permitted measurement of the $Cl^{37}(\alpha,n)K^{40}$ reaction as well. A ground-state Q value of -3.86 ± 0.06 Mev was obtained. A tentative value of -5.89 ± 0.06 Mev can be given for the $Cl^{35}(\alpha,n)K^{38}$ ground state.

INTRODUCTION

THE self-conjugate nuclei of odd Z are of special interest among the various low-mass isobaric polyads. A comparison of their lowest energy levels, in principle at least, can give reasonable estimates of the neutron-proton pairing energy. As noted by Moszkowski and Peaslee,[1] the singlet and triplet pairings of the two odd nucleons have about the same energy in the region above $A=30$. While in general the ground state configuration is singlet in nature, for this particular sequence instances of inversion, resulting in triplet ground states, are not unexpected. The Sc^{42} nucleus is the heaviest of this series which is readily amenable to investigation. The β de-excitation of this nucleus to Ca^{42} has been observed[2,3] and would seem to be consistent with a 0^+ description of the decaying level. Since for this family of nuclides the triplet configuration is necessarily of this form, an inversion would be suggested. The singlet would then form a low-lying isomeric state. The absence of any long-lived activity would seem to rule out the reverse (i.e., normal) order.

EXPERIMENTAL RESULTS

A magnetically analyzed beam of 8.29 ± 0.03-Mev alpha particles from the Yale cyclotron was used to initiate the reactions studied. The experimental arrangement was essentially as previously described.[4] The targets used were 0.3 mg/cm^2 of natural potassium (93% K^{39}) iodide on a gold backing and 0.4 mg/cm^2 of potassium chloride enriched to 82% in K^{41} on a tantalum backing.[5] Since the primary purpose of the second target was to confirm the assignment of levels to Sc^{42}, the presence of the chlorine was not considered untenable, particularly in the absence of other separated isotope compounds or targets available at the time. Targets consisting only of the backing material, but first subject to the usual depositing techniques, were also used to check background yields. All charged particles coming from the target were stopped in 67 mg/cm^2 of gold foil backed by 434 mg/cm^2 of tantalum. The gold leaf used was of sufficient thickness to stop all elastic alphas and of sufficient purity to render secondary reactions highly unlikely. The reaction neutrons were detected by their proton recoils in 50-μ Ilford C-2 emulsions arranged at various angles relative to the incident beam. In the $K^{39}(\alpha,n)Sc^{42}$ run, angles from 5°–175° in 10° intervals were used. For the $K^{41}(\alpha,n)Sc^{44}$ data, angles of 0°, from $2\frac{1}{2}$°–$62\frac{1}{2}$° in 5° intervals, and from $62\frac{1}{2}$°–$162\frac{1}{2}$° in 10° intervals were used. Identical angles were taken for the respective background runs. Total integrated beam current was in each case of the order of 10 000 μc. The proton ranges were obtained by scanning with microprojectors at 1000× magnification. Only recoils within 10° of the nominal neutron direction were accepted.

The range histogram for the natural-potassium target as observed at 5° is shown in Fig. 1. The comparative yield of the equivalent background run is shaded in. On the basis of the relative intensities, the group labeled p may be tentatively identified with the $K^{39}(\alpha,n)Sc^{42}$ reaction. The remaining groups would then be assigned to the $K^{41}(\alpha,n)Sc^{44}$ reaction. For any of the latter to arise from the K^{39} reaction would imply differential cross sections down by a factor of over 20 relative to that characteristic of the low-energy group. The approximate coincidence in range of group o with a background peak is accidental. Group o would appear to rise somewhat above the background level and further would appear to follow an angle-dependent shift in range. The background peak remains constant at 14 μ. The location of groups a, b, d, e, and i are indicated as predicted from the K^{41} reaction data. The first four do not show up significantly at any angle observed. The last, group i, only appears at the three forwardmost angles, and even then only weakly. The groups g, h, j, and m appear at the same relative ranges as in the subsequent K^{41} run. The remaining group l could not be verified in this second run, however.

The range histogram for the enriched-isotope target as observed at 0° is shown in Fig. 2. Again the background target yield is shaded in. In this case, the location of the groups l and p are indicated as predicted

† This work was supported in part by the Office of Naval Research.
[1] S. A. Moszkowski and D. C. Peaslee, Phys. Rev. **93**, 455 (1954).
[2] J. A. R. Cloutier and A. Henrikson, Can. J. Phys. **35**, 1190
[3] H. Morinaga, Phys. Rev. **100**, 431 (1955).
[4] H. S. Plendl and F. E. Steigert, Phys. Rev. **116**, 1534 (1959).
[5] Target loaned through courtesy of the Oak Ridge National Laboratory.

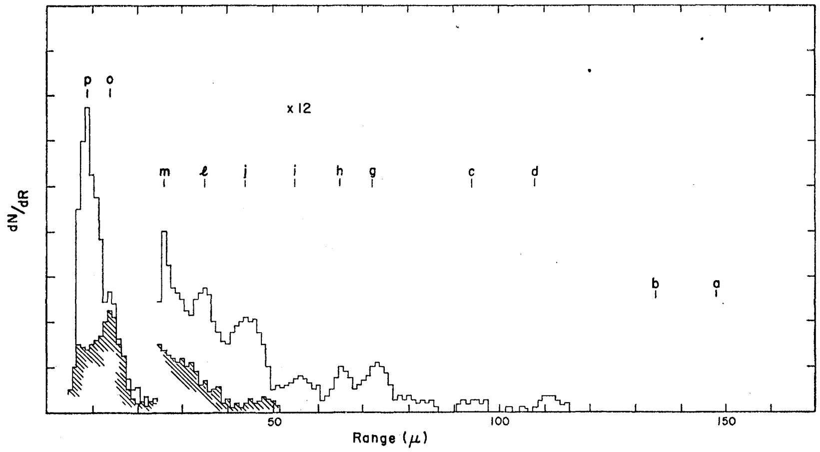

FIG. 1. Range histogram of $K^{39}(\alpha,n)Sc^{42}$ at 5° for natural potassium target. All groups are labeled as enumerated in Table I. Note magnification of vertical scale above 25 μ. Background run of Au(α,n) at 5° is shaded in. Peaks *a*, *b*, *d*, *e*, and *i* are indicated as predicted on the basis of the enriched target data.

from the natural-abundance target. The marked decrease in the relative yield of group *p* is immediately obvious. It would further appear to be somewhat less distinct, as might be expected in the presence of interfering groups from the K^{41} (and possibly even Cl) reactions. Several of the other groups also require qualifying remarks. The three groups *b*, *e*, and *i* are in general rather indistinct, with evidence for the last two being confined to angles less than about 60°. Group *g* is likewise only consistently observed at these forward angles, but does not exhibit the generally washed-out appearance of the others. Group *a* also occurs predominantly at forward angles. However, in the absence of low-energy tails from longer-range groups, it can still be reliably isolated even though it is weak.

TABLE I. Summary of probable identification of neutron groups.[a]

Group	Reaction	Q (Mev)	Predicted Q (Mev)	E (Mev)	Known levels (Mev)
a	$K^{41}(\alpha,n)Sc^{44}$	−3.42±0.06	−3.376	0	0 0.069 0.14
b		−3.66		0.24	0.27
d		−4.21		0.79	
e		−4.45		1.03	
g		−4.80		1.38	
h		−5.24		1.82	
i		−5.41		1.93	
j		−5.76		2.34	
l		−6.03		2.61	
m		−6.35		2.93	
o		−6.76		3.34	
p	$K^{39}(\alpha,n)Sc^{42}$	−7.16±0.06	−6.72±0.9	0	
c	$Cl^{37}(\alpha,n)K^{40}$	−3.86	−3.877	0	0.031
f		−4.72		0.86	0.80 0.89
i		−5.48		1.62	1.64
k		−5.89		2.03	2.06
n		−6.35		2.59	2.56
k	$Cl^{35}(\alpha,n)K^{38}$	−5.89	−5.867	0	

[a] Note duplicate entries of groups *i* and *k*.

Since the enriched target was in the form of a chloride, it was necessary to at least identify the structure due to this source. Preliminary runs on separated chlorine isotopes[6] would indicate that groups *c*, *f*, *k*, and *n* are very likely to have at least large contributions from the chlorine contaminant. Their spacing would further seem to agree reasonably well with the reported level structure in K^{40}.[7] The group *k*, however, is also consistent with assignment to the $Cl^{35}(\alpha,n)K^{38}$ reaction. In fact, on the basis of relative intensities, it is more likely to represent particles from the latter reaction. The remaining three would all appear to be ascribable only to the Cl^{37} fraction. The group *i* would further be consistent with a recently reported level at 1.64 Mev in K^{40}.

The various peaks observed are identified and summarized in Table I. In each case, the shift of the peak range with angle is consistent with the assignment. While the chlorine groups could only be marginally distinguished from the potassium if this were the only criterion, it should be noted that in each case the assignment made affords the better systematic agreement. This obviously does not apply to the weak and forward-peaked groups mentioned above, *b*, *e*, *g*, and *i*, respectively. In particular, group *k* is definitely inconsistent with an assignment of target mass as heavy as 41 amu. On the basis of the relative intensities in the two sets of data, group *p* is then assigned to the K^{39} reaction. On the basis of their presence in the chlorine background run and the previously reported level structure of K^{40}, groups *c*, *f*, and *n*, along with some unknown fraction of groups *k* and *i*, may be tentatively assigned to the Cl^{37} reaction. On the basis of relative intensities in both this and the preliminary background run, group *k* is very likely largely due to the Cl^{35} reaction. The known isomeric level, 0.128 Mev, in K^{38} would give rise to a group at about 35 μ in Fig. 2. Due to the

[6] A. J. Howard (private communication).
[7] *Nuclear Data Sheets*, National Academy of Sciences, National Research Council (U. S. Government Printing Office, Washington, D. C., 1960).

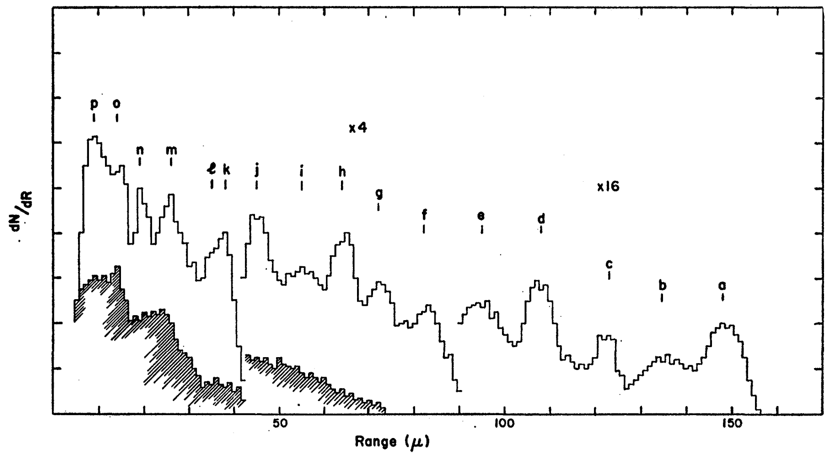

FIG. 2. Range histogram of $K^{41}(\alpha,n)Sc^{44}$ at 0° for target enriched in K^{41}. All groups are labeled as enumerated in Table I. Note successive magnifications of the vertical scale at 42 μ and 90 μ, respectively. Background run of $Ta(\alpha,n)$ at 0° is shaded in. Peaks l and p are indicated as predicted on the basis of the natural isotopic target data.

probable presence of group l, this could not have been resolved. The remaining groups are then assigned to the K^{41} reaction by default. Group l appears in the K^{39} data but would seem to be masked by the very strong chlorine group k in the K^{41} run. As mentioned above, the groups g, h, j, and m are in evidence in both sets of data. The remaining groups are very poorly defined in the K^{39} run, however. Some structure appears to persist at about the location of group i but, even if real, it is open to question considering the possible presence of a chlorine group.

The computed ground-state Q values for the chlorine reactions are compared to calculated mass values[8] in Table I. The levels in K^{40} which appear to have been excited are similarly compared to the reported structure. In all cases, the agreement is well within the experimental errors. The computed ground-state Q values for the potassium reactions are compared to the values obtained from closure of the reaction cycles using the appropriate $K(\alpha,p)Ca$ reactions[9] and the β end points.[2,10] Except for the Sc^{42} β decay, the numbers actually used in the computations enumerated in Table II are the adopted mass values.[8] The agreement is again within the quoted errors. It should be noted at this point that assigning group o to the ground state $K^{39}(\alpha,n)$ reaction would give excellent agreement with the computed mean value but would appear extremely unreasonable on the basis of intensity arguments. Comparison of the level data to the known structure at low excitation in Sc^{44} is quite meaningless. The techniques employed are inherently incapable of the resolution required. In general, only an integration over these closely spaced levels ought to be expected. The washed-out nature of group b would be consistent with this. Group a is also somewhat broad compared to what might be expected on the basis of range straggling and angular divergence. However, in the same vein, it is too narrow to be the sum of two peaks of about 70-kev spacing with comparable yields. Considering both this and the absence of any systematic fluctuation of range relative to that predicted by the Q value quoted, group a has been identified with the ground-state reaction.

Extrapolating this reported level density for Sc^{44} would seem to indicate that the structure observed might represent more of a general envelope over groups of levels than evidence of individual states of excitation. The absence of any significant structure between groups m and o in Fig. 1 would on this basis imply a very low level density at this excitation. Alternatively, this might argue for coarser structure than anticipated and for association of individual levels with a number of the narrower peaks. It is further quite probable that additional levels lie hidden under the various chlorine and K^{39} peaks in the same manner as the group l which was observed in the chlorine-free run.

Regardless of the interpretation of the structure observed, it would appear that at least the four respective ground-state groups have been detected. In all cases these represent consistency with computed mass values. Unfortunately, in the case of most interest, namely the $K^{39}(\alpha,n)Sc^{42}$ reaction, the magnitude of the error quoted for the $Sc^{42}-Ca^{42}$ positron end point (4.8±0.9 Mev) precludes confirmation (or denial) of the observation of the ground-state decay. It is obvious, however, that the reported mean value is somewhat low. An end

TABLE II. Reaction cycles pertinent to $K(\alpha,n)Sc$ reactions.

Reaction	Q Value (Mev)
$K^{39}(\alpha,p)Ca^{42}$	-0.118 ± 0.007
$-Sc^{42}(\beta^+)Ca^{42}$	-5.82 ± 0.9
$-(m_n-m_p)c^2$	-0.783
$K^{39}(\alpha,n)Sc^{42}$	-6.72 ± 0.9
$K^{41}(\alpha,p)Ca^{44}$	1.054 ± 0.01
$-Sc^{44}(\beta^+)Ca^{44}$	-3.649
$-(m_n-m_p)c^2$	-0.783
$K^{41}(\alpha,n)Sc^{44}$	-3.376 ± 0.02

[8] P. M. Endt and C. M. Braams, Revs. Modern Phys. **29**, 683 (1957).
[9] J. P. Schiffer, Phys. Rev. **97**, 428 (1954).
[10] J. W. Blue and E. Bleuler, Phys. Rev. **100**, 1324 (1955).

point of the order of 5.24 Mev would be more compatible with the present data. In fact, recognizing the problems inherent in measuring short-range particles, even this value could be interpreted as only a lower limit. It is conceivable, for instance, that tracks of shorter range than the peak p were heavily discriminated against because of difficulty in recognition. Further, both latent-image fading and incomplete development, when effecting a track of the order of, say, 5 μ, would severely reduce the observation efficiency. Thus group p might actually only represent the distorted high-energy tail of a more intense group with a range several microns shorter. Two microns, for example, would imply an error of about 100 kev. Considering this possibility, most of the plates involved were scanned by four different observers. In the absence of any systematic disagreement, it was concluded that the effect probably did not occur, and no account of it was taken in the error estimates.

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Core Excitations in Nondeformed, Odd-A, Nuclei*

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The possibility of describing some excited states of odd-A nuclei in terms of excitations of the even-even core is investigated. No assumption is made on the nature of the core excitation, but certain relations involving electromagnetic transitions and moments are deduced. These seem to fit well some data available on Ag^{107}, Ag^{109}, Au^{197}, Hg^{199}, Tl^{203}, and Tl^{205}. More experimental data are required to test the validity of this picture in other cases.

INTRODUCTION

THERE are several known ways of exciting a nucleus from its ground state. The simplest of them is described, in the approximation of independent particle motion, by the elevation of a single particle from one state to another. These single particle excited states show up especially well[1] in stripping, pickup, and possibly other reactions. A slightly more complex excitation is that in which the ground-state configuration remains unchanged but the nucleons in this configuration change the relative orientation of their orbits. A typical case is offered by ${}_{23}V_{28}{}^{51}$ whose neutron shell is a closed one. Its ground state has $J=\frac{7}{2}$ and is believed to be the $J=\frac{7}{2}$ state of the configuration $(1f_{7/2})^3$. The first excited state has $J=\frac{5}{2}$ and is believed to be the $J=\frac{5}{2}$ state of the same configuration $(1f_{7/2})^3$. A slightly different example[2] is that of ${}_{17}Cl_{21}{}^{38}$ whose ground state and three lowest excited states are believed to be the four states of the configuration $(1d_{\frac{3}{2}};1f_{7/2})$, i.e., the configuration of one proton in $1d_{\frac{3}{2}}$ and one neutron in $1f_{7/2}$. A third class of excitations is that due to the collective motion of many nucleons.[3] These well-known modes of excitation include collective rotations, vibrations, etc.

The above modes of excitations may combine in characteristic ways. Thus it is well known that in the regions of large deformations, where collective rotations generally represent the lowest excitations, it is possible to excite a single nucleon from one orbit in the deformed-potential to another. This excited single-particle state then forms the basis for a new rotational band.

Another interesting "combined" excitation is suggested by the jj-coupling shell model, as was stressed by Lawson and Uretsky.[4] Let the ground-state configuration of an odd-even nucleus be described by $|(j_p{}^2)_{J_p=0}j_n\rangle$, i.e., by a pair of protons in j_p coupled to $J_p=0$ and a neutron in j_n. Then in addition to the single-particle excitation, which will be described by the configurations $|(j_p{}^2)_{J_p=0}j_n'\rangle$, one should expect also excitations described by $[(j_p{}^2)_{J_p\neq 0}j_n]_J$. In such states the neutron remains in its lowest state, while the proton pair is decoupled and excited to a state with $J_p\neq 0$, J_p and j_n then being coupled to the total angular momentum J.

This mode of excitation can be generalized slightly. In fact, consider an even-even nucleus A. Its ground state has $J=0$ followed by various excited states. Let us now

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† On leave from the Weizmann Institute of Science, Rehovoth, Israel.
[1] See, for instance, N. H. McFarlane and J. B. French, Revs. Modern Phys. **32**, 567 (1960).
[2] S. Goldstein and I. Talmi, Phys. Rev. **102**, 589 (1956); S. P. Pandya, *ibid.* **105**, 956 (1956).
[3] K. Alder, N. Bohr, T. Huus, B. Mottelson, and A. Winther, Revs. Modern Phys. **28**, 432 (1956).
[4] R. D. Lawson and J. L. Uretsky, Phys. Rev. **108**, 1300 (1957).