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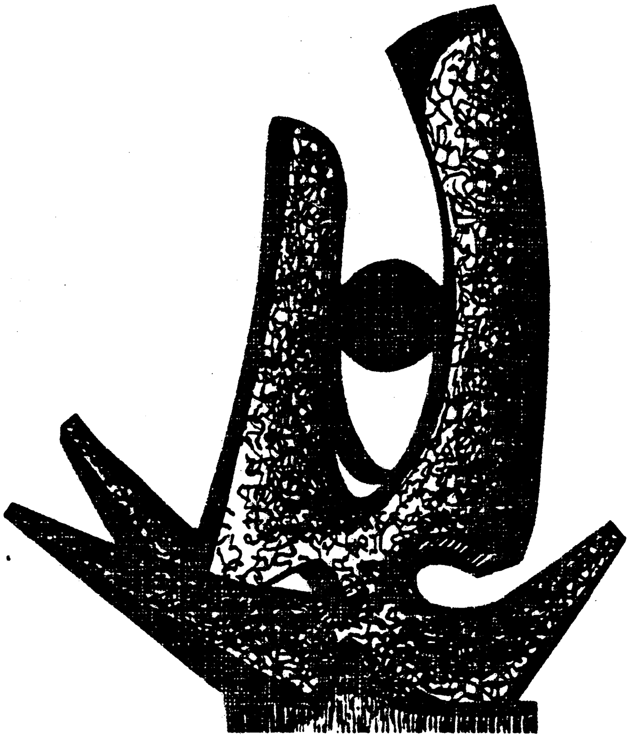

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Abstract:

Transfer reactions with beams of ^{14}C on a target of ^{48}Ca were used to measure the masses of ^{51}Ca and ^{47}Ar. A natural Ca target was used to estimate the background due to impurities in the ^{48}Ca target. In the case of ^{47}Ar this is the first reported measurement, but in the case of ^{51}Ca the results do not corroborate a previous experiment.

One of the difficulties in studying previously uncharacterized neutron-rich nuclei with transfer reactions is in identifying the peaks which are due to excitation of the ground state of the nucleus in question. If the spectra are not absolutely clean, then the background may obscure the peak, or fluctuations in the background may cause a spurious peak to appear. This is a particularly difficult problem in heavy-ion induced transfer reactions, in which excitation of the ground state is seldom favored, and the low yield prevents measuring at more than one angle to check the expected kinematic shift. On the other hand, information on such nuclei is often unobtainable by any other means and is very valuable in nuclear structure studies. For example, ^{51}Ca is an important nucleus in efforts to extend the mass surface out to the very neutron-rich Ca isotopes. In what follows below we will show that the information on ^{51}Ca is far from clear and that therefore the question of whether ^{52}Ca is a closed shell nucleus, as predicted by Tondeur[1], is far from resolved.

The experiments were carried out with the QDDD spectrograph at the Brookhaven National Laboratory tandem accelerator laboratory. Beams of ^{14}C were used with energies between 100 and 110 MeV. Two self supporting targets of 90 μg/cm^2 were prepared with identical evaporating techniques. One was made with 96% enriched ^{48}Ca, and the second was made of natural Ca (97% ^{40}Ca) for background measurements. The target thicknesses were measured at 0° with reduced beam intensity by determining the shift in the beam energy that occurred when the target was inserted. The focal plane of the QDDD was calibrated by sweeping the fully stripped elastic peak across it. Corrections for field scaling were taken from a previous work[2] in which masses of neutron rich nuclei were determined with high precision. The corrections and the overall calibration procedure were verified by observing

^{12}C, ^{14}N, and ^{15}N ejectiles which produced the nuclei ^{50}Ca, ^{47}K and ^{48}K, the masses of which are accurately known. In all cases the agreement was better than 20 keV, which is a good estimate of the accuracy of the overall calibration procedure. Particle identification, although somewhat complex because of the large number of possible products at any rigidity, followed standard methods similar to those described in ref 2., and clean separation was obtained for all of the isotopes under study in this paper.

The nucleus ^{47}Ar has not been observed in any previous measurement. In the present experiment spectra of the $^{48}Ca(^{14}C,^{15}O)^{47}Ar$ reaction were obtained at 101.6 MeV beam energy and 10° and at 100.0 MeV and 21°. The resulting spectra are shown in Figs 1 and 2. Background spectra taken with the natural Ca target indicated that the peaks labelled ^{47}Ar g.s. in the two spectra are due to the ^{48}Ca in the target and are not contaminants such as the very strong ^{12}C and ^{16}O peaks in the spectra. The labelled peaks are the only features of the spectra which showed the correct kinematics for ^{47}Ar and agree in Q-value and therefore mass excess. The peak at 10° corresponds to a Q-value of -18.14(10) MeV and a cross section of 0.6(2) μb/sr, whereas at 21°, -18.0(2) MeV and 0.08(6) μb/sr was obtained. The mass excess determined from the average of the two runs is given in Table 1 along with the predictions from the compilation of Maripuu[3]. As can be seen from these results, the ^{47}Ar mass determined from the peaks in the two spectra is in good agreement with the various theoretical predictions but fails to distinguish between them.

The situation on ^{51}Ca is quite a bit more complicated. There have been two previous attempts to measure the mass, which were very similar to the present work in that they used three-nucleon transfer reactions and QDDD spectrographs. The first by Mayer et al.[4] used the ^{48}Ca(^{14}C,^{11}C)^{51}Ca reaction at 75 MeV. This work was very limited by statistics and gave only an upper limit for the mass excess of -35.94(5) MeV. No mention of the possibility that the counts in question could come from the ^{40}Ca contaminant in the target is made in the published paper, but this is a distinct possibility in the light of the data presented here. The second measurement was made by Brauner et al.[5] with the ^{48}Ca(^{18}O,^{15}O)^{51}Ca reaction at 102 MeV. The statistics of this experiment are much better than in Ref 4, and the possibility that the counts are due to the ^{40}Ca contaminant is discussed. The authors point out that the ^{40}Ca(^{14}C,^{11}C)^{43}Ca reaction at the same rigidity as the ^{48}Ca(^{14}C,^{11}C)^{51}Ca(G.S.) reaction would correspond to an excitation of 12 MeV in ^{43}Ca and therefore would be expected to produce a smooth spectrum. However, they did not make a measurement with a natural Ca target to determine the magnitude of the contribution. The present results, which are discussed below, indicate that many of the counts attributed by Brauner et al.[5] to the ground and excited states of ^{51}Ca may be due to the ^{40}Ca in the target. The first peak that appears to be truly distinguishable with statistical significance from a smooth background lies at an excitation of 0.97 MeV (with respect to the quite weak peak identified as the ground state) and at a mass excess of -35.15 MeV. In the analysis by Brauner et al.[5], five states were found at the energies given in Fig 3.

The spectra given in Fig. 4 were taken at 13° and 110 MeV. The dashed line in the figure represents a line drawn through the spectrum obtained at the same field from a natural Ca target after scaling it to the known amount of natural Ca in the ^{48}Ca target. The spectrum taken with the natural Ca target is given in the upper part of Fig 4. The contribution, although at 15 MeV excitation in ^{43}Ca, is quite strong and obscures the spectrum up to the peak labelled B, which we tentatively identify as the ground state of ^{51}Ca. The arrow labelled A in the figure corresponds to the ground state mass excess given by Brauner et al.[5]. There is no indication of a peak at this point, but the peak labelled B lies at a Q-value of -16.93(10) MeV. This value corresponds to a mass excess of -34.96(10) in agreement with the 0.97 MeV state of Ref 5 (-35.15(15) MeV). Under the assumption that peak B is the ground state, then the peaks labelled C and D lie at an excitation energy of 2.35(5) and 3.02(5) MeV in ^{51}Ca.

The existence of low lying levels in ^{51}Ca is interpreted by Brauner et al.[5] as evidence against the doubly magic nature of ^{52}Ca. They point out the similarities of their proposed spectrum to those of ^{59}Ni and ^{43}Ca, which also have three neutrons outside of a closed shell. However, they present no shell model calculations to support this idea quantitatively. If shell model calculations were to give ^{51}Ca several low lying states as proposed, than this would be an argument for accepting Brauner at al.'s identification of the ground state. Since the orbitals in question are different for ^{43}Ca, and the single particle energies are different for ^{59}Ni, the shell model structure of ^{51}Ca could be quite different from that of the other two three-neutron nuclei. The results of such a calculation are given in Fig. 5. The shell model calculations were done assuming active f7/2 proton orbitals and active 2p3/2, f5/2, and 2p1/2 orbitals. The code OXBASH[6] was used with n-n and n-p matrix elements taken from Ref 7, while the p-p matrix elements were taken from states in ^{50}Ti. The single particle energies were taken from ^{49}Ca. As can be seen from Fig 5, the excitation spectra of known nuclei agree with the model calculations. The energy levels of ^{59}Ni and ^{51}Ca are predicted to be quite different fom each other because of the change on the single particle orbitals between ^{49}Ca and ^{57}Ni. In more complicated nuclei such as ^{53}Cr and ^{55}Cr the shell model also does a good job of reproducing the structure. Hence unless there is a dramatic change in the nature of ^{51}Ca compared to other nuclei in this region, these calculations should be accurate to 200 keV. In the light of this, the observation by Brauner et al.[5] of three excited states below 1 MeV excitation is surprising. The shell model calculations do not support Tondeur's conjecture, which is based on the energy density method, that ^{52}Ca might be a doubly magic nucleus. As can be seen in Fig 6, the present calculations predict a high lying first excited 2^+ state for ^{54}Ca and not for ^{52}Ca. The mass excess predicted by the Garvey-Kelson[3] mass relation (-35.15 MeV) agrees well with the results of the present experiment. The comparison of the present results to theoretical predictions and previous results is summarised in Table 1.

In conclusion, difficulties in identifying the ground state of neutron-rich nuclei far from the line of beta stability can lead to substantial errors in determining the mass excess. In the case of ^{47}Ar we present the only known information on that nucleus and at least were able to observe the peak under two quite different experimental situations. In the case of ^{51}Ca we can not rule out the possibility that states at lower mass excess such as the ones found by Brauner et al.[5] exist, but we have shown that the evidence for them is weak.

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Table 1. Theoretical and Experimental Mass Excesses of ^{47}Ar and ^{51}Ca.

Model	^{47}Ar	^{51}Ca
Myers	-25.08	-32.39
Groote-Hilf-Takahashi	-26.18	-34.48
Seeger-Howard	------	-33.2
Liran-Zeldes	------	-34.69
Beiner-Lombard-Mas	-25.0	-35.1
Janecke-Garvey-Kelson	-25.82	-35.25
Comay-Kelson	-25.70	-35.24
Previous experiments	------	-35.94(5)[a]
		-36.12(12)[b]
Present Experiment	-25.91(10)	-34.96(10)

a. Ref 4 upper limit.
b. Ref 5

Figure Captions:

1. Spectrum of the ^{48}Ca(^{14}C,^{15}O)^{47}Ar reaction at 10° and 101.6 MeV.

2. Spectrum of the ^{48}Ca(^{14}C,^{15}O)^{47}Ar reaction at 21° and 100.0 MeV.

3. Energy levels of ^{51}Ca as given by the shell model calculations described in the text and by the present experiment and Brauner et al.[5].

4. Spectrum of the ^{48}Ca(^{14}C,^{11}C)^{51}Ca reaction at 13° and 100.0 MeV. Also shown are data taken at the same field setting with a natural Ca target. The dashed line in the figure is a fit to the natural Ca data scaled to the amount of ^{40}Ca in the ^{48}Ca target.

5. Comparison between experimental energy levels and the shell model predictions described in the text for the low lying states of several nuclei in the region near ^{51}Ca.

6. Shell model predictions for the excitation energy of 2^+ first excited states of the neutron rich Ca isotopes. The solid lines are known states whereas the dashed lines represent the theoretical predictions described in the text.

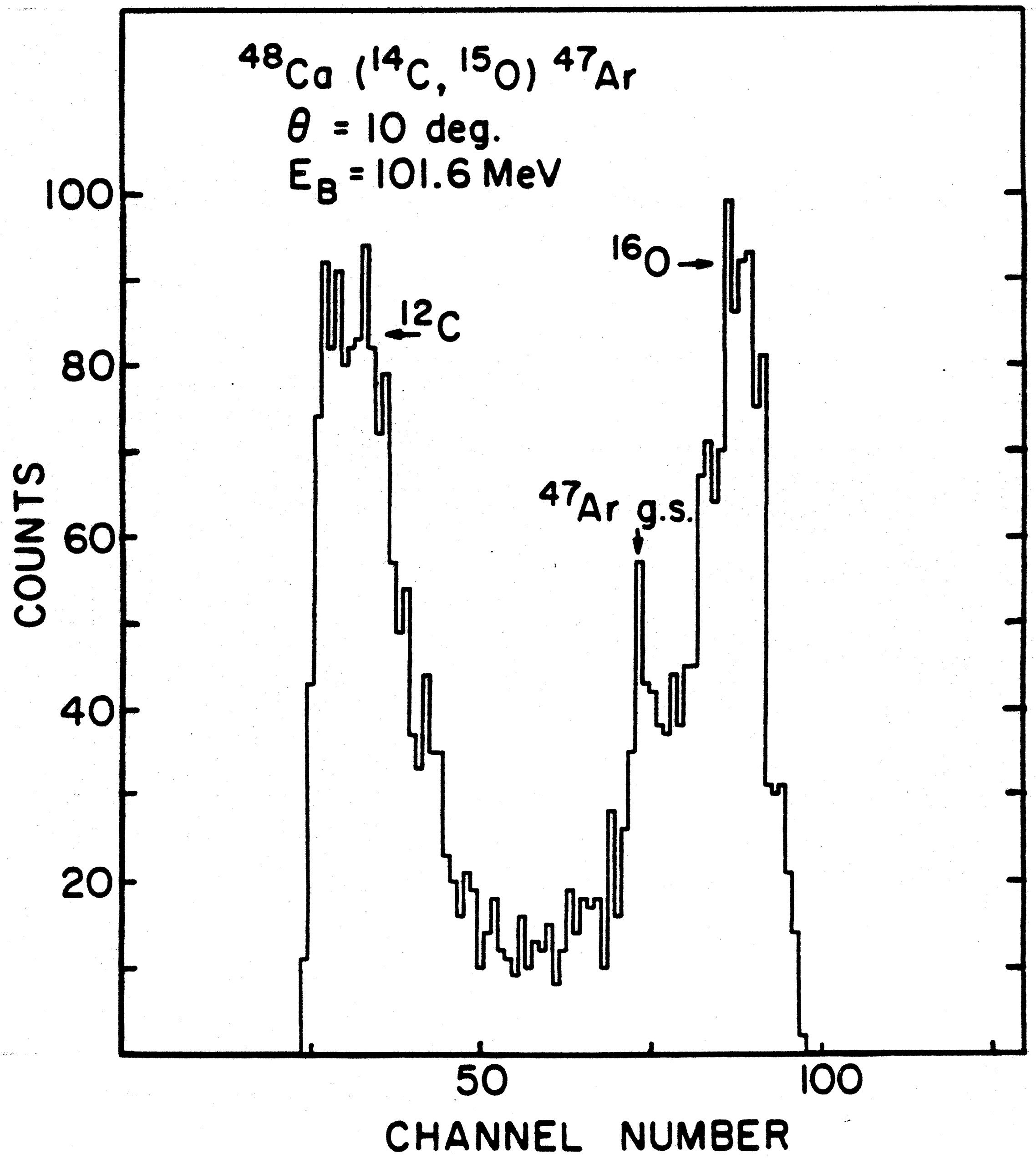
48Ca (14C, 15O) 47Ar
θ = 10 deg.
E_B = 101.6 MeV
12C
16O
47Ar g.s.
COUNTS
100
80
60
40
20
50
100
CHANNEL NUMBER

Fig 1

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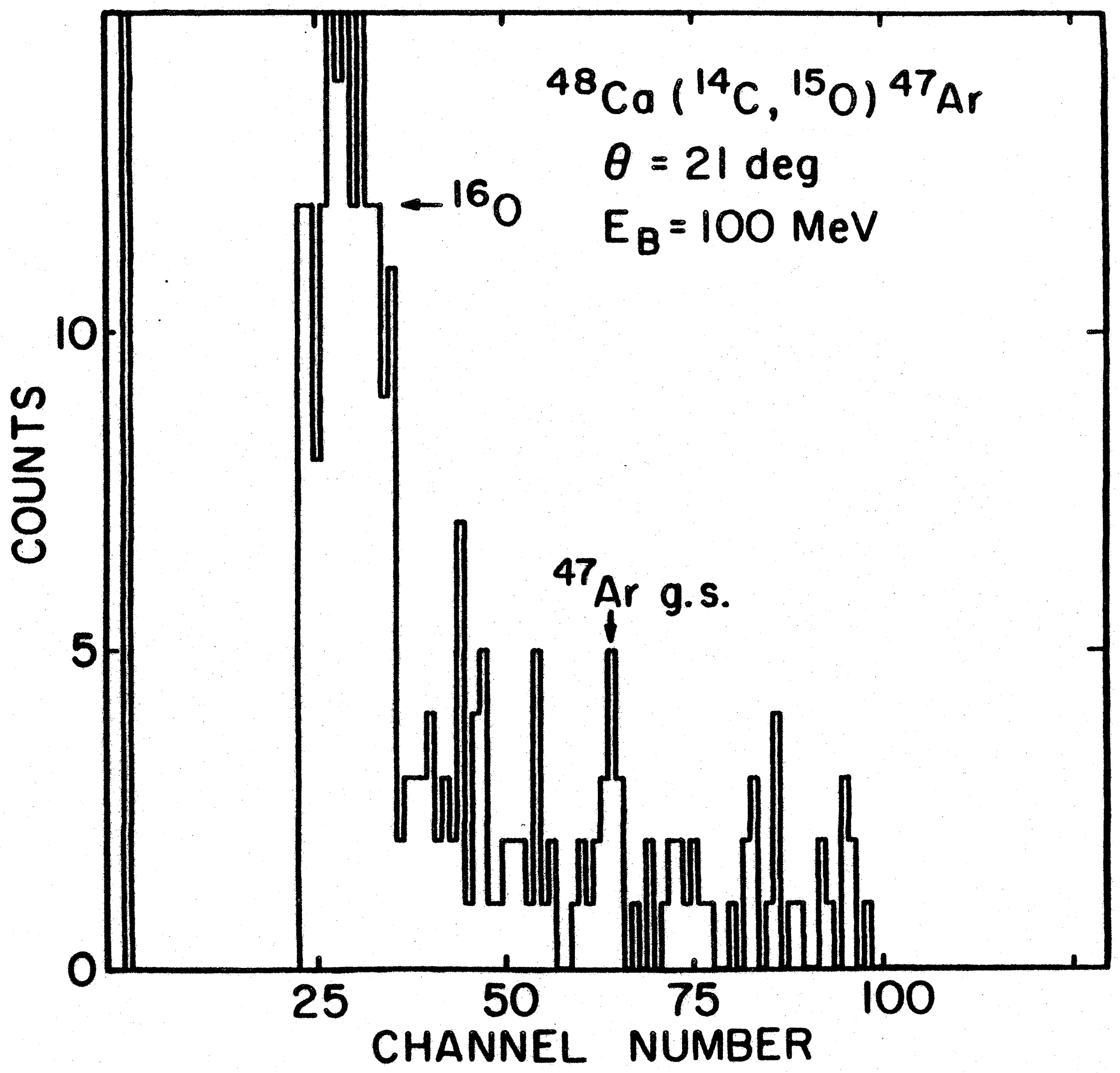

Fig 2

MSU-85-139

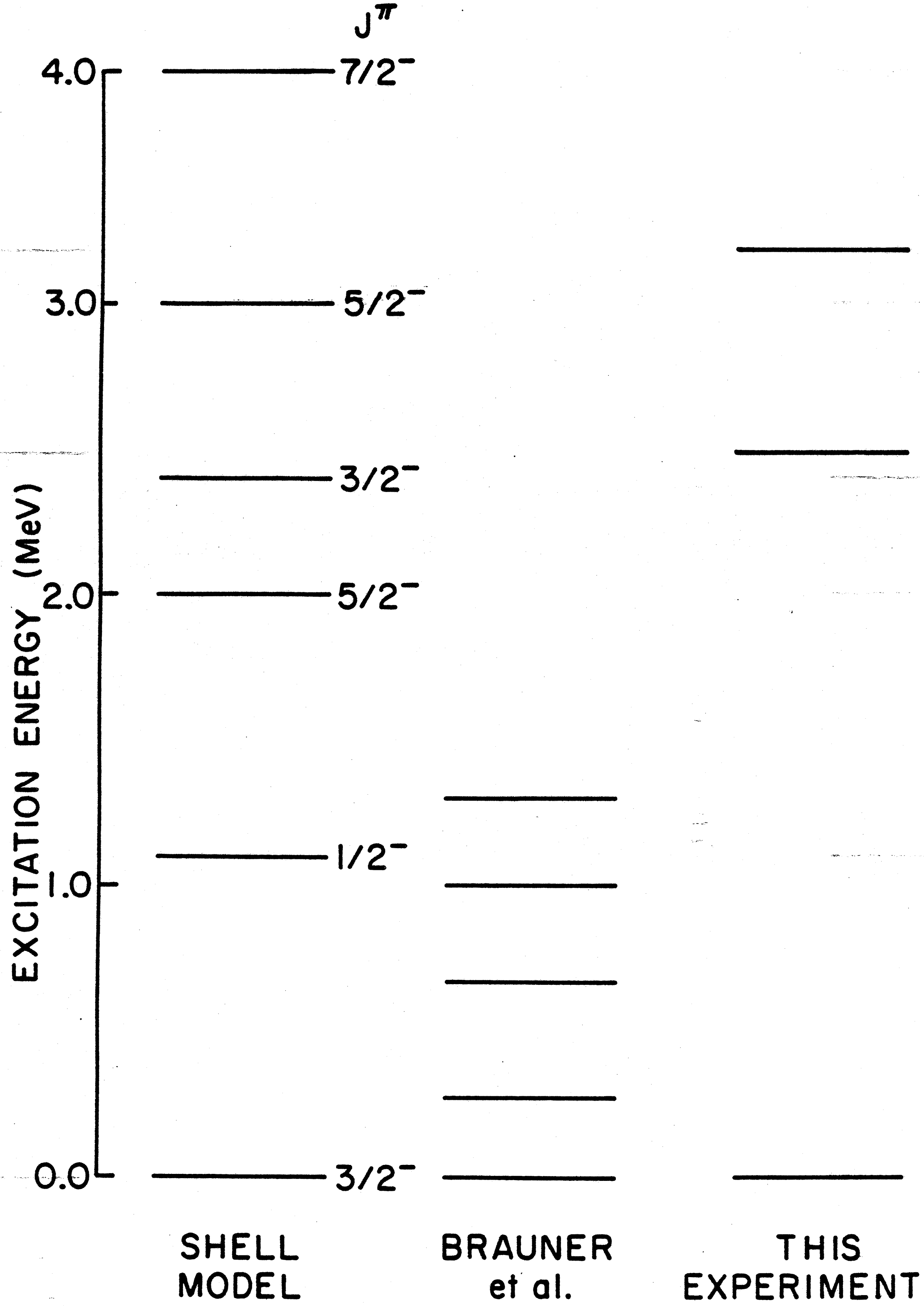

Fig 3

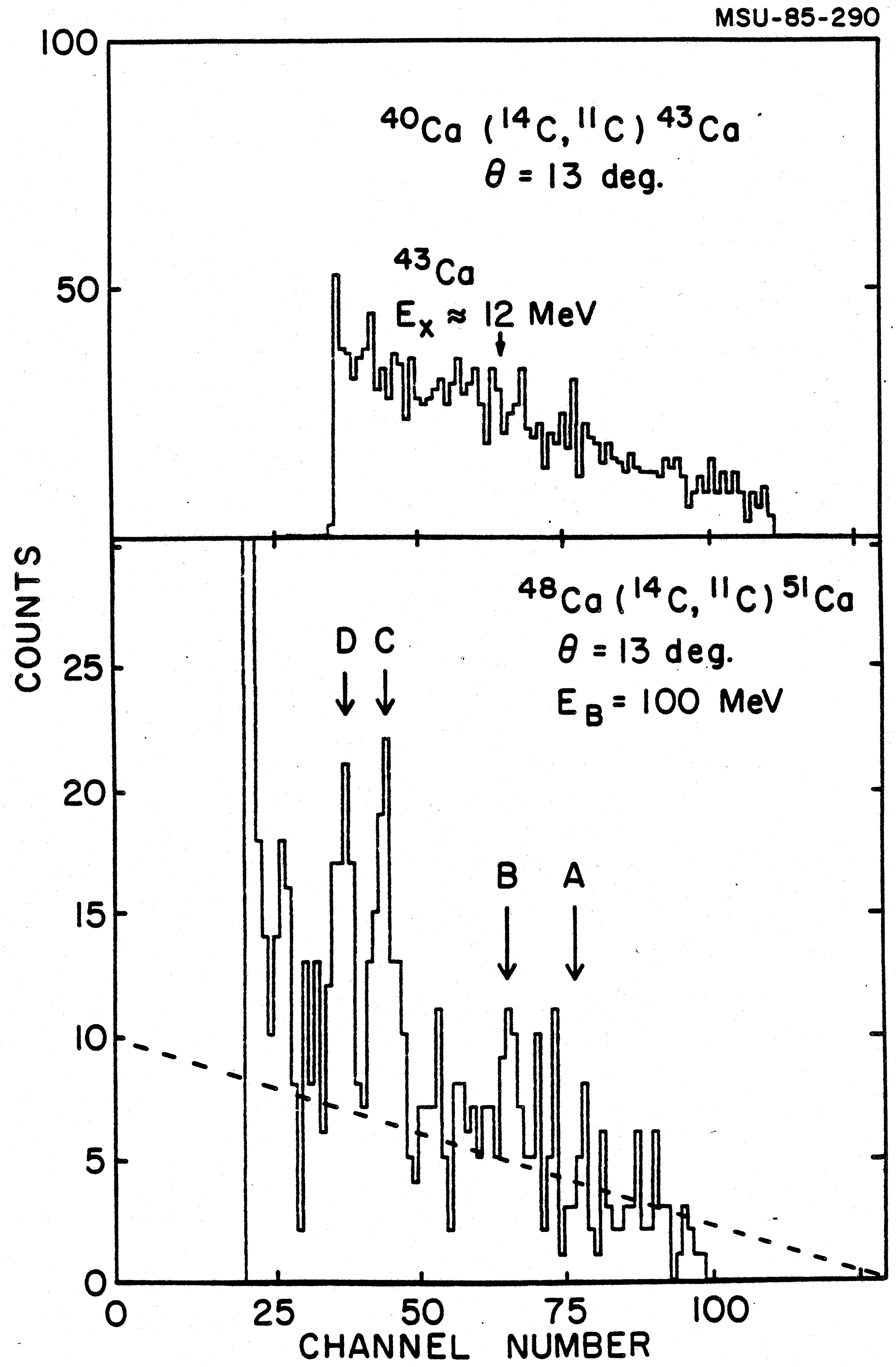
MSU-85-290
100
50
$^{40}Ca\,(^{14}C,{}^{11}C)\,^{43}Ca$
θ = 13 deg.
^{43}Ca
$E_x \approx 12$ MeV
COUNTS
25
20
15
10
5
0
$^{48}Ca\,(^{14}C,{}^{11}C)\,^{51}Ca$
θ = 13 deg.
E_B = 100 MeV
D
C
B
A
0
25
50
75
100
CHANNEL NUMBER

Fig 4

MSU-85-313

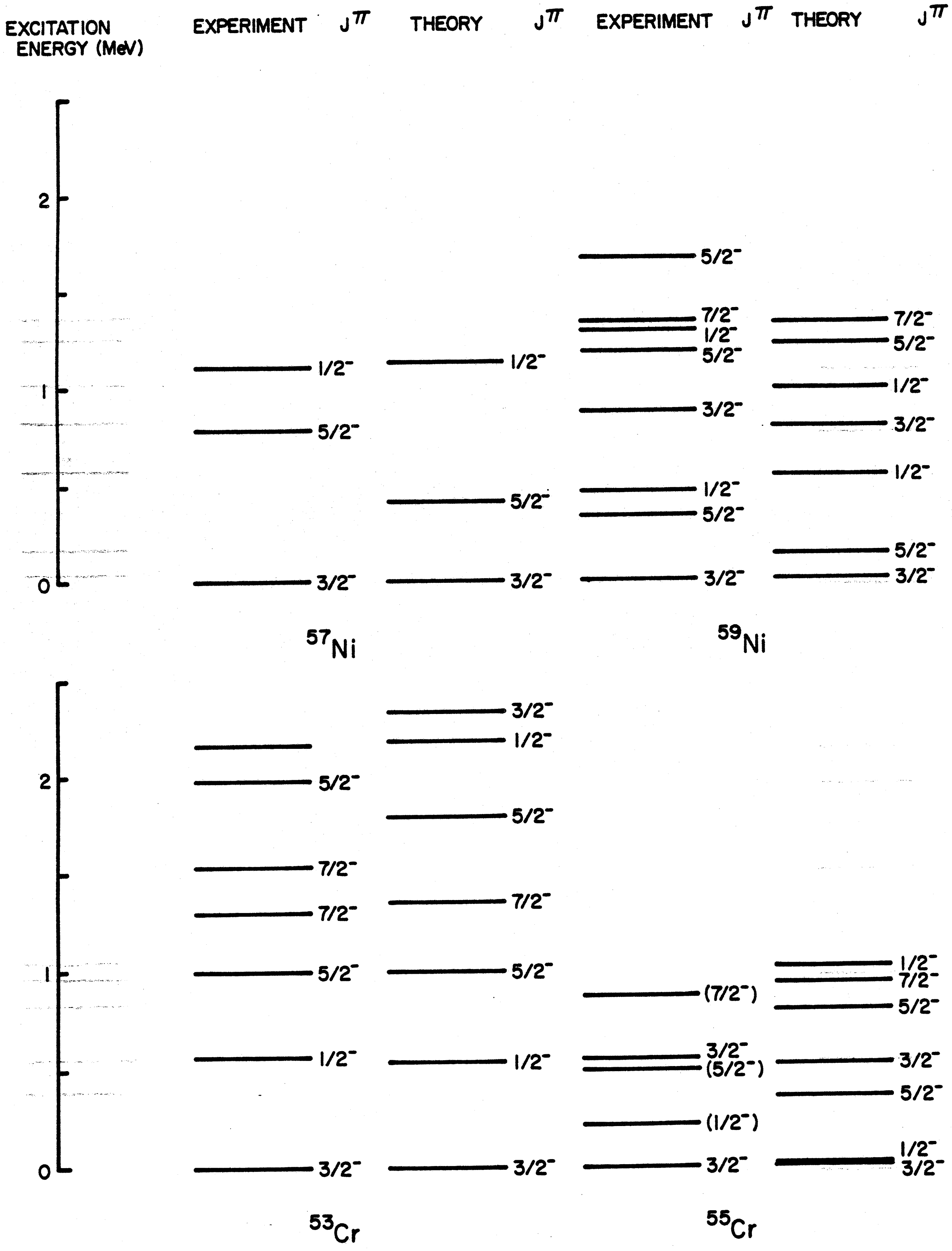

Fig 5

Fig 6

MSU-85-31

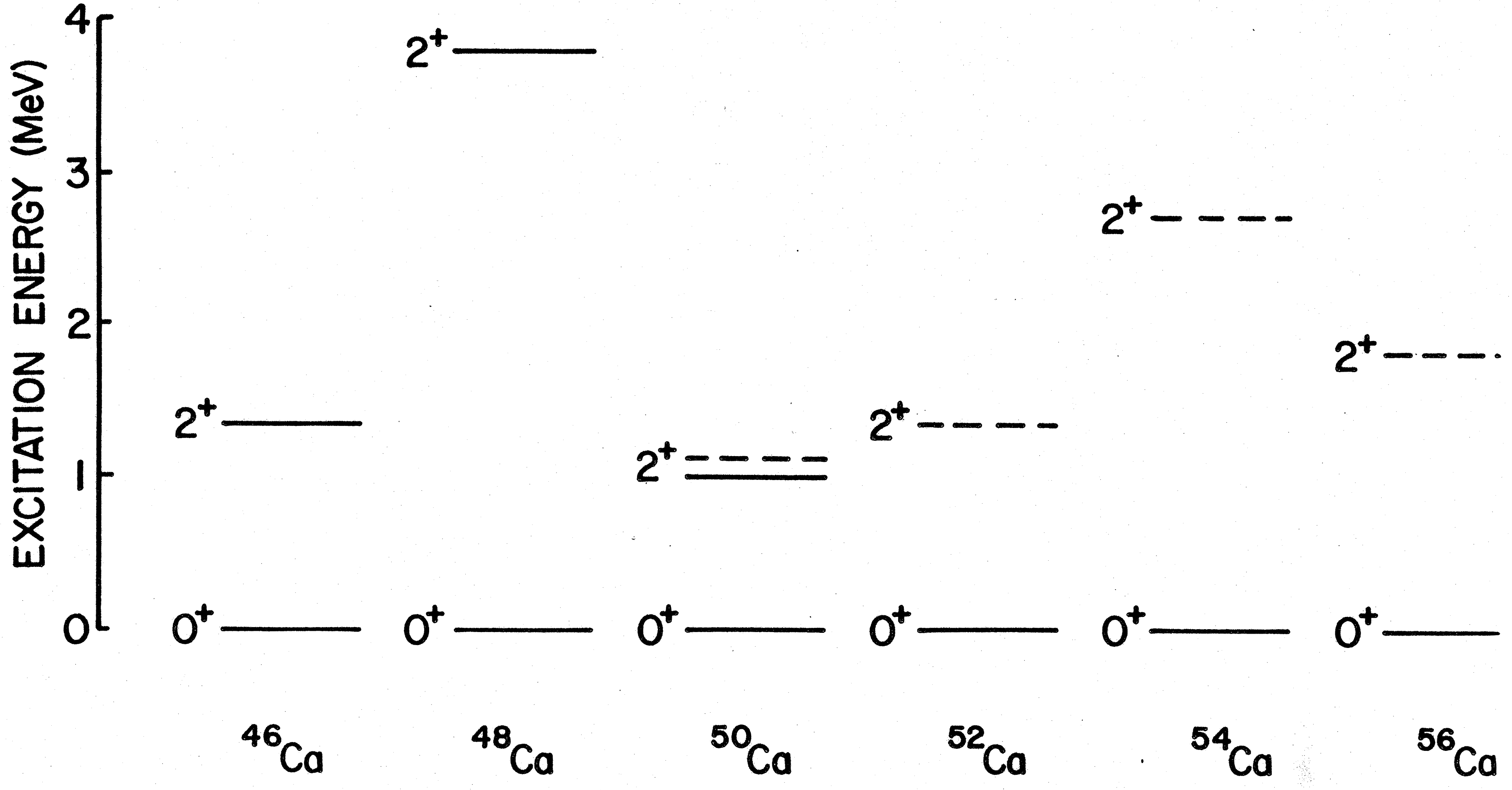

Fig 6