Direct (p,n) Reaction in Medium A Nuclei: A Configuration-Selective Process

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Time-of-flight techniques have been used on the Livermore variable energy cyclotron to study (p,n) spectra from selected target nuclei. Previously reported neutron spectra for 14.8-MeV protons all showed one strong neutron group at an energy corresponding in excitation in the final nucleus to the isobaric counterpart (analog state) of the target ground state, i.e., the Q value is the usual Coulomb displacement energy. With the increase in cyclotron energy to 18.5 MeV, measurements of isobaric ground states have been extended to include Rh^{103}, Ag, In^{115}, Sn, and Pr^{141}. The measured width of the isobaric state is less than 100 keV even for elements as heavy as Ag and Sn where the Coulomb displacement energy is $\simeq$13.5 MeV. Excited isobaric states are found in bombarding even-even nuclei from Ar^{40} to Se, in correspondence with the excited states of the *target* nucleus. No such prominent excited states are observed in odd-even target nuclei V^{51} and Co^{59}. For the "deformable" odd-even nuclei Rh^{103} and Ag, excited isobaric states are observed corresponding to states in the target nucleus with large Coulomb excitation cross sections. Prominent high-energy neutron groups are observed corresponding to the configuration states predicted by Lane and Soper.

I. INTRODUCTION

USING the (p,n) reaction, the existence of isobaric states[1,2] in nonmirror nuclei has recently been demonstrated. This direct (p,n) reaction was assumed to go as follows[3]: The incoming proton reacts with an "excess neutron" (a neutron corresponding to an unfilled proton state), exchanges its charge, and is emitted as a neutron. The isotopic spin considerations[4] ($\Delta T=0$) in "mirror-nuclei" (p,n) reactions are also valid for nonmirror nuclei. Since all the nuclear interactions within the initial and final nucleus are the same, the Q for the (p,n) reaction leading to the isobaric state is the Coulomb displacement energy.

The Livermore variable energy cyclotron and time-of-flight techniques[5] have been used to study (p,n) spectra from various target nuclei. Previously reported[2] spectra for 14.8-MeV protons all showed one strong neutron group at an energy corresponding in excitation in the final nucleus to the isobaric counterpart (analog state) of the target ground state. Recent cyclotron modifications enabled us to obtain protons with energies in excess of 18 MeV. This higher proton energy makes possible Q-value measurements for heavier elements (larger Coulomb displacement energies) and also permits us to look at higher excitations in the residual nucleus ($A\leq 103$) in the region of the isobaric ground state (analog state). With higher initial energies, background effects are considerably reduced, since the principal background obscuring neutrons from the isobaric state is composed of neutrons from compound nucleus decay.

These new higher energy data may be summarized as follows:

(1) Q-value measurements for isobaric ground states have been extended to include Rh^{103}, Ag, In^{115}, and Pr^{141}.

(2) The energy width of the isobaric ground states is found experimentally to be less than 100 keV even for elements as heavy as Rh and Ag where the Coulomb displacement energy is $\simeq$13.5 MeV.

(3) Excited isobaric states have been observed[6] with even-even target nuclei between Ar^{40} and Se. These states are shown to correspond to the excited states of the target nucleus. No such prominent excited states are observed with odd-even target nuclei in the same mass region.

In the region of "deformable" nuclei ($A\sim 105$), excited isobaric states are observed in odd-even nuclei corresponding to states in the target nucleus with large Coulomb excitation cross sections.

(4) Prominent high-energy neutron groups are observed corresponding to the configuration states of Lane and Soper.[7] These are states in which the overall configuration of the nucleus is unchanged (apart from the exchange of a neutron for a proton).

II. EXPERIMENTAL METHOD

The experimental geometry for the measurement of neutron spectra is essentially the same as previously reported (reference 2, Fig. 1). The electronic system, including proton-electron pulse shape discrimination, has also been previously described.[2,5] A larger stilbene crystal (2-in. diam by 1 in. thick) is used to increase the neutron detection efficiency.

III. RESULTS

A. Ar and Ti

The time-of-flight spectrum resulting from 18-MeV proton bombardment of argon is shown in Fig. 1. The target gamma ray appears twice since a double display

[1] J. D. Anderson and C. Wong, Phys. Rev. Letters **7**, 250 (1961).
[2] J. D. Anderson, C. Wong, and J. W. McClure, Phys. Rev. **126**, 2170 (1962).
[3] What may be an intuitively more attractive description in terms of the optical model is offered by A. M. Lane, Phys. Rev. Letters **8**, 171 (1962).
[4] S. D. Bloom, N. K. Glendenning, and S. A. Moszkowski, Phys. Rev. Letters **3**, 98 (1959).
[5] J. D. Anderson and C. Wong, Nucl. Instr. Methods **15**, 178 (1962).
[6] J. D. Anderson and C. Wong, Phys. Rev. Letters **8**, 442 (1962).
[7] A. M. Lane and J. M. Soper (to be published).

is used—one converter stop pulse for every two beam pulses. The three prominent peaks correspond to a configuration state,[7] isobaric state, and excited isobaric state. At lower proton bombarding energy (13 MeV), the configuration state is resolved into two states [Fig. 2(a)]. It should be noted that there is no appreciable neutron production resulting in the ground state of K^{40}.

From the $K^{39}(d,p)K^{40}$ stripping data of Enge *et al.*,[8] the ground and first three levels in K^{40} (up to 1-MeV excitation) are $(d_{3/2}^{-1})_p(f_{7/2})_n$ configuration states. If Ar^{40} is $(d_{3/2}^{2})_p(f_{7/2}^{2})_n$ then presumably we should see configuration states $(d_{3/2}^{-1})_p(d_{3/2}^{-1})_n(f_{7/2}^{2})_n$ and $(d_{3/2}^{2})_p \times (f_{7/2})_p(f_{7/2})_n$. The absence of ground-state neutrons and the presence of a prominent neutron group at 2.3-MeV residual excitation in K^{40} is considered evidence that the 2.3-MeV level is indeed a configuration state. The further assumption that the splitting of the peak corresponds to the two configuration states is not warranted considering the uncertainties of "gross structure" analysis recently pointed out in (d,p) stripping analysis.[9,10]

For 18-MeV protons incident on Ti [Fig. 3(a)], the only prominent structure in the neutron spectrum is the analog state. For 13-MeV protons, [Fig. 2(b)] however, there is, in addition, a prominent group of neutrons corresponding to very low ($\approx$200 keV) residual excitation. There is also a second group at $\approx$2-MeV residual excitation.

All the "valence" nucleons in Ti are $f_{7/2}$ and presumably the ground state of V^{48} would also consist of $f_{7/2}$ nucleons. Since Lane and Soper have shown that configuration states are preferentially excited in the (p,n) reaction, we should expect a prominent peak near the ground state of V^{48} corresponding to a configuration state.

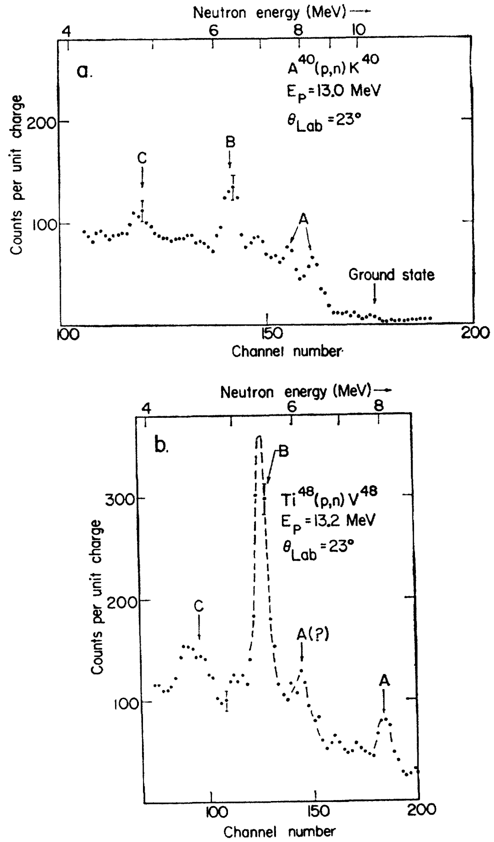


FIG. 2. Time-of-flight spectrum for 13-MeV proton bombardment of (a) argon and (b) titanium. The time calibration is 2.2 nsec/channel. The notation is the same as in Fig. 1.

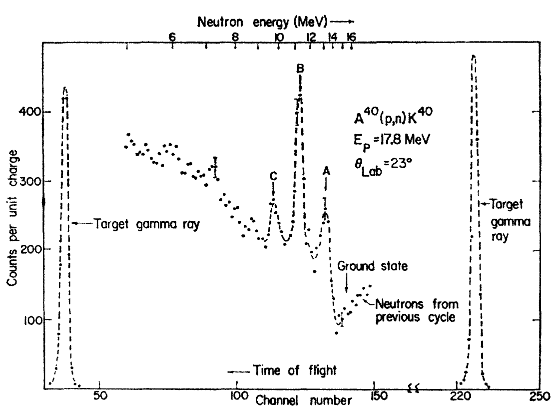


FIG. 1. Time-of-flight spectrum from proton bombardment of argon. Time calibration of the system is 2.0 nsec/channel and increasing time-of-flight is toward the left. The flight path was 11.3 m. The prominent peaks are identified as follows: (A) configuration state ($\Delta T=1$), (B) isobaric analog of target ground state ($\Delta T=0$), and (C) excited isobaric state ($\Delta T=0$).

B. V, Fe, Co, and Ni

Although the Fe spectrum [Fig. 3(b)] shows additional excited isobaric states, the increase in proton bombarding energy to 18 MeV produced essentially no change in the neutron spectrum previously reported for 17-MeV protons. The spectra for the four elements show no prominent configuration states, but this is due at least in part to poor statistics.

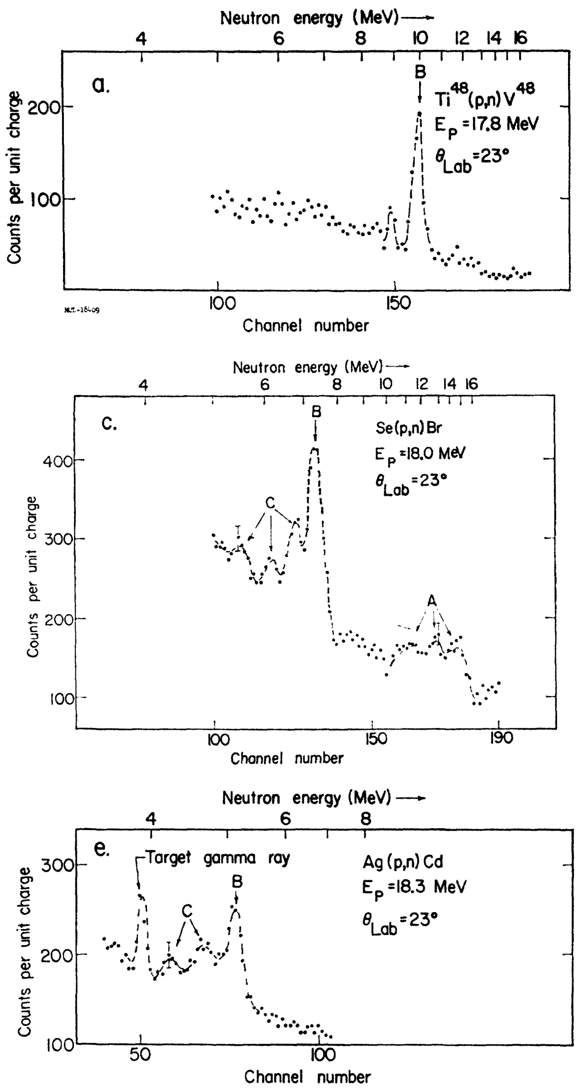
C. Se

In Fig. 3(c) the time-of-flight neutron spectrum for 18-MeV proton bombardment of selenium is displayed. The prominent structure at high neutron energies corresponds to at least three neutron groups. If one assumes that these are configuration states and averages over them one obtains an energy width of $\simeq$3 MeV in good agreement with the width predicted by Lane and Soper.[7] In addition to the high-energy structure, one sees at least three excited isobaric states.

[8] H. A. Enge, E. J. Irwin, Jr., and D. H. Werner, Phys. Rev. **115**, 949 (1959).

[9] W. C. Parkinson and J. R. Maxwell, Phys. Rev. **126**, 1160 (1962).

[10] B. L. Cohen, R. H. Fulmer, and A. L. McCarthy, Phys. Rev. **126**, 698 (1962).



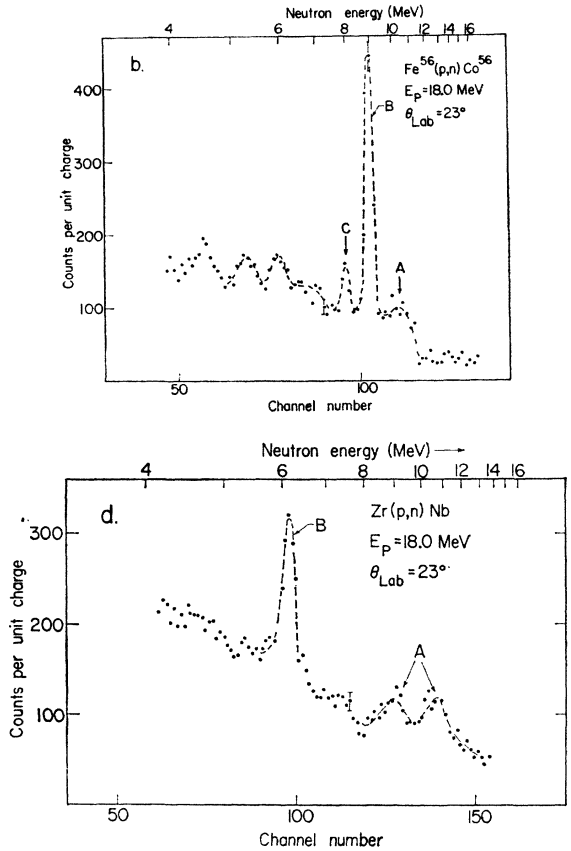


FIG. 3(a). Time-of-flight spectrum for 18-MeV proton bombardment of titanium. The time calibration and notation is the same as in Fig. 1. (b) Time-of-flight spectrum for 18-MeV proton bombardment of iron. The time calibration and notation is the same as in Fig. 1. (c) Time-of-flight spectrum for 18-MeV proton bombardment of selenium. The time calibration and notation is the same as in Fig. 1. (d) Time-of-flight spectrum for 18-MeV proton bombardment of zirconium. The time calibration and notation is the same as in Fig. 1. (e) Time-of-flight spectrum for 18-MeV proton bombardment of silver. The time calibration and notation is the same as in Fig. 1.

D. Y, Zr, and Nb

These nuclei show similar structure in that the high neutron energy group contains several peaks and that there is no prominent structure below the analog state. In Fig. 3(d) the Zr spectrum is displayed.

E. Rh, Ag, In, Sn, and Pr

As discussed previously,[6] there has been no evidence for the existence of prominent excited isobaric states resulting from the (p,n) reaction on odd-even target nuclei. As can be seen from Fig. 3(e), this is no longer the case. Both Rh and Ag show evidence for excited isobaric states for 18-MeV incident protons. The poor statistics in the case of In, Sn, and Pr makes the identification of excited isobaric states impossible. Additional measurements on Ag and Rh at slightly reduced energy (17.5 MeV) and longer flight path (11.3 m) confirm the existence of at least two excited isobaric states in both elements.

IV. CONCLUSIONS

A. Coulomb Energy

As pointed out in the introduction, the Q for the (p,n) reaction leading to the analog state is the Coulomb displacement energy. The agreement of Coulomb displacement energies derived from the nonmirror (p,n) reaction and those obtained from mirror and nonmirror $(T=1)$ nuclei beta decay has been previously demonstrated.[2]

In Fig. 4 the Coulomb displacement energy obtained from the (p,n) reaction is plotted vs $Z/A^{1/3}$. The pres-

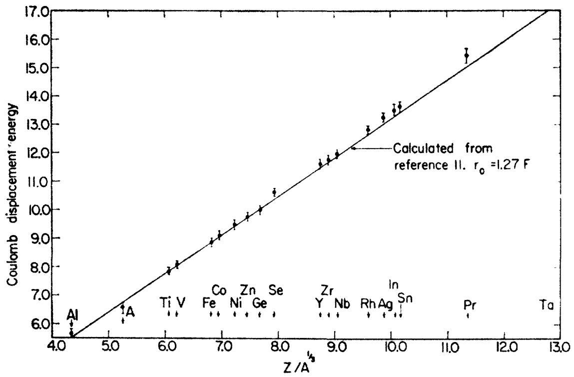


FIG. 4. The experimental Coulomb displacement energy (the Q value for the isobaric state) is plotted vs $Z/A^{1/3}$.

ent data are in agreement with our previous measurements (Table I). The calculated Coulomb energies[11] are in good agreement with the data up to Nb using $r_0 = 1.27$ F. Above Nb a smaller radius $r_0 = 1.25$ F produces an appreciably better fit. This is compatible with electron scattering data[12] which have indicated changes in the root mean square charge radius varying from $r_0 = 1.32$ F at calcium to $r_0 = 1.2$ F at bismuth. It is also possible that these deviations are due to a combination of effects such as nuclear deformation and shell closure. Targets are presently being fabricated to more carefully map out the regions of deviations around $A \simeq 80$ and $A \simeq 100$.

B. Energy Width of Analog State

Accurate energy width measurements on the analog state for heavy nuclei ($A \sim 100$) were previously hampered by a poor signal-to-background ratio and by the nonuniformity of colloidal targets. With 18-MeV protons the background neutrons due to compound nucleus decay are greatly reduced and the higher available energy enables us to make meaningful measurements on Rh and Ag targets which are available as rather uniform metal foils. These present measurements at 17.5-MeV proton energy and 11.3-m flight path yield energy widths comparable to the energy width of the targets, i.e., ≈ 150 keV. It is concluded that the width of the analog state is $\lesssim 100$ keV. This limit is in excellent agreement with the recent predictions of Lane and Soper[13] who have pointed out that if the measured width is significantly narrower than 100 keV it infers (indirectly) the validity of the shell model as opposed to the pairing force model.

C. Excited Isobaric States

The existence of excited isobaric states and the correspondence between the excited isobars and the first excited state of even-even target nuclei have been previously demonstrated.[6] A summary of excited isobaric state Q values is given in Table II. It is interesting to note that in some nuclei such as Fe and Se, many excited isobaric states are observed. As previously noted,[6] only even-even target nuclei in the $A = 40$–80 mass region display prominent excited isobaric states. No excited states are observed for Y, Zr, and Nb. However, for the odd-even target nuclei Rh and Ag, excited isobaric states are observed. Additional observations in heavier nuclei were obscured by poor statistics.

Tbe formation of low-lying excited isobaric states depends upon a statistical weight factor $W \equiv (2J_f+1)/(2J_i+1)$ and a model-dependent nuclear matrix element. For even-even target nuclei where $J_i = 0$ and J_f is typically 2, 4, $\cdots$, then $W = 5$, 9, $\cdots$. For odd-even nuclei such as V and Co, $J_i = \frac{7}{2}$ and $W \simeq 1$. For the odd-even targets Rh and Ag in which excited isobars are

TABLE I. Experimental Q values for isobaric states as determined from the (p,n) reaction.

Target	Q (MeV) $E_p = 14.8$ MeV	$E_p = 16$–18 MeV
Ar^{40}		6.55±0.20
Ti^{48}	7.91±0.10	7.80±0.15
V^{51}	8.05±0.10	8.10±0.15
Fe^{56}	8.73±0.13	9.00±0.15
Co^{59}	9.04±0.13	9.20±0.15
Ni	9.42±0.13	9.47±0.15
Zn	9.76±0.15	9.77±0.15
Ge	9.96±0.20	10.00±0.15
Se	10.60±0.15	10.60±0.15
Y^{89}	11.60±0.15	11.60±0.15
Zr		11.75±0.15
Nb^{93}	11.90±0.15	11.95±0.15
Rh^{103}		12.80±0.15
Ag		13.25±0.15
In^{115}		13.50±0.20
Sn		13.60±0.15
Pr^{141}		15.43±0.25

TABLE II. Q values for low-lying excited isobaric states (measured from the analog state).

Target	Excited isobaric state Q (MeV)
Ar^{40}	1.50±0.10
Ti^{48}	0.95±0.05
	2.40±0.10
Fe^{56}	0.83±0.05
	1.8 ± ?
	2.55±0.10
	3.10±0.10
Ni	1.44±0.10
	2.55±0.10
Zn	1.07±0.10
Se	0.58±0.07
	1.20±0.10
	1.80±0.10
Rh^{103}	0.40±0.10
	0.80±0.10
Ag	0.45±0.10
	0.80±0.10

[11] N. V. V. J. Swamy and A. E. S. Green, Phys. Rev. **112**, 1719 (1958).
[12] D. G. Ravenhall, Rev. Mod. Phys. **30**, 430 (1958).
[13] A. M. Lane and J. M. Soper, Phys. Rev. Letters **1**, 33 (1962).

TABLE III. Experimental ratio of Q value for configuration state ($\Delta T=1$) to the Coulomb displacement energy ($\Delta T=0$).

Target	$Q/\Delta E_c$
Ar^{40}	0.7
Ti^{48}	0.7
Fe^{56}	0.9
Se	0.5
Y^{89}	0.6
Zr	0.7

present, $J_i=\frac{1}{2}$ and $W\sim 5$. However, no excited states are seen for Y where the initial state spin is also $\frac{1}{2}$. For Y one again expects $W\sim 5$. Although it is clear that at least part of the suppression of excited isobars for odd-even target nuclei is due to the statistical weighting factor, the absence of levels corresponding to Y and Zr target nuclei indicates that the model dependent nuclear matrix element is perhaps the dominant term. One might argue that the Y and Zr are special cases in that they are "closed shell' nuclei; however, Ni which is another "closed shell" nucleus exhibits a prominent excited isobaric state.

It seems plausible that there are at least two mechanisms for the formation of excited isobaric states. In the $A=40$–60 region the data may be explained by the extreme pairing model where seniority is a relevant quantum number.[14] For the "deformable" nuclei Rh and Ag, an explanation in terms of quasi inelastic scattering seems appropriate, i.e., the incident proton excites a collective state and charge exchanges, leaving the residual nucleus in a low lying state with respect to the analog state. Such an explanation in terms of "Coulomb excitation with charge exchange" could account for absence of excited isobaric states for Y, Zr, and Nb since the quadrupole distortion parameter β is known to be small for neutron number $\simeq 50$.[15] The tentative nature of these conclusions is obvious and additional measurements will be made, as soon as adequate targets can be fabricated, to supply additional information on the spin and deformation dependence of excited isobaric state cross sections.

[14] E. Rost (private communication).

[15] P. H. Stelson, in *Proceedings of the International Conference on Nuclear Structure, Kingston, Canada, 1960,* edited by D. A. Bromley and E. Vogt (University of Toronto Press, Toronto, 1960), p. 787.

D. Configuration States

Lane and Soper[7] have pointed out that one expects the (p,n) process to preferentially excite states in the residual nucleus with the same configuration as the target nucleus. It is clear that the excited isobaric states and analog states are special cases of configuration states for which the isotopic spin of the residual nucleus is the same as that of the target nucleus. The prominent high-energy neutrons groups from Ar, Ti, Se, and Zr adequately point up the existence of configuration states ($\Delta T=1$).

The Q values for configuration states in terms of the Coulomb displacement energy are listed in Table III. The expected value is ≈ 0.9 which is in qualitative agreement with the data. It should be remembered that these data are "gross structure" measurements which do not necessarily correspond to "fine structure" data appropriately averaged.[9] The experimental widths are also in agreement with the calculations of Lane and Soper.[7]

It seems clear that the direct (p,n) process is indeed configuration selective and that one may locate configuration states experimentally using the (p,n) reaction. The gross structure data possibly suffer from the same limitations as have recently been noted in the (d,p) stripping measurements.[9] High-resolution (p,n) data are preferable and should yield accurate information regarding the location of configuration states.

V. ACKNOWLEDGMENTS

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