第28卷 第9期
2004年9月

高 能 物 理 与 核 物 理
HIGH ENERGY PHYSICS AND NUCLEAR PHYSICS

Vol.28, No.9
Sep., 2004

Level Scheme of ^{94}Mo at High Angular Momentum *

ZHANG Yu-Hu[1;1)] LIU Min-Liang[1,2] G.de Angelis[3,4] Zs.Podolyak[5] GUO Wen-Tao[1]
A.Gadea[3] C.Ur[6] N.Marginean[3] C.Rusu[3] R.Schwengner[7] D.R.Napoli[3] R.Menegazzo[6] S.Lunardi[6]
D.Bazzacco[6] T.Martinez[3] M.Axiotis[3] A.Gargano[8] S.M.Lenzi[6] F.Brandolini[6] W.von Oertzen[4,9]

1(Institute of Modern Physics, CAS, Lanzhou 730000, China)
2(Graduate School, Chinese Academy of Sciences, Beijing 100039, China)
3(Istituto Nazionale di Fisisca Nucleare, Laboratori Nazionali di Legnaro, Legnaro, Italy)
4(Hahn-Meitner-Institut, Berlin, Germany)
5(Department of Physics, University of Surrey, Guildford, Surrey, United Kingdom)
6(Dipartimento di Fisica dell'Universitá and Istituto Nzaionale di Fisica Nucleare, Sezione di Padova, Padova, Italy)
7(Institut für Kern-und Hadronenphysik, Forschungszentrum Rossendorf, Dresden, Germany)
8(Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, Napoli, Italy)
9(Freie Universität Berlin, Fachbereich Physik, Berlin, Germany)

Abstract High-spin level structure of ^{94}Mo has been re-investigated using the modern multidetector array of GASP via the ^{16}O(^{82}Se, 4nγ)^{94}Mo reaction at E(^{82}Se) = 459 MeV. The previously reported level scheme has been largely modified up to ~ 10 MeV in excitation energy due to identifications of some important linking transitions. The level structure of ^{94}Mo has been compared with the shell model calculations. It is suggested that the valence neutron excitation within $d_{5/2}$, $g_{7/2}$, and $h_{11/2}$ orbitals should be taken into account in order to adequately describe the high-spin level structure of ^{94}Mo above $I^{\pi} = 14^{+}$.

Key words level scheme, high-spin states, shell model calculations

1 Introduction

The ^{94}Mo nucleus($Z = 42$, $N = 52$) has four valence protons and two valence neutrons outside the neutron($N = 50$) and proton($Z = 38$) subshell closure, and it is expected to be spherical with similar level structures with neighboring nuclei that can be interpreted in terms of shell model calculations. Actually. it has been shown[1,2] that the low-lying levels of nuclei with $N = 50$ are dominated by the proton excitations within the $\pi(p_{1/2}, g_{9/2})$ or $\pi(f_{5/2}, p_{3/2}, p_{1/2}, g_{9/2})$ orbitals. The medium spin levels in the $N > 50$ nuclei can thus be understood as the neutron excitations within the $\nu(d_{5/2}, s_{1/2}, g_{7/2}, h_{11/2})$ orbitals coupled to the valence proton configurations. Shell model calculations[2,3] have shown that the neutron particle-hole excitation across the $N = 50$ shell gap must be taken into account in order to adequately describe the high-spin level structure of nuclei in the $N \approx 50$ region. Experimental investigations of high-spin level structures in these nuclei can provide information on the interplay between proton and neutron excitations across the subshell closure at $Z = 38$ and $N = 50$.

The high-spin states of ^{94}Mo were investigated a long time ago by Lederer et al[4]. via the(α, xnγ) reactions. The level scheme has been extended recently up to $I \approx 16$ at 12 MeV excitation energy by Kharraja and co-workers[5] using a heavy-ion induced fusion-evaporation reaction and the early implementation phase of the Gammasphere array. In a recent experiment in GASP devoted to study the level structures of

---

Received 2 January 2004

* Supported in part by the National Natural Sciences Foundation(10025525, 10375007, 10221003), the Major State Basic Research Development Program of China(G2000077402) and the Chinese Academy of Sciences

1) E-mail: yhzhang@ns.lzb.ac.cn

neutron-rich nuclei in the ^{82}Se + ^{192}Os collision system, numerous γ rays emanating from ^{94}Mo have been detected. This is due to the oxidization of the thick ^{192}Os target; the ^{16}O(^{82}Se, 4nγ)^{94}Mo fusion-evaporation reaction populated the high-spin states of ^{94}Mo. Although, the production yield for the ^{94}Mo isotope was rather low, important information could be extracted with the help of high detection sensitivity of the modern multidetector array of GASP. This paper presents the high-spin level scheme of ^{94}Mo in which some important modifications have been made. The revised level scheme seems to be in a better agreement with theoretical predictions.

2 Experimental details and results

The high-spin states in ^{94}Mo were populated via the ^{16}O(^{82}Se, 4nγ)^{94}Mo reaction at a bombarding energy of 459.3 MeV. The ^{82}Se beam was provided by the accelerator complex of the Tandem-XTU and ALPI at the Laboratori Nazionali di Legnero, Italy, and focussed on an isotopically enriched ^{192}Os target of 60 mg/cm^2 thickness. The emitting γ rays from the reaction products were detected by the multidetector array of GASP which consists of 40 Compton suppressed large volume Ge detectors and a multiplicity filter of 80 BGO elements. The energy and efficiency calibrations were made using ^{56,60}Co, ^{133}Ba, and ^{152}Eu standard sources. Typical energy resolutions were about 2.0 —2.5 keV at *FWHM* for the 1332.5 keV line. Events were collected when at least three suppressed Ge and two inner multiplicity filter detectors were fired. With this condition about 1.5×10^9 coincidence events were recorded. After gain matching, the data were sorted into fully symmetrized matrices and cubes for off-line analyses.

The coincidence events with one γ ray detected in one of the 12 detectors placed at 31.7°, 36°, 144°, and 148.3° (average angle is 34°/146° relative to the beam direction) and the other one detected in one of the 8 detectors at 90° were sorted into an asymmetric matrix. The γ ray intensities $I_\gamma(34°)$ and $I_\gamma(90°)$, used to determine the DCO ratios $R_{\rm DCO} = I_\gamma(34°)/I_\gamma(90°)$, were extracted from the coincidence spectra by setting gates on the 90° and 34° axis of the above-mentioned asymmetric matrix. In the GASP geometry, stretched quadrupole transitions were adopted if $R_{\rm DCO}$ values were close to unity, and dipole ones were assumed if $R_{\rm DCO} \approx 0.5$ using the stretched quadrupole transitions as the gates. The DCO ratios depend on the multipolarity of the gating transitions[6], therefore, γ-ray anisotropies have been analyzed and extracted from the coincidence data. This method has been described in Ref.[7]; the advantage of this method is that the extracted γ-ray anisotropies were not sensitive to the multipolarities of the gating transitions. Multipolarity information for the emitting γ rays has been cross-checked using the two techniques. However, one has to keep in mind that the uncertainties still exist for the spin assignments on the basis of γ-ray anisotropy and DCO ratio analyses. The stretched quadrupole transitions cannot be distinguished from $\Delta I = 0$ dipoles or certain mixed $\Delta I = 1$ transtions. In such cases, crosschecks from the parallel transitions and their branching ratios provide supplementary arguments for the spin and parity assignments. In fact, the combination of the high statistics and the superior efficiency for three-and higher-fold coincidence events make it possible to identify many weak γ transitions. The selectivity power of double-gating technique and presence of crossover transitions provide many checks for the multipolarity, placement and ordering of transitions in the proposed level scheme.

From the detailed analyses of γ-ray coincidence relationships in the double-gated spectra, the level scheme of ^{94}Mo has been established and shown in Fig.1. Two representative double-gated coincidence spectra are given in Fig.2. The present level scheme is consistent with the result of Kharraja et al[5]. below the (12^+) and (13^-) levels. In addition, several new transitions of energy 504, 671, 1140, 1168, and 1307 keV connecting the negative-and positive-parity levels have been newly identified due to the high statistics of the data. These new transitions can be clearly seen in Fig.2. The 449 keV line de-exciting the second 6^+ level[4], which was not observed in Ref.[5], has been confirmed in this work. The extracted $R_{\rm DCO}$ values for the linking transitions support the spin and parity assignments of Refs.[4,5]. Based on the DCO ratio analyses, we have assigned an E2 multipolarity for the 1168 and 1307 keV γ rays, and an E1 transition for the 504 and 485 keV lines. These assignments lead to an identification of the second (8^+) and (10^+) levels at 3591 and 4262 keV excitations, respectively. The assignment of (10^+) to the 4262 keV level is further supported by the 366 keV, $\Delta I = 0$ dipole transition.

For the positive parity levels above the (12^+) state, some important modifications have been made in the present level scheme as compared with the previous work of Kharraja et al[5]. First, the 1609, 1060, 973, and 714 keV transitions were found to be quadrupole rather than dipole ones as proposed in Ref.[5]. Second, the ordering of γ rays in the intense 241-442-791-1244 transition sequence has been changed

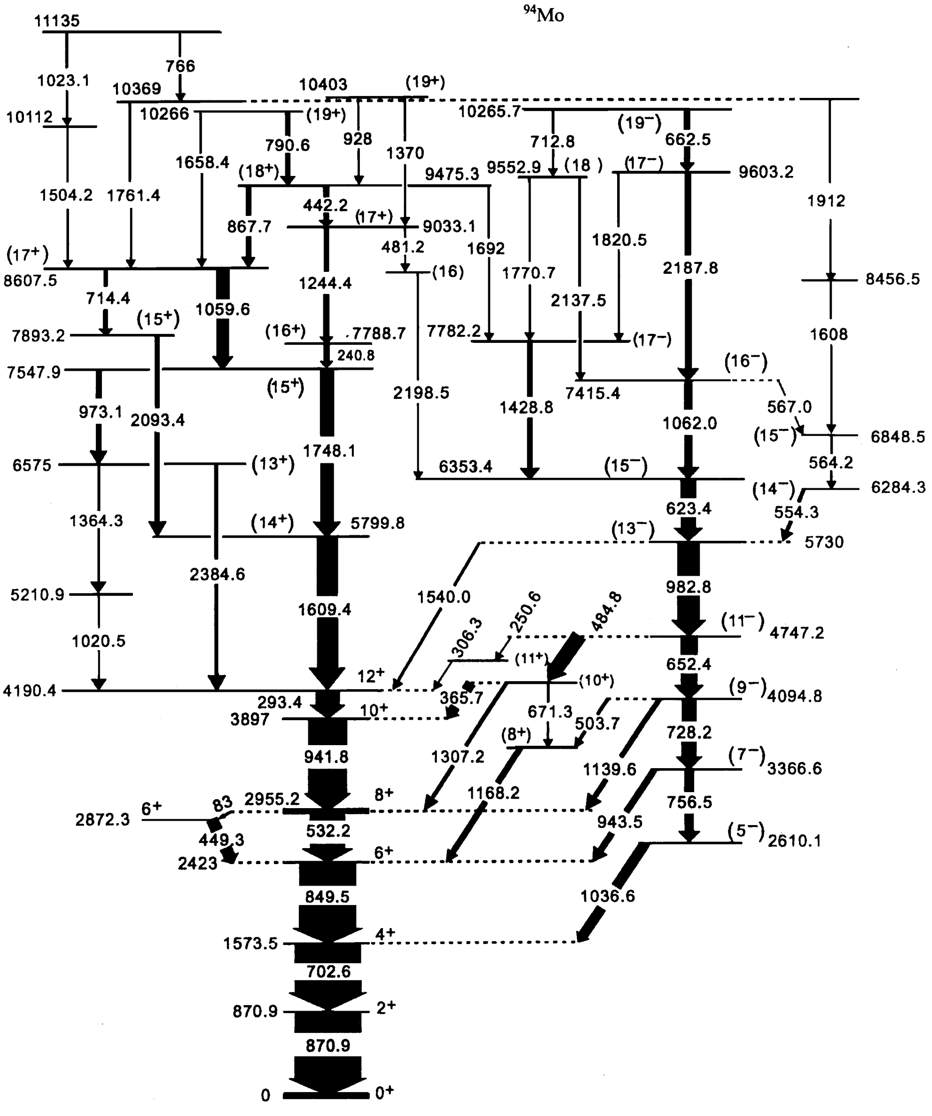

Fig. 1.　Level scheme of ^{94}Mo deduced from the present work.

in the present level scheme; this is supported by the observation of a new dipole (868 keV) and a new quadrupole (1658 keV) crossover transitions. Furthermore, the 1341 and 1740 keV lines[5] have not been observed in this work, and the 1367 keV line could be the 1370 keV γ ray observed in our data; the energy and the placement of this line in the level scheme $(19^+) \rightarrow (17^+)$ are supported by the new 928 keV $(19^+) \rightarrow (18^+)$ transition. The 1609 keV line seems to be a triplet; two of them have been assigned in the level scheme, and the third one may feeds to the yrast (19^+) at 10266 keV since it appears in the coincidence spectra shown in Fig. 2.

The cascade γ rays of energy 623, 663, 1062 and 2188 keV have been assigned to the present level scheme feeding the negative parity levels. The ordering of these transitions is quite different from that proposed in Ref. [5]. One can see from the double-gated spectrum of Fig. 2(a) that the 623 keV transition is much stronger than the 663 keV line. Therefore we have placed this line to feed directly to the (13^-) level and the latter on top of this cascade. This placement is strongly supported by several crossover transitions shown in Fig. 1. On the other hand, the R_{DCO} values for the 623 and 663 keV lines are consistent with those of pure $\Delta I = 2$ quadrupole transitions, it is reasonable to assign these two lines as the $(15^-) \rightarrow (13^-)$ and $(19^-) \rightarrow (17^-)$ transitions, respectively.

Finally, it is worth noting that the γ-ray energies measured in this work were found different up to 4 keV from the previous results[5]; for example the previously reported 2389 keV line should be the 2384.6 keV γ ray observed in this work. Numerous γ rays emitted from the target-like, projectile-like, and fusion-evaporation residues have been identified, and

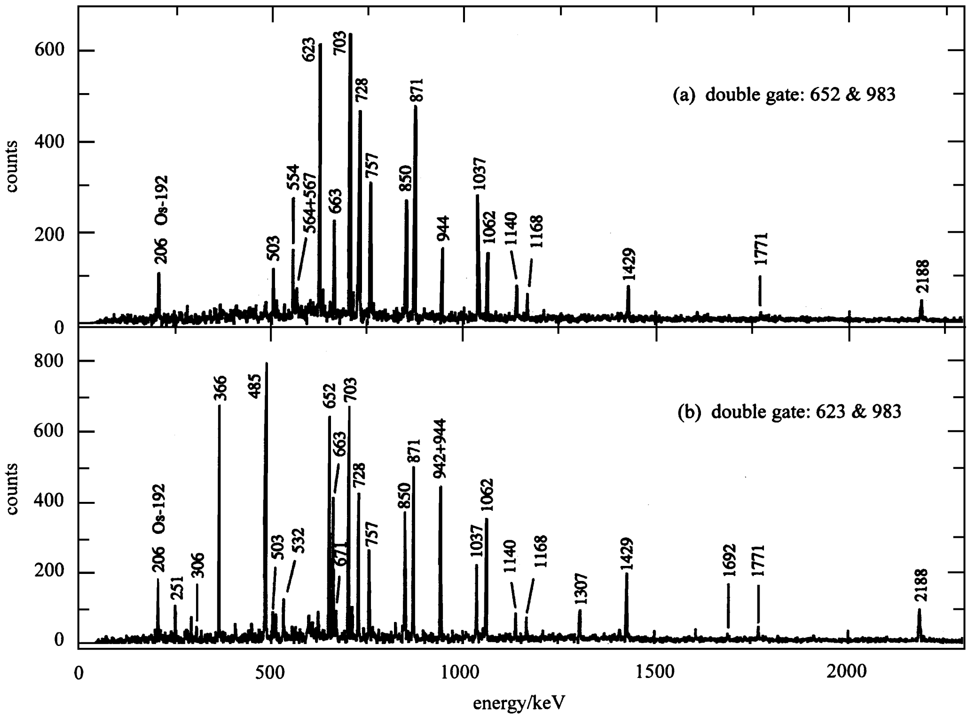

Fig.2. Representative double-gated coincidence spectra for ^{94}Mo.

their energies determined in this work are consistent with the adopted values within an uncertainty of 0.5 keV. The larger uncertainties in γ-ray energies of Ref.[5] may be due to the thin target used in their experiment.

3 Discussion

As the ^{94}Mo nucleus has two valence neutrons outside the $N = 50$ shell closure, the excited level structure can be described by the simple shell-model configurations. Given the reduced $2^+ \rightarrow 0^+$ energy spacing in ^{94}Mo with respect to $E_\gamma(2^+ \rightarrow 0^+) = 1510$ keV in ^{92}Mo[8], one has attributed the first 2^+ and 4^+ states to the seniority-2 neutron$(\nu d_{5/2})^2_{2^+,4^+}$ configuration. The first 6^+ state at 2423 keV was assigned to the $(\nu d_{5/2})(\nu g_{7/2})_{6^+}$ excitation[4] based on the low log*ft* value for the β^+/EC decay from the $(\nu d_{5/2})(\pi g_{9/2})_{7^+}$ ground state of ^{94}Tc. The next 6_2^+ at 2872 keV and the 8_1^+ could be related to the predominant proton configuration$(\pi g_{9/2})^2_{8^+,6^+}$. The g-factor of the first 8^+ in ^{94}Mo has been measured[9] to be 1.317 ± 0.015; this value is close to the ones for the first 8^+ in ^{90}Zr and ^{92}Mo, and the $9/2^+$ in ^{93}Nb indicating that the only components of non-zero seniority in the dominant configuration of these levels are of $g_{9/2}$ protons. To form the higher spin states shell model configurations of seniority-4 should be involved; the yrast 10^+ and 12^+ levels may correspond most probably to the $(\pi g_{9/2})^2(\nu d_{5/2})^2$ configuration.

Shell model calculations had been performed earlier by Lederer et al[4]. under a limited configuration of $(\pi p_{1/2})^2(\pi g_{9/2})^2 \otimes (\nu d_{5/2})^2$. The calculated results are compared with experiment in Fig.3. One can see that the newly identified 8_2^+, 10_2^+, and 11_1^+ states are in very good agreement with the theoretical predictions both in level ordering and spacing. The high-spin level structure of ^{94}Mo has been investigated recently by Kharraja and co-workers using the Code OXBASH[5], taking ^{88}Sr as the inert core and the model space of$[\pi(p_{1/2}, g_{9/2});\nu(d_{5/2}, s_{1/2})]$. The calculated results are presented in Fig.3 from which good agreement between theory and experiment can be found up to 16^+ and 15^- if the present spin-assignments are accepted. The yrast 14^+ level could not be reproduced by this theory. This discrepancy could be attributed to the contributions which were not incorporated in this restricted model space. Given single particle excitation energies[10,11] of $E_x(\nu(d_{5/2}) = 0, E_x(\nu(g_{7/2}) = 766$ keV, and the $(\pi g_{9/2})^2_{8^+}(\nu d_{5/2})^2_{4^+}$ configuration for the lowest 12^+ level, the yrast 14^+ state could be generated predominantly by the $(\pi g_{9/2})^2_{8^+}(\nu g_{7/2})^2_{6^+}$ (with possible admixture of$(\pi g_{9/2})^2_{8^+}(\nu d_{5/2}\nu g_{7/2})^2_{6^+}$) configuration. The excitation energy for such a fully aligned 4-particle state may be estimated as $E_x = 2 \times E_x(\nu g_{7/2}) = 1532$ keV. This is consistent with the experimental observation that the 14^+ state is 1609 keV higher than the

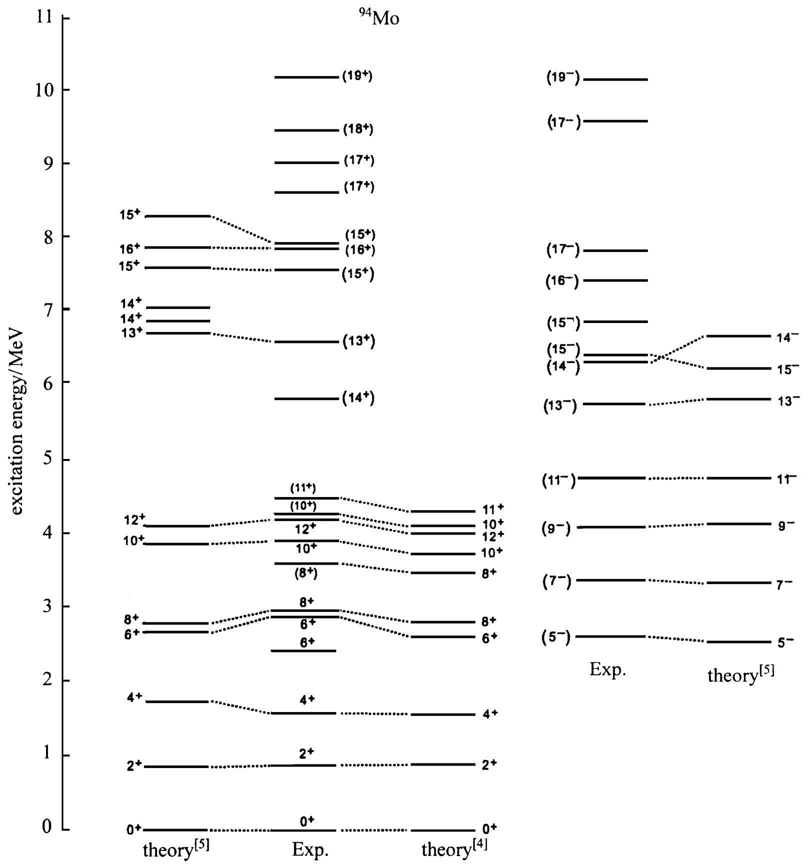

Fig. 3.　Comparison of level structure of ^{94}Mo with simple shell model calculations of Refs. [4,5].
See text for details.

12^+ level. Same mechanism of $\nu d_{5/2} \rightarrow \nu g_{7/2}$ neutron excitations may be involved for generating the yrast levels up to 18^+ and 17^-. In fact, with the limited configuration space of $[\pi(p_{1/2}, g_{9/2}); \nu(d_{5/2}, s_{1/2})]$, the maximum angular momentum for ^{94}Mo (with four valence protons and two valence neutrons) is $I^\pi = 16^+ (15^-)$ for positive-parity (negative-parity) levels. The $\nu d_{5/2} \rightarrow \nu g_{7/2}$ neutron excitation in ^{94}Mo may easily provide 2 angular momentum unit leading to the maximum angular momentum up to $I^\pi = 18^+ (17^-)$.

It has been pointed out that the $\nu g_{9/2}^{-1}$ neutron-hole excitation across the $N = 50$ shell gap is responsible for generating the higher-spin states for the $N \approx 50$ nuclei[2,3,5]. Theoretical calculations show that the excitation of a single neutron across $N = 50$ gap comes to play for the levels above $I^\pi = 12^+$ and 14^- in ^{92}Mo and ^{94}Ru[2]. The same interpretation has been proposed for ^{94}Mo[5]; this seems not consistent with our interpretation. In fact, if the core-breaking dominate the level structure above $I^\pi = 12^+$ in ^{92}Mo, the two extra $d_{5/2}$ neutrons in ^{94}Mo could easily provide 4 angular momentum unit, and thus augment the critical spin up to $I = 16$. Furthermore, this critical spin can reach to 18^+ and 17^- if the $\nu d_{5/2} \rightarrow \nu g_{7/2}$ neutron excitations are involved. Good agreement between theory and experiment (see Fig. 3) seems to suggest that the single neutron excitation across the $N = 50$ shell gap may not dominate the high-spin level structures up to 18^+ at ~ 9 MeV. We did observe a gap of about 2 MeV for the negative parity level at ~ 9 MeV and several parallel high-energy γ transitions. This has been regarded as the indication of a $\nu g_{9/2}^{-1}$ neutron-hole excitation (or the $N = 50$ shell breaking). However, one has to note the fact that the predicted energy gap is much larger than 2 Mev[5] observed in ^{94}Mo and the $h_{11/2}$ neutron orbital was not practically included in their theoretical calculations[1,2]; the valence neutron excitation in the $h_{11/2}$ orbital might be important for generating the higher-spin levels in ^{94}Mo.

4 Summary

The high-spin states of ^{94}Mo has been re-investigated in a thick-target experiment of the heavy-ion-induced ^{16}O(^{82}Se, 4nγ)^{94}Mo fusion-evaporation reaction. With the help of high

detection sensitivity of the multidetector array of GASP and the double-gating technique, a much revised level scheme of ^{94}Mo has been constructed. The level structure has been compared with the shell model calculations within the limited model space of $[\pi(p_{1/2}, g_{9/2}); \nu(d_{5/2}, s_{1/2})]$. It is found that the observed yrast levels up to 16^+ and 15^- can be well reproduced with only an exception of the first 14^+. This yrast state may be understood, at least qualitatively, when considering the $\nu d_{5/2} \rightarrow \nu g_{7/2}$ valence neutron excitation. Good agreement between simple theory and experimental observations suggests that the single neutron excitation across the $N = 50$ shell gap may not dominate the high-spin level structures up to 18^+, 17^-. Instead, the valence neutron excitation within the $d_{5/2}$, $g_{7/2}$ and $h_{11/2}$ orbitals may play an important role in generating high-spin states above 16^+ and 15^-.

References

1 JI Xian-Dong, Wildenthal B H, Phys. Rev., 1988, **C37**: 1256

2 Ghugre S S, Datta S K. Phys. Rev., 1995, **C52**: 1881

3 Kharraja B, Ghugre S S, Garg U et al. Phys. Rev., 1998, **C57**: 83

4 Lederer C M, Jaklevic J M, Hollander J M. Nucl. Phys., 1971, **A169**: 449

5 Kharraja B, Ghugre S S, Garg U et al. Phys. Rev., 1998, **C57**: 2903

6 Petrache C M, Bazzacco D, Lunardi S et al. Nucl. Phys., 1996, **A597**: 106

7 ZHANG Y H, Oshima M, Toh Y et al. Phys. Rev., 2003, **C68**: 054313

8 Singh P, Pillay R G, Sheikh G A et al. Phys. Rev., 1992, **C45**: 2161

9 Faestermann T, Feilitzsch F, Raghavan R S et al. Z. Phys., 1975, **A273**: 157

10 Lederer C M, Jaklevic J M, Hollander J M. Nucl. Phys., 1971, **A169**: 489

11 Mesko L, Nilsson A, Hjorth S A et al. Nucl. Phys., 1972, **A181**: 566

^{94}Mo高自旋态能级纲图*

张玉虎[1;1)] 柳敏良[1,2] G. de Angelis[3,4] Zs. Podolyak[5]
郭文涛[1] A. Gadea[3] C. Ur[6] N. Marginean[3] C. Rusu[3] R. Schwengner[7]
D. R. Napoli[3] R. Menegazzo[6] S. Lunardi[6] D. Bazzacco[6] T. Martinez[3]
M. Axiotis[3] A. Gargano[8] S. M. Lenzi[6] F. Brandolini[6] W. von Oertzen[4,9]

1(中国科学院近代物理研究所 兰州 730000)
2(中国科学院研究生院 北京 100039)
3(Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, Legnaro, Italy)
4(Hahn-Meitner-Institut, Berlin, Germany)
5(Department of Physics, University of Surrey, Guildford, Surrey, United Kingdom)
6(Dipartimento di Fisica dell'Universitá and Istituto Nzaionale di Fisica Nucleare, Sezione di Padova, Padova, Italy)
7(Institut für Kern-und Hadronenphysik, Forschungszentrum Rossendorf, Dresden, Germany)
8(Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, Napoli, Italy)
9(Freie Universität Berlin, Fachbereich Physik, Berlin, Germany)

摘要 通过重离子融合蒸发反应^{16}O(^{82}Se+4n)^{94}Mo布局了^{94}Mo核的高自旋态.利用多探头探测器阵列GASP进行了在束γ测量,从而重新研究了^{94}Mo核的高自旋态能级结构.基于新发现的一些重要的连接跃迁,对^{94}Mo核的高自旋态能级纲图做了重要修改.将新的能级结构与壳模型计算进行了比较和讨论.结果表明要正确的描述^{94}Mo核的高自旋态(自旋值大于14)能级结构,应考虑价中子在$d_{5/2}$,$g_{7/2}$和$h_{11/2}$轨道上的激发.

关键词 能级纲图 高自旋态 壳模型计算

2004-01-02收稿

*国家自然科学基金(10025525,10375007,10221003),国家重大基础研究发展规划项目(TG2000077402)和中国科学院资助

1) E-mail: yhzhang@ns.lzb.ac.cn