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High-spin states in ^{94}Tc and the shell-model interpretation

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High-spin states in the $N = 51$ nucleus ^{94}Tc have been investigated with γ-ray spectroscopic techniques following the reactions ^{66}Zn(^{31}P,$2pn$)^{94}Tc and ^{65}Cu(^{36}S,$\alpha 3n$)^{94}Tc. Shell-model calculations have been performed. The excitation of a single neutron across the $N = 50$ core adequately describes the observed high-spin states in ^{94}Tc.

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It is possible to understand the low-lying levels in nuclei near and at the neutron magic number $N = 50$, by taking ^{88}Sr as the core and the valence nucleons occupying the ($1p_{1/2}$, $0g_{9/2}$) configuration space [1,2]. However, to describe the high-spin states in these nuclei, an enlarged configuration space is required. Breaking of the $N = 50$ neutron core is another plausible mechanism to generate high-spin states in these nuclei [3]. A systematic investigation of the nuclei in this region is very important for the understanding of the nature of the high-spin states near the $N = 50$ closed shell. Another motivating factor to study these nuclei is that they form the neutron equivalent of the nuclei near the $Z = 50$ closed shell where a number of deformed intruder bands have been observed in recent years (see, for example, [4,5]). In this paper we report our study of the ^{94}Tc nucleus; this is part of a detailed investigation of the interplay between shell and collective structures at and near the $N = 50$ closed shell. We have extended the level scheme of ^{94}Tc up to 20^- in the negative parity band. Shell-model calculations have been performed and we have found that these calculations adequately describe the observed high-spin states in ^{94}Tc.

High-spin states in ^{94}Tc were populated using the reaction ^{66}Zn(^{31}P,$2pn$)^{94}Tc at a beam energy of 115 MeV. The ^{31}P beam was provided by the 15 UD Pelletron Accelerator at the Nuclear Science Centre (NSC), New Delhi. The isotopically enriched (99%) ^{66}Zn target had a thickness of about 1.2 mg/cm^2 on a 25 mg/cm^2 Pb backing. γ-γ coincidences were measured using the gamma detector array (GDA) [3] at NSC which, at the time of this experiment, comprised of 6 Compton-suppressed high-purity germanium detectors (CSG) and a 14-element bismuth germanate (BGO) multiplicity filter. A total of about 25×10^6 events corresponding to two or higher-fold coincidences (within a system timing resolution of 40 ns) were recorded in the list mode.

The data was sorted into an E_γ-E_γ matrix for a detailed off-line analysis. From the processed data, background subtracted one-dimensional histograms for γ energies in one detector gated by a suitable transition in the other detector were generated. Multipolarities of the observed γ rays were assigned using the procedure described in [3,6].

In a complementary experiment, high-spin states in ^{94}Tc were also populated with the ^{65}Cu(^{36}S,$\alpha 3n$)^{94}Tc reaction, at beam energies of 135 and 142 MeV. The ^{36}S beam was provided by the ATLAS system at the Argonne National Laboratory. A 0.9 mg/cm^2 thick ^{65}Cu target with a 15.5 mg/cm^2 thick gold backing was used, and γ rays were detected with the Argonne–Notre Dame BGO γ-ray facility which contains 12 CSG's located at 34°, 90°, and 146°, with respect to the beam direction, and a fifty-element BGO array for multiplicity selection. Approximately 135×10^6 events with a prompt array multiplicity $K \geq 4$ were recorded. The strongest reaction products in the observed data were the $^{96-98}$Ru isotopes which are the subject of a separate investigation [7]. The same set of E_γ-E_γ ($K \geq 8$ and $K \geq 15$) coincidence matrices as reported in [7] also were used for the off-line analysis in the present work because they were "selective" for the high-spin states in the Tc nuclei as well. In the matrix containing the $K \geq 8$ events, for example, approximately 20% of the total number of events belonged to the various Tc nuclei. A detailed γ-γ coincidence analysis of the ATLAS data confirmed the level scheme for ^{94}Tc obtained from the NSC data including spin assignments of the levels on the basis of the measured differential correlation orientation (DCO) ratios in accordance with the definition given in [8]. A representative γ-γ coincidence spectrum from the ATLAS data, gated on the 185 keV ($10^- \rightarrow 9^-$) transition, is shown in Fig. 1 and representative DCO ratios from the same data are displayed in Fig. 2; the dotted lines in Fig. 2 correspond to the best fits for the DCO ratios of the previously known quadrupole and dipole transitions.

The level scheme for ^{94}Tc is shown in Fig. 3. The low lying levels of ^{94}Tc are well established [9–11]. We have observed 6 new transitions which have been placed in the decay scheme on the basis of coincidence relationships and intensity arguments. Four of the new transitions have been observed in coincidence with those in the known negative parity "band." They are, in order of increasing energy: 355, 366, 704, and 1105 keV. Based on the DCO ratios, all these transitions have been as-

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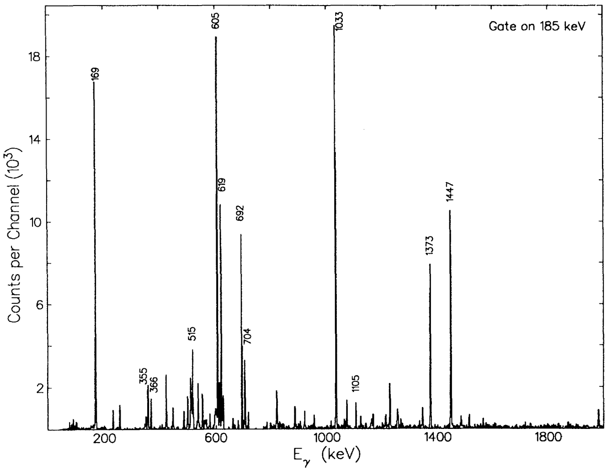

FIG. 1. γ-γ coincidence spectrum, gated on the 185 KeV ($10^- \rightarrow 9^-$) transition. The energies of the γ rays placed in the level scheme of ^{94}Tc are labeled.

signed an $M1$ character. In addition, we have observed a weak 1228-keV transition which is in coincidence with the negative parity "band"; this transition, however, was too weak to enable us to draw definite conclusions about its multipolarity. All these transitions have been placed above the $I = 15^-$ level. The level scheme of ^{94}Tc has, thus, been established tentatively up to a spin of $I = 20^-$. We also have observed a 90 keV ($15^- \rightarrow 14^+$) transition connecting the positive and negative parity structures. Incidentally, Behar *et al.* [11] had reported a 90-keV transition but were unable to place it in the level scheme, Lee *et al.* [9], on the other hand, had not observed this transition at all. In light of the unavailability of correct parity information from DCO data and of the tentative assignment of 8^+ for the 1447-keV level by Behar *et al.* [11], all parity assignments for the negative parity structure have to be taken as tentative and, therefore, have been shown in parentheses in Fig. 3.

No new transitions have been observed in the positive parity "band." Lee *et al.* [9] had reported the observation of an 882-keV γ ray in coincidence with the 515-, 606-, 1033-, 168-, 186-, 619-, and 1447-keV transitions and had placed the 882-keV transition above the 515-keV transition; this 882-keV transition has not been observed in the present experiments. We do, however, see a weak 879-keV ($10^- \rightarrow 9^+$) transition. The placement of this and the 1228-keV transition in the level scheme is tentative; these are, therefore, indicated by "dashed" lines. In addition, we have cleared the existing discrepancy regarding the ordering of the 168-keV (169 keV in our case) and 185-keV transitions and confirmed the assignment of Lee *et al.* [9]. The 169-keV transition evidently is a doublet; but, there also is an identical transition belonging to the nucleus ^{95}Rh and, hence, the second 169-keV transition could not be placed reliably in the level scheme.

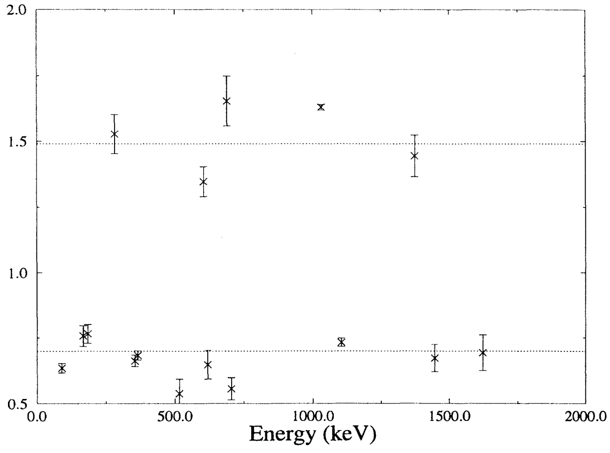

FIG. 2. DCO ratios for a number of γ rays belonging to ^{94}Tc. The upper and lower dotted lines represent best fits to the known quadrupole and dipole transitions, respectively.

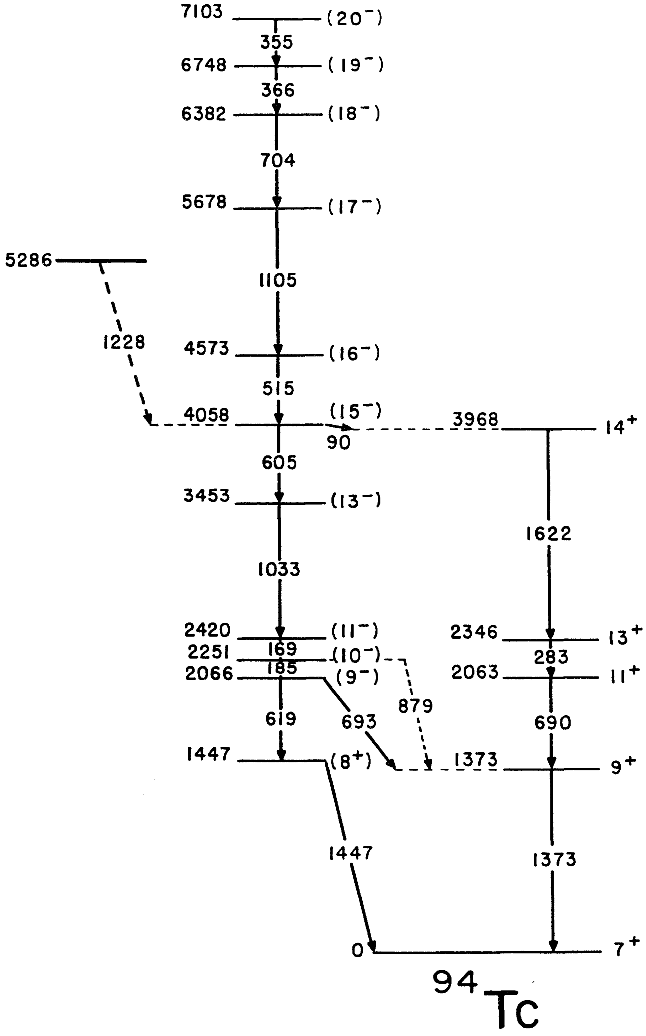

FIG. 3. Level scheme of ^{94}Tc as obtained in the present work. The tentatively placed transitions are indicated by "dashed" lines.

Adamides *et al.* [10] had performed shell-model calculations using the $\pi(0g_{9/2})$ and $\nu(1d_{5/2}, 2s_{1/2}, 0g_{9/2})$ orbits outside ^{90}Zr as the inert core. The calculations were performed with two effective interactions derived from the Sussex and Yale bare interactions, by considering second-order corrections evaluated in the space of $2\hbar\omega$ excitations. However, the model space chosen in Ref. [10] was not adequate to describe the observed level structure of ^{94}Tc for the following reasons: (i) Extensive shell-model calculations for low-lying levels in the nuclei near the magic number $N = 50$ [1,2] have established that the $\pi(1p_{1/2}, 0g_{9/2})$ model space outside ^{88}Sr as the inert core is essential to adequately describe the observed level structure up to moderate spins in this mass region [for the $N = 51$ nuclei, for example, the $\pi(1p_{1/2}, 0g_{9/2})$ and $\nu(d_{5/2}, 2s_{1/2})$ orbitals were quite sufficient to describe the observed level structure up to $I \sim 14$ [12]]; and, (ii) within the model space used by Adamides *et al.* [10], it would not be possible to generate negative parity states which have been observed in ^{94}Tc.

Spherical shell-model calculations using the code OXBASH [13] were carried out for ^{94}Tc with ^{88}Sr as the core and the $\pi(1p_{1/2}, 0g_{9/2})$, $\nu(1d_{5/2}, 2s_{1/2})$ orbits. The two-body matrix elements (TBME) were taken from the Gloeckner-Lawson interaction [14]. Within this restricted model space, the maximum angular momenta possible for ^{94}Tc (with 5 valence protons and 1 valence neutron outside ^{88}Sr of the core) are $I = 15^-$ and 14^+. Figure 4 shows the comparison of the experimental excitation energies and the shell-model predictions; indeed, there is a good agreement between the two up to $I = 15^-$ and 13^+. We also note that a good agreement exists between our results and those of Adamides *et al.* [10] for the even parity states.

There are two mechanisms by which the observed higher angular momentum states can be generated for these nuclei within the framework of the shell model: (i) use of an enlarged proton space; and, (ii) the excitation of a single neutron across the $N = 50$ core. Consequently, a model space that encompasses a large proton space and also allows for the excitation of a neutron across the $N = 50$ core would be expected to adequately describe the higher angular momentum states in these nuclei. However such large-basis shell-model calculations were beyond the scope of this investigation due to the large dimensionality of the matrices involved. A truncation scheme had, therefore, to be devised to make these calculations feasible; the details of this procedure are described in Refs. [15,16]. Calculations were performed within a model space which had ^{66}Ni as the core, and the $\pi(0f_{5/2}, 1p_{3/2}, 1p_{1/2}, 0g_{9/2})$ and $\nu(1p_{1/2}, 0g_{9/2}, 0g_{7/2}, 1d_{5/2}, 1d_{3/2}, 2s_{1/2})$ orbits. This model space was code named GWB in OXBASH [13]. The 974 TBME of the interaction were generated from the bare G matrix of Hosaka *et al.* [17]. Within the model space, the TBME for the $\pi(0f_{5/2}, 1p_{3/2})$ orbits were taken from the Ji and Wildenthal interaction [18], and the TBME connecting the $\pi(1p_{1/2}, 0g_{9/2})$ and $\nu(1d_{5/2}, 2s_{1/2})$ orbits were taken from the Gloeckner and Lawson interaction [14]. Further, the TBME for the $\pi(1p_{1/2}, 0g_{9/2})$ and $\nu(1p_{1/2}, 0g_{9/2})$ orbits were taken from the Serduke, Lawson, and Gloeckner interaction [19] while those connecting the $\pi(1p_{1/2}, 0g_{9/2})$ and $\pi(1p_{1/2}, 0g_{9/2})$ orbits were taken from the Gloeckner and Lawson interaction [14].

Figure 5 shows the comparison of the shell-model predictions (with neutron core excitation) with the experimental excitation energies. Large discrepancies between the theoretical and experimental levels still remain for the states above $I = 15^-$. In the single particle picture,

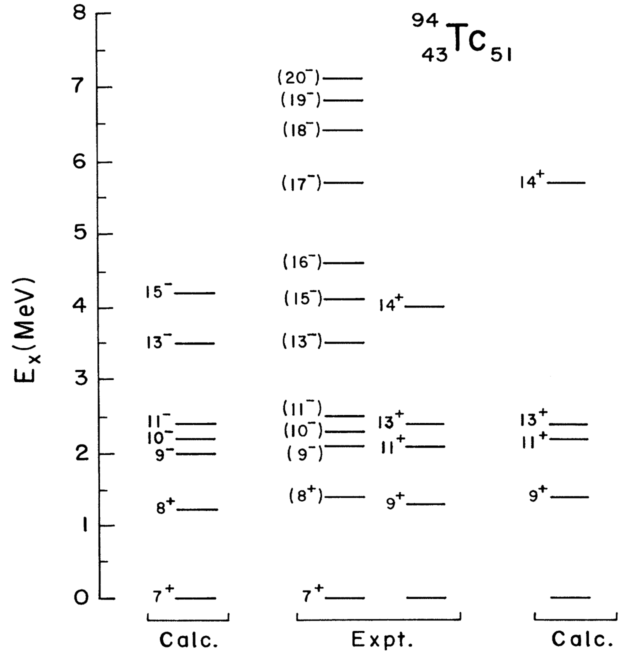

FIG. 4. Comparison of experimental and calculated energy levels in ^{94}Tc using a restricted model space (see text).

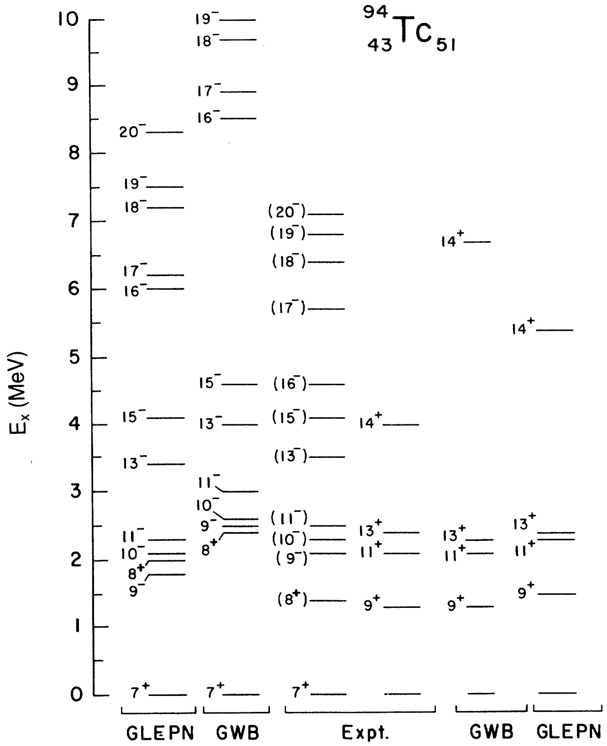

FIG. 5. Same as Fig. 4 but for calculations involving neutron core excitation. GWB and GLEPN refer to calculations performed using ^{66}Ni and ^{56}Ni as the inert core, respectively.

the excitation of a neutron across the $N = 50$ core requires an excitation energy of the order of 7–8 MeV. The reduction of this excitation energy to $\sim$ 2–3 MeV in this mass region is attributed to many-body correlations. To properly account for these correlations, it is imperative to perform these calculations within an enlarged model space, including both proton and neutron core excitations. Such calculations were performed using ^{56}Ni as the closed core, and the ($0f_{5/2}$, $1p_{3/2}$, $1p_{1/2}$, $0g_{9/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$) proton and neutron orbits with the model space and effective interactions code named GLEPN in OXBASH [13]. As seen from Fig. 5, there is rather good agreement between the experimental excitation energies and the predictions of these "extended" calculations. A careful comparison with the occupation numbers indicated that although the GLEPN matrix elements allowed both the proton and neutron core excitations, the yrast eigenstates were predominantly due to neutron core excitation only. The apparent anomaly between the GWB and GLEPN matrix elements must, therefore, be due to the slight difference in many-body correlations between the two sets of matrix elements.

To summarize, we have observed the high-spin structures of the nucleus ^{94}Tc using γ-ray spectroscopic methods following heavy-ion fusion evaporation reactions and compared the resultant level schemes with shell-model calculations with different model spaces. The excitation of a single neutron across the $N = 50$ core into the next major oscillator shell appears to adequately describe the observed higher angular momentum states in ^{94}Tc. Shell model calculations, performed using two model spaces (GWB and GLEPN) show discrepancies that may be attributed to (i) the effective interactions used in the calculations, since the effective interactions were model-space dependent; and, (ii) omission of certain dominant configurations in our calculations.

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