Observation of a New Isomer in ^{212}Po

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A new isomer has been established in ^{212}Po which decays by α as well as γ-ray emission and probably has spin and parity 8^+. It may consist of a superposition of the $[(\pi h_{9/2}{}^2)_{0^+} \times (\nu g_{9/2}{}^2)_{8^+}]_{8^+}$ and $[(\pi h_{9/2}{}^2)_{8^+}(\nu g_{9/2}{}^2)_{0^+}]_{8^+}$ configurations. From this result conclusions have been drawn about the configuration of the previously known high-spin isomer in ^{212}Po of spin and parity 16^+ or 18^+.

In ^{212}Po a high-spin isomer having a 45.1-s half-life was discovered by Perlman *et al.*[1] in 1962. The isomer decays primarily (> 98.5%, Ref. 1) to the ground state of ^{208}Pb by emitting a (11.66 ± 0.01)-MeV α particle.[2] This α decay is hindered by the very large factor of 4×10^{13} (Ref. 1), indicating that the isomer must have a high spin. From a study of the angular distribution of the recoiling nuclei from the reaction ^{209}Bi(α, p)^{212}Po, Chulick and Natowitz[3] concluded that the spin of the isomer has to be at least 16. Several shell-model calculations[4-8] describing this isomer have appeared in the literature. Configurations, spins, and parities of $[(\pi h_{9/2}{}^2)_{8^+}(\nu i_{11/2}{}^2)_{10^+}]_{18^+}$ (Refs. 4, 5), $[(\pi h_{9/2}{}^2)_{8^+}(\nu g_{9/2}\nu i_{11/2})_{10^+}]_{18^+}$ (Ref. 6), and $[(\pi h_{9/2}{}^2)_{8^+}(\nu g_{9/2}{}^2)_{8^+}]_{16^+}$ (Refs. 7, 8) have been proposed. In some of these theoretical studies, detailed predictions about excitation energies, spins, and parities of low-spin yrast states have been made.[4,6,7] Experimental knowledge about these states may, therefore, allow one to distinguish between these predictions and to obtain a better understanding of the nucleus ^{212}Po. However, to our knowledge, no further experimental information about yrast states in ^{212}Po has appeared in the literature since 1962. The present knowledge about low-spin states as observed in decay studies has been collected by Pancholi and Martin.[9] An in-beam spectroscopic study of ^{212}Po was started, therefore, in this laboratory. As a result of this investigation yrast states up to (8^+) have been established in ^{212}Po. The (8^+) state was found to be an isomer with a half-life of 14.2 ns, which decays by α as well as γ-ray emission.

The final nucleus ^{212}Po was produced using the reaction ^{209}Bi(α,p). Self-supporting metallic targets of 600 μg/cm^2 were irradiated with α particles from the Jülich isochronous cyclotron JULIC. The cross section of the (α,p) reaction, which peaks at 45 MeV, was found to be about 400 times smaller than that of the competing (α,xn) reactions. Therefore, the transitions in ^{212}Po were too weak to be observed in standard in-beam γ-ray experiments. To obtain new information about states in ^{212}Po the following in-beam experiments have been carried out: (i) study of the α decay including measurement of excitation functions, (ii) α-γ coincidence experiments, and (iii) p-γ coincidence experiments.

The in-beam study of the α decay consisted of a two-parameter timing experiment. The parameters were the α energy and the time between the α ray and the beam burst. The α particles were detected with a Si surface-barrier detector of 450 mm^2 area and 300 μm thickness mounted at a distance of 45 mm from the target. To reduce the α-particle background resulting from nuclear reactions, off-beam α spectra taken between the beam bursts have been extracted from the data. The off-beam α spectra measured at beam energies of 45, 61, 75, and 90 MeV show, in addition to the well-known[10,11] 8.78- and 11.66-MeV lines de-exciting the ground state and the high-spin isomer in ^{212}Po, respectively, a line of 10.18 $\pm$ 0.03 MeV. From the time spectrum of the 10.18-MeV line the half-life of the initial state was determined to be 14.2 ± 2.4 ns. The cross section for production of the isomer decreases steadily from 130 ± 30 μb at 45 MeV to 7.6 ± 3.1 μb at 90 MeV. Although the excitation function of the 10.18-MeV line has a similar energy dependence to those of the 8.78- and 11.66-MeV lines of ^{212}Po no definite assignment to a certain nucleus could be made.

To obtain more information about the 10.18-MeV line an α-γ coincidence measurement at a beam energy of 45 MeV has been carried out. The α-γ coincidences were measured in a four-parameter experiment. The parameters were the α energy E_α, the γ energy E_γ, the time $t_{\alpha\gamma}$ between the α and γ rays, and the time $t_{\alpha\,\text{beam}}$ between the α ray and the beam bursts. A Si surface-barrier detector of 2000 mm^2 area and

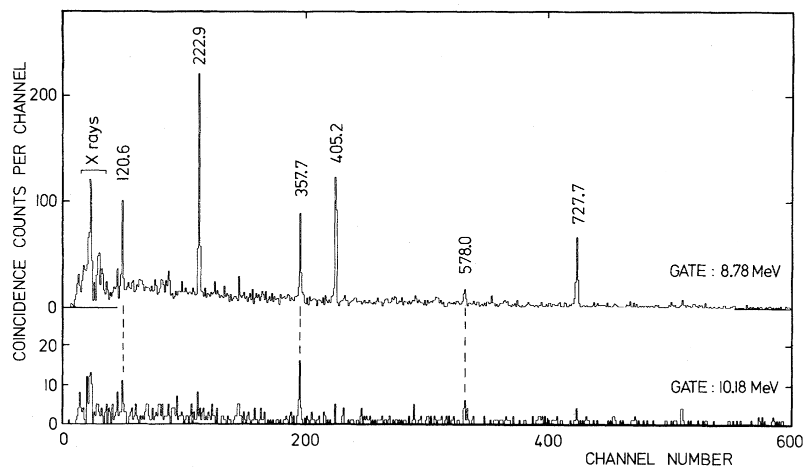

FIG. 1. Coincidence spectra gated on the 9.78- and 10.18-MeV α lines of ^{212}Po.

200 μm thickness and a Ge(Li) detector of 76 cm^3 active volume were mounted at distances of 26 and 15 mm, respectively, from the target. The α-γ coincidences were measured for 60 h with a coincidence rate of 10 counts/s. Two delayed-coincidence spectra resulting from this experiment, corrected for background and chance coincidences, are shown in Fig. 1. The upper spectrum has been gated on the α line of 8.78 MeV de-exciting the 0.3-μs ^{212}Po ground state. In this coincidence spectrum six γ lines can be clearly distinguished. In the lower coincidence spectrum gated on the new 10.18-MeV α line the strong γ rays of 222.9, 405.2, and 727.7 keV vanish but the weak γ lines at 120.6, 357.7, and 578.0 keV remain. To get further evidence for these coincidence relations, $t_{\alpha\gamma}$ time spectra resulting from the same experiment have been extracted. Gates have been set on the 8.78- and 10.18-MeV lines in the α spectrum and on the six above-mentioned γ rays in the γ spectrum. The time spectra for combinations of the 8.78-MeV line with each of the six γ transitions show the 0.3-μs half-life of the ground state of ^{212}Po. The time spectra for combinations of the 10.18-MeV line and the 120.6-, 357.7-, and 578.0-keV γ rays all display the 14.2-ns half-life of the new isomer. However, those for the 10.18-MeV line and the 222.9-, 405.2, and 727.7-keV γ rays contain only a few chance coincidence events, as expected, since these lines are not in coincidence with the 10.18-MeV α line. From all the coincidence results it has been concluded that the 222.9-, 405.2-, and 727.7-keV γ lines as well as the 10.18-MeV α line result from the de-excitation of a new isomer in ^{212}Po. The 120.6-, 357.7-, and 578.0-keV γ transitions have to be placed above this isomer.

Additional support for this placement can be gained from a study of the half-lives associated with the 222.9-, 405.2-, and 727.7-keV γ rays. Therefore, a four-parameter p-γ coincidence experiment has been carried out at a beam energy of 45 MeV. The protons have been identified by means of a ΔE-E counter telescope consisting of two Si surface-barrier detectors of 400-mm^2 areas and 100- and 1500-μm thicknesses, respectively. The γ rays were measured with a Ge(Li) detector of 67 cm^3 volume. The detectors were both placed at distances of 30 mm from the target. The parameters were ΔE and $E+\Delta E$ for the protons, the γ energy E_γ, and the time $t_{p\gamma}$ between the protons and the γ rays. The resulting $t_{p\gamma}$ time spectra gated on the 222.9-, 405.2-, and 727.7-keV lines show the half-life of 14 ± 5 ns in excellent agreement with the result of 14.2 ± 2.4 ns obtained for the 10.18-MeV α line.

The 727.7-keV line is known to be the $2^+ \to 0^+$ transition in ^{212}Po (Ref. 9). This transition as well as the 222.9- and 405.2-keV lines have the same intensities within statistical uncertainty in the α-γ coincidence experiment. The ordering of the latter two transitions could not be determined experimentally, therefore. An ordering may be obtained, however, by considering the systematic features of the low-lying yrast levels of the isotopes[12-15] ^{202,204,206,208,210}Po and the isotone ^{210}Pb.[16] They all show 2^+, 4^+, 6^+, 8^+ level sequences with decreasing energy spacings.[12-16] The 8^+ states in ^{202,204,206,208,210}Po are known to be isomeric.[12-15] These level sequences have been interpreted to result from the $\pi h_{9/2}{}^2$

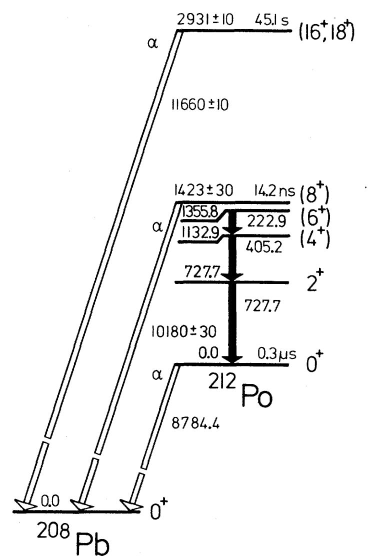

FIG. 2. Partial level scheme of ^{212}Po.

configuration in the even-mass Po isotopes[12-14] and from the $\nu g_{9/2}{}^2$ configuration for ^{210}Pb.[16,17] Similar level sequences based on either of these two configurations may be expected for ^{212}Po. The 222.9-keV transition has been placed, therefore, above the 405.9-keV transition as shown in the level scheme of Fig. 2. The excitation energy of the 14.2-ns isomer can be calculated from the energy of the 10.18-MeV α transition. By correcting for the recoil energy[18] one finds $Q_\alpha = 10.376 \pm 0.030$ MeV and an excitation energy of 1423 ± 30 keV for the isomer. The isomer lies 67 ± 30 keV above the state de-excited by the 222.9-keV line. The corresponding γ transition has not been observed. Perhaps it is either obscured by x rays or strongly converted. Considering the above-mentioned systematic features of low-lying levels in the even-mass Po isotopes and in ^{210}Pb, spins and parities of (4^+), (6^+), and (8^+) have been assigned tentatively to the new levels in ^{212}Po.

The intensities of the α and γ transitions deexciting the (8^+) isomer are $I_\alpha = 0.06 \pm 0.01$ and $I_{\gamma+e^-} = 0.94 \pm 0.01$, respectively. The corresponding partial lifetimes are $\tau_\alpha = 0.34 \pm 0.07$ μs and $\tau_{\gamma+e^-} = 22 \pm 4$ ns. This results in a hindrance factor[19] of $(0.9 \pm 0.3) \times 10^3$ for the 10.18-MeV α line. Since the particle carries off a certain angular momentum the effect of the centrifugal barrier on the hindrance factor has to be taken into account.[1,18,19] Therefore, additional information about the angular momentum of the new isomer in ^{212}Po can be deduced. The angular momentum hindrance factor has been calculated by Baur[20] for angular momenta of $6\hbar$, $8\hbar$, and $10\hbar$ to be 23, 210, and 3180, respectively, taking as radius of the barrier $R = 9.0$ fm. Corresponding reduced hindrance factors of 39 ± 13, 4.3 ± 1.4, and 0.3 ± 0.1, respectively, result for the 10.18-MeV line. A comparison of these values with reduced hindrance factors observed for other α emitters[19] shows agreement with the $I = 8$ assignment to the new isomer in ^{212}Po. A spin of $I = 10$ can be excluded since an enhancement of the α decay is highly improbable.

Information about the configuration of the 8^+ state can be derived from the $B(E2)$ value of the $(8^+) \to (6^+)$ transition of 67 30 keV. The $B(E2)$ value can be determined rather precisely despite the fact that the transition energy has a large uncertainty. This is because in the present case the product $E_\gamma{}^5(1 + \alpha_{\text{tot}})$ entering the calculation of the $B(E2)$ value varies only slowly with energy. For the $(8^+) \to (6^+)$ transition in ^{212}Po a value of $B(E2) = 630 \pm 150$ $e^2 \cdot \text{fm}^4$ results. Information about the configuration of the (6^+) and (8^+) states may be obtained from a comparison of this $B(E2)$ value with those of corresponding states in neighboring nuclei. The $8^+ \to 6^+$ transition in ^{210}Po has a value of $B(E2) = 70 \pm 5$ $e^2 \cdot \text{fm}^4$ (Ref. 13). The $B(E2)$ value of the $8^+ \to 6^+$ transition in ^{210}Pb is not known. Theoretical calculations of $B(E2)$ values which satisfactorily reproduce the experimental $B(E2)$ value of the $8^+ \to 6^+$ transition in ^{210}Po (Klemt and Speth[21]) predict for the $8^+ \to 6^+$ transition in ^{210}Pb $B(E2)_{\text{th}} = 47$ $e^2 \cdot \text{fm}^4$.[22] In these calculations the configurations of the 8^+ and 6^+ states were predominantly $\pi h_{9/2}{}^2$ for ^{210}Po (Ref. 21) and predominantly $\nu g_{9/2}{}^2$ for ^{210}Pb (Ref. 22). The fact that the $B(E2)$ value of the $(8^+) \to (6^+)$ transition in ^{212}Po is significantly larger than those of ^{210}Po and ^{210}Pb indicates that the low-spin yrast states in ^{212}Po are neigher of pure $h_{9/2}$ proton nor of pure $g_{9/2}$ neutron configuration. The increased $B(E2)$ value in ^{212}Po may be explained by assuming that the states have configurations consisting of coherent superpositions of the $[(\pi h_{9/2}{}^2)_{0^+}(\nu g_{9/2}{}^2)_{I^+}]_{I^+}$ and $[(\pi h_{9/2}{}^2)_{I^+}(\nu g_{9/2}{}^2)_{0^+}]_{I^+}$ configurations with spin $I = 6$ and 8. This assumption is supported by the fact that the 8^+ states in ^{210}Pb, ^{210}Po, and ^{212}Po have similar excitation energies, viz. 1272 (Ref. 16), 1557 (Ref. 13), and 1423 keV, respectively. Using the above configuration a $B(E2)$ value as large as ~ 250 $e^2 \cdot \text{fm}^4$ (Ref. 22) may be obtained. Since this value is still smaller than the experimental value, polarization effects may have to be taken into account.

The level scheme of ^{212}Po as given in Fig. 2 and the configuration as derived from the $B(E2)$ value of the $(8^+) \to (6^+)$ transition may be compared with prediction of shell-model calculations.[4,6,7] Glendenning[4] suggested that the low-spin yrast states may be dominated by the $\nu i_{11/2}{}^2$ configuration thus producing a 10^+ isomer. This prediction is not supported by the present results. Later Glendenning and Harada[6] proposed that a 10^+ isomer of $[(\pi h_{9/2}{}^2)_0{}_+(\nu g_{9/2}, i_{11/2})_{10^+}]_{10^+}$ configuration may exist around 1.2 MeV. This isomer should have a lifetime of $\approx 10^{-6}$ s and decay by α emission.[6] Such an α line was not observed in the present experiments. Auerbach and Talmi[7] suggested that the low-spin yrast states may have mixed $[(\pi h_{9/2}{}^2)_{0^+}(\nu g_{9/2}{}^2)_{I^+}]_{I^+}$ and $[(\pi h_{9/2}{}^2)_{I^+}(\nu g_{9/2}{}^2)_{0^+}]_{I^+}$ configurations with spins $I = 0, 2, 4, 6, 8$ in agreement with the conclusions drawn from the experimental observations.

The present results seem to support the interpretation of the ^{212}Po high-spin isomer in terms of the $[(\pi h_{9/2}{}^2)_{8^+}(\nu g_{9/2}{}^2)_{8^+}]_{16^+}$ configuration.[7,8] However, the $[(\pi h_{9/2}{}^2)_{8^+}(\nu i_{11/2}{}^2)_{10^+}]_{18^+}$ configuration[4,5] cannot be excluded since the $\nu i_{11/2}{}^2$ configuration may play a role at higher excitation energies. It seems to be unlikely that the high-spin isomer has the $[(\pi h_{9/2}{}^2)_{8^+}(\nu g_{9/2} \nu i_{11/2})_{10^+}]_{18^+}$ configuration,[6] since the corresponding 10^+ isomer has not been observed.

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[1]I. Perlman, F. Asaro, A. Ghiorso, A. Larsh, and R. Latimer, Phys. Rev. 127, 917 (1962).

[2]K. Fransson, M. af Ugglas, P. Carlé, and T. Erikson, Stockholm University Report No. 76-09, 1976 (unpublished).

[3]E. T. Chulick and J. B. Natowitz, Nucl. Phys. A173, 487 (1971).

[4]N. K. Glendenning, Phys. Rev. 127, 923 (1962).

[5]H.-D. Zeh, Z. Phys. 175, 490 (1963).

[6]N. K. Glendenning and K. Harada, Nucl. Phys. 72, 481 (1965).

[7]N. Auerbach and I. Talmi, Phys. Lett. 10, 297 (1964).

[8]L. A. Sliv and Yu. I. Kharitonov, Nucl. Phys. 60, 177 (1964).

[9]S. C. Pancholi and M. J. Martin, Nucl. Data Sheets B8, 165 (1972).

[10]A. Rytz, At. Data Nucl. Data Tables 12, 479 (1973).

[11]H. Gauvin, Y. Le Beyec, J. Livet, and L. L. Reyss, Ann. Phys. (N. Y.) 9, 241 (1975).

[12]T. Yamazaki, Phys. Rev. C 1, 290 (1970).

[13]I. Bergström, B. Fant, and K. Wikström, Phys. Scr. 3, 103 (1971).

[14]H. Beuscher, D. R. Zolnowski, D. R. Haenni, and T. T. Sugihara, Phys. Rev. Lett. 36, 1128 (1976).

[15]W. D. Schneider and K. G. Gonsior, Nucl. Instrum. Methods 130, 165 (1975).

[16]E. R. Flynn, G. J. Igo, R. A. Broglia, S. Landowne, V. Paar, and B. Nilsson, Nucl. Phys. A195, 97 (1972).

[17]M. G. Redlich, Phys. Rev. 138, B544 (1965).

[18]J. O. Rasmussen, in *Alpha-, Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland, Amsterdam, 1965), Vol. 1, Chap. 11.

[19]E. K. Hyde, I. Perlman, and G. T. Seaborg, *The Nuclear Properties of the Heavy Elements* (Prentice-Hall, Englewood Cliffs, 1964), Vol. 1, Chap. 4.

[20]G. Baur, private communication.

[21]V. Klemt and J. Speth, Z. Phys. A278, 59 (1976).

[22]J. Speth and V. Klemt, private communication.

Collisionless Intramolecular Vibratonal Relaxation in SF_6

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Time-resolved spectroscopy is applied to the problem of collisionless intramolecular relaxation within the ground electronic state of polyatomic molecules. The redistribution of vibrational energy within a molecule may be monitored by the different anharmonic shifts which occur when the energy is localized in the different modes. Picosecond infrared-laser–absorption saturation-recovery measurements on SF_6 show that the relaxation time, for statistical behavior to set in, falls within the limits 1 psec $< T_1 <$ 30 psec.

There has always been great interest in the limits of applicability of statistical mechanics. For example, the point is often made that statistical concepts describe macroscopic systems very well. On the other hand, a tiny dynamical system such as a single isolated molecule may behave in a nonergodic manner.

While the question of ergodicity may seem high-

