Two-Neutron Configurations in the Even Calcium Isotopes as Observed in the (t,p) Reaction.* David C. Williams, Sandia Laboratory. Recent data[1] on the reactions $^{40, 44, 46, 48}Ca(t,p)$ are summarized. The strong transitions may be interpreted without assuming heavy mixing of the various two-neutron configurations that are the principal contributors to the (t,p) reaction amplitude, though these configurations evidently do mix with configurations involving core excitation. Thus, the strong transitions of a given L value are grouped in such a way that each group may be assigned to one of the expected two-neutron configurations having the appropriate $J(\pi)$. The interpretation offered indicates that the configurations $\left[\left(f_{7/2}^{\,n-2}\right)_{J_1=0} f_{7/2}\, p_{3/2}\right]$ and $\left[\left(f_{7/2}^{\,n-2}\right)_{J_1=0} p_{3/2}^2\right]$ constitute at most minor components of states below 4.4 MeV in $^{42,46}Ca$; recent $^{43}Ca(d,p)$ data[2] indicate the same is true of ^{44}Ca. States of the (20/20) core are important. This description differs from treatments of these isotopes which emphasize mixtures of the various $1f_{7/2}$ - $2p_{3/2}$ neutron configurations and consider states of the (20/20) core only secondarily, if at all.

*Work supported by the U. S. Atomic Energy Commission.

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(Analytical Index No.: [illegible])

(To be presented at the Division of Nuclear Physics, APS, meeting Oct. 23-25, 1967, in Madison, Wisconsin.)

DISCLAIMER

In most discussions of double stripping (or pickup) reactions such as the (t,p) reaction, the emphasis has been on the fact that the reaction amplitude may represent the coherent sum of many two-particle terms. In such cases the cross section gives information as to this coherent sum, but tells nothing about the amplitude of any one term in the final-state wave function. However, if the two-particle states that contribute actively to the reaction amplitude do not mix strongly with each other, a description similar to the simpler single-nucleon stripping reaction should be approximately valid. Even in this case, each of the two-particle states may still mix with states that involve target excitation, and therefore do not contribute strongly to the reaction amplitude. The strength available for each two-particle state will then be shared among the several levels involved, just as usually is the case for single-particle strengths as observed in single-nucleon stripping reactions.

It is the purpose of this paper to suggest that, as a first approximation, this simpler situation actually prevails for the even -A calcium nuclei. I consider here data obtained by Williams, Knight and Leland[1,2] on (t,p) transitions to states of $^{42,46,50}Ca$ and also the (t,p) transitions to 0+ states of ^{48}Ca and ^{50}Ca, reported by Hinds, Bjerregaarde, Hansen and Nathan[3].

I define the zero-order energy of a two-neutron configuration to be the sum of the corresponding unperturbed single-particle energies in the adjacent odd -A nucleus, as deduced from (d,p) measurements[4], plus the ground-state pairing energy, as deduced from the odd-even mass difference (Fig. 1). For the $p_{3/2}{}^2$, 0+ configuration, I subtract off an estimate of the $p_{3/2}$ pairing energy derived from the masses[2,5] of ^{48}Ca, ^{49}Ca, and ^{50}Ca. Other than this pairing estimate, the zero-order energies contain no allowance at all for the residual interaction between the two neutrons, and thus they may differ considerably from the actual configuration energies. If the residual interactions are not too large, however, it should be possible to associate each zero-order configuration energy with a group of one or more strong transitions of the appropriate L value, and vice versa, provided the two-neutron configurations do not mix strongly with each other. If the latter assumption fails, some transitions will be enhanced at the expense of others, destroying any correspondence between the strong transitions and the location of the individual two-neutron configurations. Some states may also be lowered well below any of the zero-order energies, especially if they possess considerable collective character, as is the case with the lowest 2+ and 3- states of most nuclei, including ^{42}Ca and ^{46}Ca.

The comparison is made in Fig. 2. The horizontal lines to the left indicate the zero-order energies of all available two-neutron configurations; the length of these lines is of no significance. Vertical bars at the ends give the uncertainties in these energies that correspond to the quoted uncertainties in the unperturbed single-particle energies derived from the (d,p) data. The horizontal lines to the right show the observed transitions to states of the indicated spin and parity; the length of these lines gives the transition intensity. Dashed lines and question marks indicate the less certain intensities and spin assignments, respectively.

Except for the first 2+ states, the correspondence is good in ^{42}Ca, with all the strong transitions being grouped near an appropriate zero-order configuration energy. Likewise, all expected configurations are accounted for except the $(f_{7/2}\ p_{1/2})$ 4+ configuration; however, the limited experimental resolution ($\sim$ 50 keV)[1] would have made it very difficult to identify $\underline{L} = 4$ transitions at this high excitation energy. The 0+ states of ^{48}Ca and 2+ states of ^{50}Ca also show good agreement. In general, there is a tendency for the strongly excited states to lie somewhat lower than the zero-order energies, especially for the $(f_{7/2}\ p_{3/2})$2+ configuration. This downward displacement is larger in ^{46}Ca, though the general pattern is still correctly reproduced; that is, the strong transitions above 4 MeV come in the predicted order: 2+, 4+, 0+, 2+. Part of the quantitative discrepancy may be due to the relatively large uncertainties in the zero-order energies. In all cases, it is to be remembered that the treatment involves no adjustable parameters.

According to this interpretation, population of the strongly excited 2+ and 4+ states between 4.4 and 5.4 MeV in ^{42}Ca and ^{46}Ca represents capture of an $f_{7/2}\ p_{3/2}$ neutron pair. This has the important implication that states in these isotopes having configurations of Type I in Fig. 3, with J_1=0, as their major components lie above 4 MeV, with the $(p_{3/2}{}^2)$ states lying still higher. The same appears to be true of ^{44}Ca, as states up to 6.2 MeV excitation in ^{44}Ca have been observed in the $^{43}Ca(d,p)$ reaction[6] and less than 4% of all the observed $\underline{\ell} = 1$ strength was found to lie below 4.6 MeV excitation. There are, of course, many more states at lower excitation energies in these isotopes than can be accounted for by means of the $f_{7/2}$ neutrons alone. In ^{42}Ca, these states must involve rearrangement of the ^{40}Ca core. In ^{44}Ca and ^{46}Ca, a large number of states of Type II, with $\underline{J}_1 \neq 0$, are available, but it is not clear why these should lie much lower than the $\underline{J}_1 = 0$ states. Since states of the ^{40}Ca core must be involved in

^{42}Ca, they are probably important in ^{44}Ca and ^{46}Ca as well. This picture differs significantly from the more usual interpretations[7] of the states below 4 MeV in these isotopes, which emphasize the interaction of the various Type I and Type II states involving $1f_{7/2}$ and $2p_{3/2}$ neutrons and treat states of the ^{40}Ca core only secondarily, if at all.

Although some mixing of the various two-neutron configurations must occur, in the cases described so far, it is evidently not large enough so that the resulting coherence effects destroy the basic pattern set by the zero-order configuration energies. To find a case where the reverse is true one need look no further than the 0+ spectrum of ^{50}Ca. Here the simple approach predicts the existence of a strongly excited 0+ state in the spectrum immediately above 4 MeV (Fig. 2). Hinds and others[3] have reported the (t,p) spectrum up to 5.6 MeV excitation and only exceedingly weak 0+ states were found. As they suggest, it appears that the configuration mixing is so strong in ^{50}Ca that almost the entire L=0 transition strength is concentrated in the ground state.

The fact that the ground state of ^{50}Ca appears to show strong configuration mixing suggests that the same may be true of the strongly excited 0+ states in the lighter calcium isotopes. Thus, these states probably contain large $p_{1/2}{}^2$ components as well as $p_{3/2}{}^2$; other configurations may also be involved. In any case, there appears to be a relationship between the strongly excited 0+ states lying at between 5 and 6 MeV excitation in the lighter calcium isotopes and the ground state of ^{50}Ca (Fig. 4). The open circles plotted here along the line marked $p_{3/2}{}^2$, 0+ show the binding energy of the neutron pair when captured into the strongly excited 0+ states in calcium-42,-46, and-48. The solid circle at A=50 is the two-neutron separation energy for ^{50}Ca. Obviously, the latter falls nicely in line with the trend set by the former, even though the designation $p_{3/2}{}^2$, 0+ is probably an oversimplification. If the 0+ states of calcium-48 do correspond to calcium-50 minus an $f_{7/2}$ neutron pair, we may derive a value for the latter separation energy (open circle at A=50 in Fig. 4); this falls in line with the ground-state masses of the lighter isotopes.

The existence of 0+ states that are strongly excited in the (t,p) reaction seems to be general to nuclei immediately preceding closed neutron shells (Fig. 5)[8]. In all cases of which I am aware, whenever closure of a neutron shell or subshell leads to a distinct discontinuity in the two-neutron separation energies (S_{2n}) for the ground states (solid symbols in Fig. 5), the nucleus immediately below the discontinuity exhibits relatively strongly excited 0+ states (open symbols) with S_{2n} falling in line with the ground-state values above the discontinuity. The case of ^{96}Zr is interesting, as N=56 only corresponds to closure of the $2d_{5/2}$ subshell, rather than to closure of a major shell; nonetheless, there is a discontinuity in the S_{2n} values here and a corresponding 0+ state that is fairly strongly excited in the ^{94}Zr (t,p) reaction[8]. In contrast to ^{96}Zr, the low-lying 0+ states in $^{92,94}Zr$ are only weakly excited in the (t,p) reaction[8].

If it is true that the strong 0+ states in the closed shell nuclei do correspond to capture of the neutron pair into a state with a wave function corresponding to the ground state of the nucleus having two neutrons more than the magic number, the same states should also be strongly excited in the (p,t) reaction with the latter nucleus as target. ^{52}Cr (not shown in Fig. 5) is the only closed-shell nucleus for which both reactions[9,10] have been carried out. As expected, a 0+ state, located at 2.65 MeV, was strongly excited in both the ^{54}Cr(p,t) and the ^{50}Cr(t,p) reactions.

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ZERO-ORDER ENERGIES

$$E_{A+2}(j_1 j_2, J \neq 0) \approx E_{A+1}(j_1) + E_{A+1}(j_2) + 2M(A+1) - M(A+2) - M(A)$$

FOR $E_{A+2}(p_{3/2}{}^2, 0+)$, subtract off the pairing energy $P(p_{3/2}{}^2, 0+)$:

$$P(p_{3/2}{}^2, 0+) \approx 2M\,(^{49}Ca) - M\,(^{50}Ca) - M\,(^{48}Ca)$$

FIG. 1

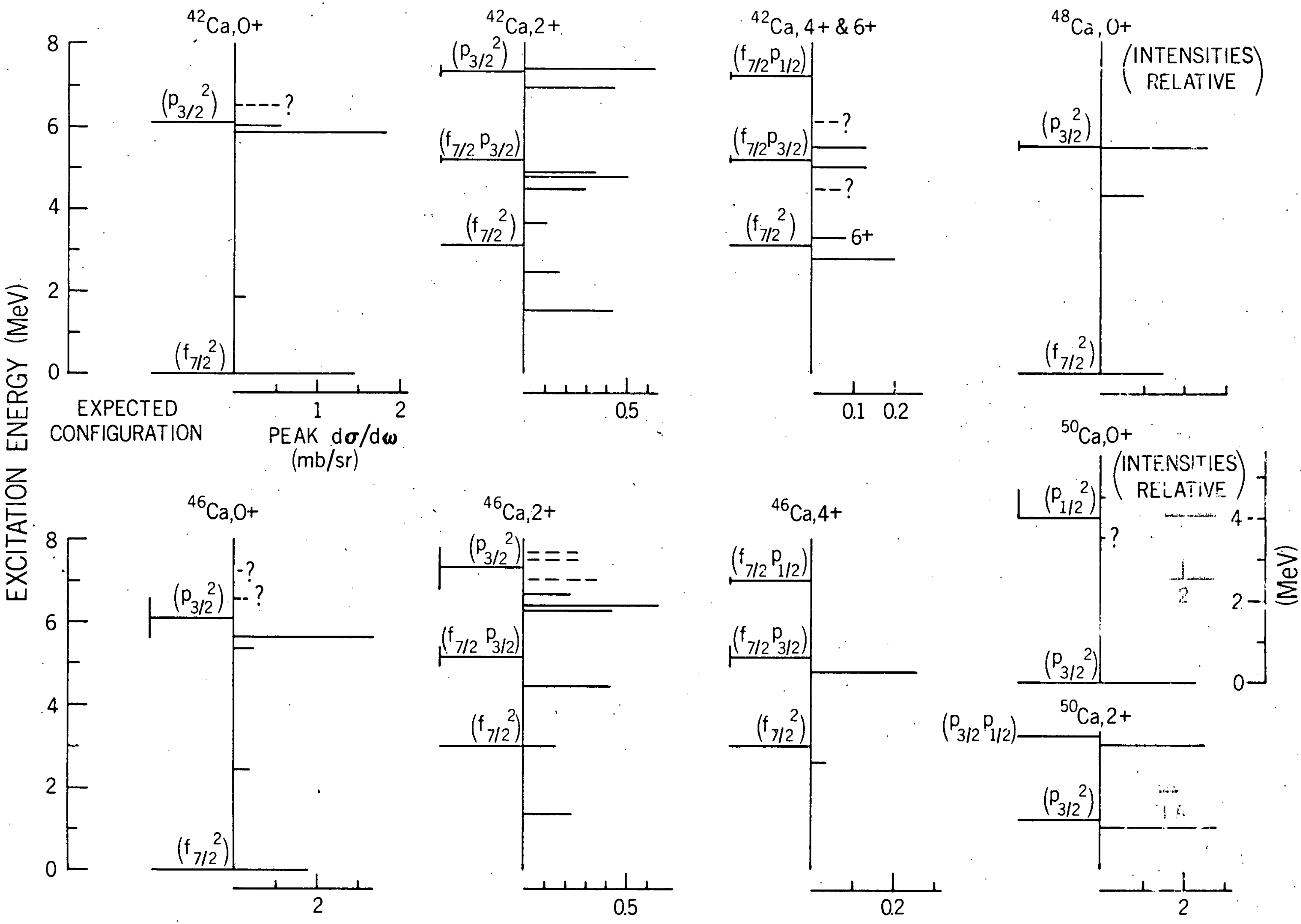

^{42}Ca,0+
^{42}Ca,2+
^{42}Ca, 4+ & 6+
^{48}Ca, 0+
(INTENSITIES RELATIVE)
$(p_{3/2}^2)$
$(f_{7/2}p_{3/2})$
$(f_{7/2}^2)$
$(f_{7/2}p_{1/2})$
6+
?
EXCITATION ENERGY (MeV)
EXPECTED CONFIGURATION
PEAK $d\sigma/d\omega$ (mb/sr)
0
2
4
6
8
1
2
0.5
0.1
0.2
^{50}Ca,0+
(INTENSITIES RELATIVE)
$(p_{1/2}^2)$
(MeV)
^{46}Ca,0+
^{46}Ca,2+
^{46}Ca,4+
^{50}Ca,2+
$(p_{3/2}p_{1/2})$

Fig 2

Ca CONFIGURATIONS

TYPE 1

$$\nu\left[\left(f_{7/2}^{\,n-2}\right)_{J_1=0} f_{7/2}\, p_{3/2}\right]$$

$$\nu\left[\left(f_{7/2}^{\,n-2}\right)_{J_1=0} p_{3/2}^{\,2}\right]$$

TYPE 2

(Absent in ^{42}Ca)

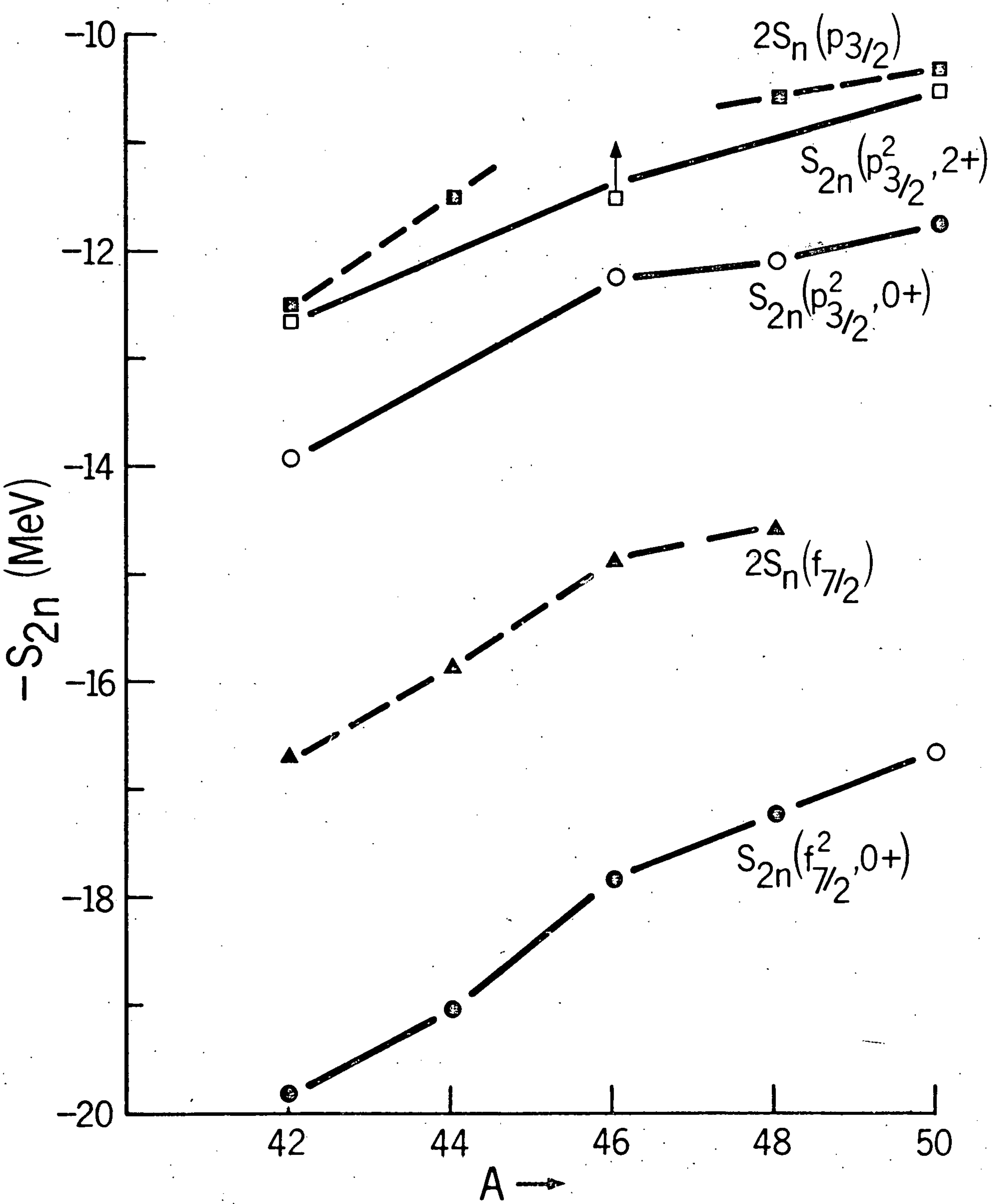
$$\nu\left[\left(f_{7/2}^{\,n-2}\right)_{J_1\neq 0} f_{7/2}\, p_{3/2}\right]$$

$$\nu\left[\left(f_{7/2}^{\,n-2}\right)_{J_1\neq 0} p_{3/2}^{\,2}\right]$$

TYPE 3

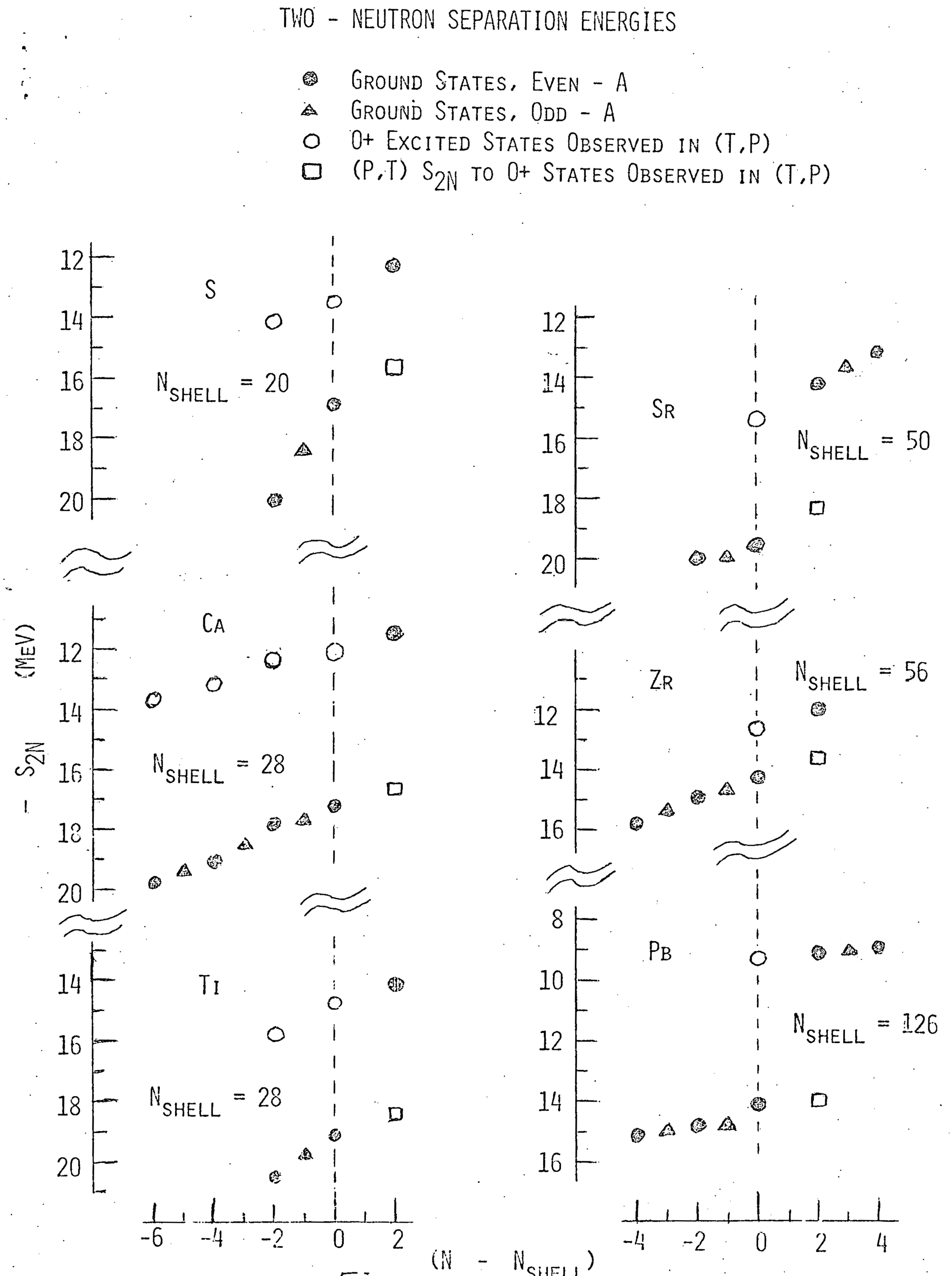
Excitations involving the "^{40}Ca CORE"

FIG 3



-10
-12
-14
-16
-18
-20
$-S_{2n}$ (MeV)
42
44
46
48
50
A →
$2S_n(p_{3/2})$
$S_{2n}(p^2_{3/2}, 2+)$
$S_{2n}(p^2_{3/2}, 0+)$
$2S_n(f_{7/2})$
$S_{2n}(f^2_{7/2}, 0+)$

FIG. 4



TWO - NEUTRON SEPARATION ENERGIES
GROUND STATES, EVEN - A
GROUND STATES, ODD - A
0+ EXCITED STATES OBSERVED IN (T,P)
(P,T) S2N TO 0+ STATES OBSERVED IN (T,P)
S
NSHELL = 20
CA
NSHELL = 28
TI
NSHELL = 28
SR
NSHELL = 50
ZR
NSHELL = 56
PB
NSHELL = 126
- S2N (MEV)
(N - NSHELL)

Fig. 5