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Evolution of collectivity along the $N=Z$ line: The ^{84}Mo nucleus

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The reaction ^{58}Ni(^{28}Si,$2n\gamma$) at 90 MeV incident energy has been used to populate the $N=Z$ nucleus ^{84}Mo. The GASP array was used together with the ISIS Silicon ball, which allowed a subtraction of the charged particle channels in the γ-γ coincidences. The only known transition $2_1^+ \rightarrow 0_1^+$ of 443.8 keV in ^{84}Mo has been found in coincidence with a γ ray of 673.5±0.4 keV which was assigned as the second ($4_1^+ \rightarrow 2_1^+$) yrast transition. The behavior of the resulting yrast line indicates that ^{84}Mo is a transitional nucleus. The correlation between the excitation energies of the 2_1^+ and 4_1^+ levels of the $N=Z$ nuclei reveals a systematic deviation from the average behavior defined by all collective even-even nuclei. [S0556-2813(97)06011-1]

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I. INTRODUCTION

There is great interest in the structure of the $N=Z$ nuclei since, unlike in all other nuclei, it will be dominated by the $T=0$ residual interaction. The presently available experimental information indicates a small region of strong deformation centered on ^{76}Sr [1] and ^{80}Zr [2], the next even-even $N=Z$ nucleus, ^{84}Mo, being apparently much less deformed [3]. Thus, in going on the $N=Z$ line from ^{76}Sr towards ^{100}Sn (very likely spherical) one has the unique opportunity of studying a shape transition dominated by the $T=0$ residual interaction.

The experimental information on $N=Z$ nuclei above $Z=38$ is, however, rather scarce, since with the presently available reactions these nuclei are populated with extremely low cross sections. Thus, only two yrast transitions could be experimentally evidenced in ^{80}Zr [2], and only one in ^{84}Mo [3], the next $N=Z$ even-even nucleus, ^{88}Ru, being still completely unknown. Even so little information is extremely valuable in defining the physics of this interesting nuclear region, especially by comparison with the large collection of similar data of the other nuclei, closer to the stability line.

In this letter we report the observation of the second transition of the ground state band of ^{84}Mo. This completes significantly the image that we have about the evolution of the collectivity along the $N=Z$ line.

The nucleus ^{84}Mo has been studied in Ref. [3] with the inverse reaction ^{58}Ni (195 MeV)+^{28}Si. The only γ ray known in this nucleus, with energy 443.8(5) keV, has been assigned on the basis of a coincidence between γ rays and recoiling ions analyzed in a recoil mass spectrometer with a Z-sensitive focal plane detector, which allowed one to eliminate the contribution of the much stronger isobaric channels pn and $2p$.

II. EXPERIMENTAL MEASUREMENTS AND DATA ANALYSIS

In our experiment we have used the same reaction, ^{58}Ni + ^{28}Si, but with a Si beam. The ^{28}Si beam at 90 MeV was delivered by the Legnaro XTU Tandem accelerator; a very stable 7^+ beam of about 15 particle nA was obtained during a six days run. The target consisted of a stack of two 0.5 mg/cm^2 ^{58}Ni foils. The γ rays were detected with the GASP array in its standard configuration with 40 Compton-suppressed HPGe detectors and the BGO inner ball. The trigger condition was that at least 2 Ge and 3 BGO detectors fired in coincidence. The 10^9 recorded events contained also information from the ISIS Silicon ball, which consists of 40 ΔE-E telescopes in a geometry similar to that of GASP.

The main problem in dealing with γ-γ coincidence data in the case of ^{84}Mo is the very small cross section of the $2n$ channel. Such cross section has been previously measured to be 0.007(3) mb [3], compared to 1.3(3) mb for the pn channel (^{84}Nb), 35(3) mb for the $2p$ channel (^{84}Zr), about 60 mb for the $2pn$ channel (^{83}Zr), and about 100 mb for the $3p$ channel (^{83}Y). The cross section of the $2n$ channel leading to ^{84}Mo represents, according to CASCADE calculations, about 4×10^{-5} of the fusion cross section. An accurate subtraction of the charged particle channels (in fact, all the other channels populated by the reaction used) is therefore of decisive importance.

Since we base our investigation on the known 444 keVγ ray of ^{84}Mo [3], it is important to review first the possible known contaminants of this line. From previous detailed studies of nuclei populated in the ^{28}Si + ^{58}Ni reaction, we have found that ^{82}Y and ^{83}Y have lines with about the same energy. Thus, in ^{82}Y there are two transitions of 442.4 and 445.1 keV which could interfere with the one of ^{84}Mo, but an examination of the spectra gated on these energies did not show any of the known lines expected according to the well-established level and decay scheme [4]. Therefore, the $3pn$ channel is of no importance as a possible contaminant. On the contrary, ^{83}Y which is very strongly populated, has a γ ray of 444.6 keV ($15/2^- \rightarrow 13/2^-$) [5] which is in coincidence with many transitions whose energies lie in the domain ~500–900 keV where we expect the second yrast tran-

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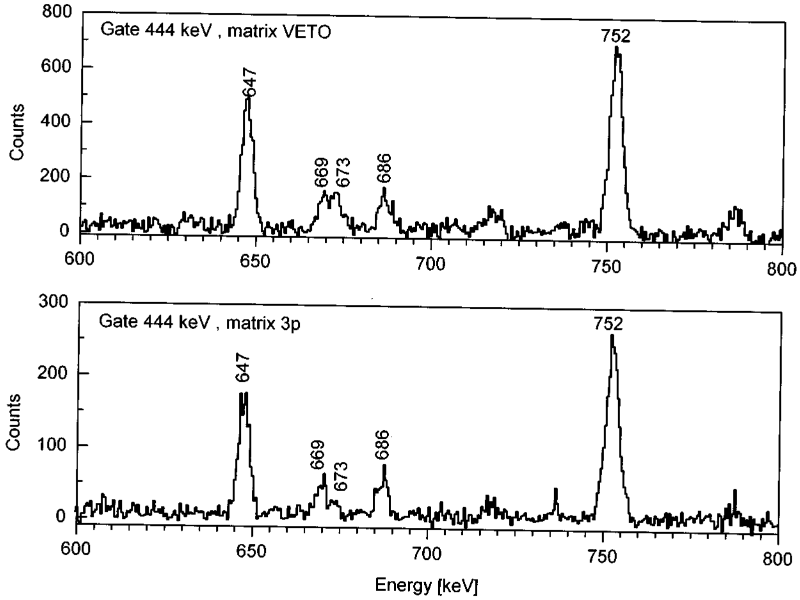

FIG. 1. Gates on the 444 keV γ ray in the VETO matrix (anticoincident with the Si ball) and in the ''3p'' γ-γ matrix (coincident with the 3 proton events in the Si ball). The peaks labeled with their energy belong to ^{83}Y; the candidate for the second yrast transition in ^{84}Mo is the γ ray at 673 keV (see text). The dispersion of the spectra is 0.5 keV/channel.

sition of ^{84}Mo. Thus, in coincidence with the 444.6 keV line we observe the transitions of 647, 669, 686, and 752 keV; of interest for further discussion are also other transitions belonging to the $K^{\pi}=3/2^{-}$ structure: 395, 410, and 421 keV, respectively [5].

As the channel of interest is the 2n, we have used the information from the Si ball in two ways. First, we have created a γ-γ coincidence matrix in anticoincidence with the Si ball. In this way, we reduced the contribution from the light charged particle channels and enhanced the relative contribution of the 2n channel; however, since the proton and α-particle detection efficiency of the Si ball is not 100%, this matrix, which in the following is called the VETO matrix, still contains contributions from the light charged particle channels. Second, we produced γ-γ matrices coincident with different numbers of particles, such as 1p,2p,3p,α,$p\alpha$,2$p\alpha$, etc. These were used either to create ''clean'' matrices (corrected for the feedthrough effect) for different channels, to be subtracted from any matrix of interest (containing the 2n channel, such as the VETO one), or to generate spectra which were subsequently used to determine the contribution of the charged particle channels to cuts on VETO, as will be discussed below.

Figure 1 shows a comparison of two spectra obtained by setting gates centered on 444 keV, one in the 3p γ-γ matrix, the other in the VETO matrix. The ''3p'' matrix is a ''clean'' one, as it corresponds practically only to the 3p channel (^{83}Y); in the 444 keV gate on this matrix one sees the strong lines of ^{83}Y (647, 669, 686, 752 keV). The same ^{83}Y lines are seen also in the gate on the VETO matrix. Of special interest is a peak seen at 673 keV, which appears in both spectra but is obviously *enhanced* in the gate on the VETO matrix. This suggests that, although the 673 keV line exists also in the 3p channel, a part of it (which comes ''in excess'' in the VETO matrix) might belong to our 2n channel. We have verified also quantitatively how this 673 keV peak behaves in the spectra obtained from different matrices when setting a gate on the 444 keV γ-ray energy. In the matrices in coincidence only with protons, that is, 1p,2p,3p, the relative intensities of the γ rays of 752, 647, 669, 686, and 673 keV are in the ratios 1.80(4):1.00(3):0.22(2):0.48(5):0.11(2), respectively. The constancy of these ratios indicates that all these γ rays belong to the same nucleus (^{83}Y), although the 673 keV transition has not been placed in the level scheme established by the previous studies [5]. On the other hand, in the 444 keV gate on the VETO matrix, the same five γ rays appear in the ratios 1.70(3):1.00(2):0.25(3):0.45(3):0.24(3); the first four appear therefore in the ratios characteristic of ^{83}Y, whereas the 673 keV one is *doubled*, the intensity in excess (around 500 counts, roughly half of the total photopeak area) being very likely the contribution of the 2n channel that we are looking for. In a similar way, we have verified that in the gate on the 673 keV transition the γ rays known to belong to ^{83}Y remain always in the same relative intensities, whereas the 444 keV γ ray is enhanced in the gate on the VETO matrix. We thus conclude, at this point of the analysis, that the 673 keV γ ray is a strong candidate for a ^{84}Mo transition (actually, the only one we could find).

The next step has been to produce a spectrum cleaned of the contribution of the charged particle channels and to show that the 444–673 keV coincidence survives at the level of ~500 counts (in the photopeak) and can therefore be firmly attributed to ^{84}Mo.

The first procedure we adopted was the following. We have first determined ''clean'' 1p,2p, . . . ,α,$p\alpha$, etc., matrices, according to the general procedure described, e.g., in Ref. [6]. These matrices, suitably normalized, were subtracted from the VETO matrix. Ideally, this procedure should lead, in the end, to a clean ''2n'' matrix, in which all contributions due to the charged particle channels have been removed. This procedure has, nevertheless, two shortcom-

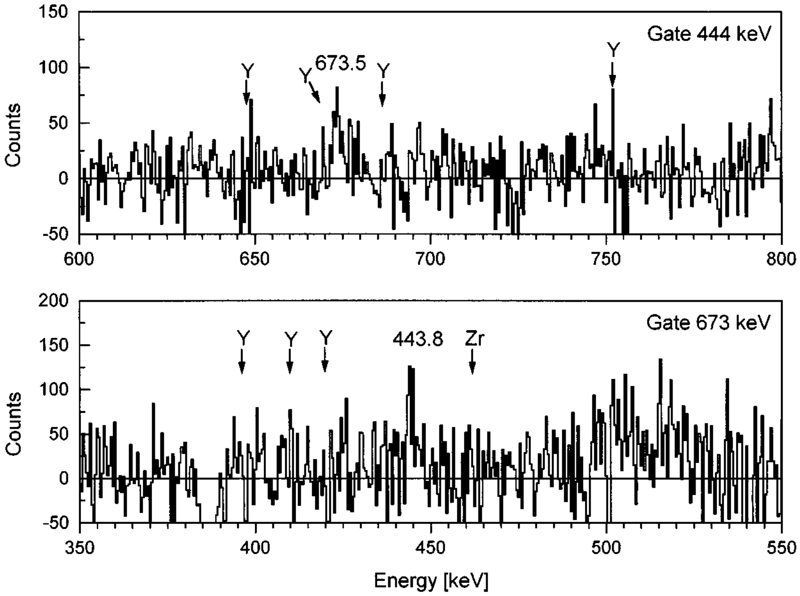

FIG. 2. Gamma-ray spectra coincident with the 444 keV and 673 keV γ rays. These spectra are cleaned of the contribution of the charged particle channels, according to the procedure described in the text. The arrows indicate the position of transitions which would be expected from ^{83}Y (396, 410, 420, 647, 669, 686, and 752 keV, marked with ''Y'') and ^{83}Zr (462 keV, marked with ''Zr''). The spectra have the same dispersion as those of Fig. 1.

ings. One is the large number of matrix subtractions which introduces errors difficult to control especially at the level of the final step where we should be left only with the tiny contribution of the $2n$ channel. The second is related to our particular data. We have found out that the $2p$ (^{84}Zr) and $2pn$ (^{83}Zr) channels had different detection efficiencies in the Si ball, very likely due to different average energy of the protons which led to different losses in the absorbant foils placed in front of the detectors. Due to this fact we could never clean off the two nuclei simultaneously: if ^{84}Zr (which had the strongest peaks) was correctly subtracted, we were left with some ^{83}Zr, which is somewhat disturbing, the 673 keV transition of interest being on the side of a strong 675 keV transition of this nucleus [7]. We have nevertheless verified by this method of matrix subtraction that we see the 444–673 keV coincidence in both directions, at a level of $\sim$500 counts.

A second procedure of removing the ''background'' due to the charged particle channels was the following. Consider one of the peaks which is assumed to have a contribution from the ^{84}Mo transitions (like 444 or 673 keV) in the VETO matrix. The spectrum generated by gating on this peak, without any ''background'' subtraction (which will be denoted by ''P'') is composed by a superposition of spectra corresponding to both the $2n$ channel and the ''charged particle'' channels. Similarly, a gate on the ''background'' region near this peak (which will be denoted by ''B'') will have a negligible contribution from the $2n$ channel, but a *similar* superposition of ''charged particle'' channel spectra. The ''charged particle'' channel contributions for both the P and B gates were generated by setting the same gates on all the important γ-γ matrices in coincidence with charged particles: $1p,2p,3p,\alpha,p\alpha$, and $2p\alpha$. The B spectrum from the VETO matrix has been fitted (with a χ^2 minimization procedure) with a linear combination of the six B spectra obtained from the above mentioned particle-coincident matrices. The six resulting coefficients were then used to multiply the P spectra from the same matrices, which added together represented the ''particle background'' spectrum which was finally subtracted from the P spectrum of the VETO matrix. This procedure has been applied for the gates on both the 444 keV and 673 keV transitions. The results are shown in Fig. 2. Both spectra show very clearly the coincidence between the two γ rays. Other transitions clearly coincident with these γ rays were not seen. One should note, in both cases, the clean subtraction of the strong contaminant channels. In fact, in the 444 keV gate (compare to Fig. 1) all the strong transitions due to ^{83}Y are absent. The same thing happens in the 673 keV gate where the transitions of 395, 410, and 421 keV of ^{83}Y (which do appear in the proton-coincident spectra) are now absent; also, a 462 keV transition of ^{83}Zr, which would be due to the coincidence with the strong, contaminant line at 675 keV [7], is completely absent. The areas of the 444 keV and 673 keV peaks in the spectra of Fig. 2 are of about 500 counts. Given the GASP efficiency and the conditions of our experiment, this corresponds reasonably well with a cross section of about 10 μb of the $2n$ channel. These results show that the 443.8 keV transition in ^{84}Mo is coincident with the 673.5±0.4 keV γ ray, which we assign to the second ($4_1^+ \rightarrow 2_1^+$) yrast transition.

III. DISCUSSION AND CONCLUSIONS

With this new experimental information, which confirms and completes the one from Ref. [3], the yrast line of ^{84}Mo is known now up to the 4_1^+ state. What does this tell us about the structure of this nucleus? The $E(2_1^+)$ energy alone can be used to get some indication about the collectivity of an even-even nucleus. Based on the empirical relation of Grodzins

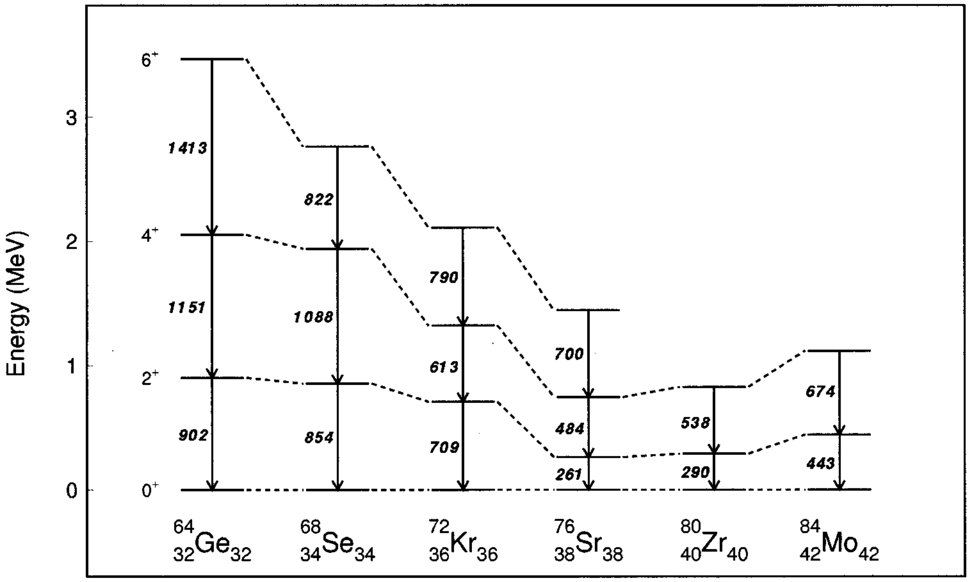

FIG. 3. The evolution of the yrast levels in $N=Z$ even-even nuclei.

[11] between the $E(2_1^+)$ and $B(E2;2_1^+ \to 0_1^+)$ quantities, one can estimate the quadrupole deformation of a nucleus in its 2_1^+ state from the $E(2_1^+)$ energy. This procedure was used in Refs. [1–3] for ^{76}Sr, ^{80}Zr, and ^{84}Mo, and led to the interesting conclusion that while the first two nuclei are rather strongly deformed ($\varepsilon_2 \approx 0.40$) [1,2], ^{84}Mo should have a smaller deformation ($\varepsilon_2 \approx 0.30$) [3]. Such a conclusion is however limited by the uncertainty on the validity (or degree of accuracy) of the Grodzins relation for such special nuclei, which are rather far from the line of stability.

We can now examine another indicator of nuclear collectivity, namely the ratio $R_{4/2} \equiv E(4_1^+)/E(2_1^+)$. This shows indeed ^{84}Mo as a nucleus with a much lower quadrupole deformation than ^{76}Sr and ^{80}Zr. The later two have a ratio $R_{4/2}$ of about 2.86, whereas ^{84}Mo has $R_{4/2}=2.52$, a value which is typical of transitional nuclei.

This result is in contrast with a recent theoretical investigation within the EXCITED VAMPIR approximation with complex mean fields [12]. This calculation gives in fact a too ‘‘rotational’’ picture of ^{84}Mo, as it predicts a $R_{4/2}$ ratio of about 3.15, compared to the experimental one of 2.52.

Figure 3 shows the evolution of the known first yrast levels in the $N=Z$ nuclei from Ge to Mo. The level scheme gets more compressed with increasing Z, showing a maximum collectivity at Sr and Zr. The trend is clearly reversed in going to Mo.

It is also interesting to see how the yrast line of the $N=Z$ nuclei compares to those of the other even-even nuclei. A very convenient way to do this is to look at the correlation between the $E(4_1^+)$ and $E(2_1^+)$ energies. It was shown that for the collective even-even nuclei with $2.05 < R_{4/2} < 3.15$ and Z between 28 and 50 this correlation is a very tight envelope which is well described by a universal anharmonic vibrator (AHV) with an almost constant unharmonicity: $E(4_1^+) = 2E(2_1^+) + 0.156$ MeV [8]. This average behavior, shown as a straight line in Fig. 4 is very well obeyed by the majority of the known nuclei: the data show a 1σ deviation of only 5% from this line. All $N=Z$ nuclei from ^{52}Fe to ^{84}Mo (except the doubly magic ^{56}Ni) are also shown by symbols in Fig. 4. Erratic deviations from the AHV line are shown only by ^{52}Fe (a ‘‘shell model’’ nucleus [9]) and by ^{72}Kr [10] (where one suspects a shape coexistence). The other $N=Z$ nuclei show a rather systematic behavior, in the sense that all of them lie well above the average AHV line. The largest deviations are shown by Sr, Zr, and Mo (between 70 and 90 keV, the equivalent of about 2σ). This systematic deviation of the $N=Z$ nuclei from the general trend given by the ‘‘normal’’ collective nuclei is rather intriguing. It could be a special fingerprint of the nuclear structure along the $N=Z$ line, so that it remains an interesting open question whether the rest of the $N=Z$ nuclei above $Z=42$ show the same behavior.

In summary, in an experiment performed with the GASP

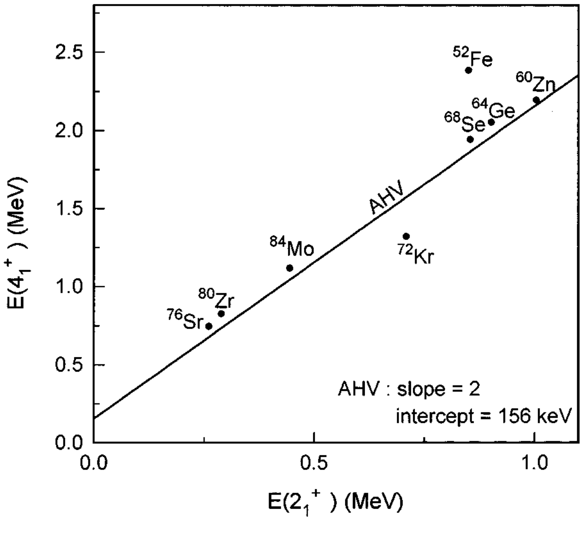

FIG. 4. Correlation between the $E(4_1^+)$ and $E(2_1^+)$ energies for the $N=Z$ nuclei between $Z=28$ and $Z=42$ (symbols). The straight line shows the average AHV behavior of the collective even-even nuclei [8] (a straight line of slope 2 and intercept 156 keV).

array and the ISIS Silicon ball we were able to assign the second yrast transition of ^{84}Mo, which has an energy of 673.5±0.4 keV. This gives clear evidence that the collectivity (or the nuclear deformation) decreases very rapidly along the $N=Z$ line as one departs from the strongly deformed nuclei at $N=Z=38$ or 40 towards ^{100}Sn. In addition, one can follow now the evolution of the correlation between the energies of the 2_1^+ and 4_1^+ states for all even-even $N=Z$ nuclei from $Z=26$ to $Z=42$. It appears that all the collective nuclei of this kind, from Zn to Mo, deviate systematically with respect to the average universal anharmonic vibrator behavior defined by the collective nonrotor nuclei known up to now. It is an interesting question whether this is a signature of the special interactions at work in the $N=Z$ nuclei.

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