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[1]D. Bohm and D. Pines, Phys. Rev. 92, 609 (1953).

[2]H. Fröhlich, Advan. Phys. 3, 325 (1954).

[3]B. I. Lundqvist, Kgl. Dan. Vidensk. Selsk., Mat.-Fys. Medd. 6, 193 (1967).

[4]L. Hedin, B. I. Lundqvist, and S. Lundqvist, *Electronic Density of States*, National Bureau of Standards Special Publication No. 323 (U. S. GPO, Washington, D. C., 1970).

[5]S. Teitler, B. D. McCombe, and R. J. Wagner, in *Proceedings of the Tenth International Conference on the Physics of Semiconductors*, edited by S. P. Keller, J. C. Hensel, and F. Stern, CONF-700801 (U. S. AEC Division of Technical Information, Springfield, Va., 1970), p. 177.

[6]R. J. Wagner and G. A. Prinz, Appl. Opt. 10, 2060 (1971).

[7]G. A. Prinz, R. J. Wagner, and B. D. McCombe, to be published.

[8]The initial observation in CdS was reported by K. J. Button, B. Lax, and D. R. Cohn, Phys. Rev. Lett. 24, 375 (1970). For a more complete bibliography concerning other materials, see T. L. Cronburg and B. Lax, Phys. Lett. 37A, 135 (1971).

[9]Cronburg and Lax, Ref. 8.

[10]B. D. McCombe, R. J. Wagner, and G. A. Prinz, Bull. Amer. Phys. Soc. 15, 364 (1970).

[11]See, for example, V. Celli and N. D. Mermin, Ann. Phys. (New York) 30, 249 (1964).

[12]This assumption is consistent with our result that the plasmons which make the dominant contribution to the observed resonance absorption satisfy the condition $cq > \omega$.

[13]J. J. Quinn and R. A. Ferrell, Bull. Amer. Phys. Soc. 1, 144 (1956).

[14]See, for example, N. J. Horing, Ann. Phys. (New York) 31, 1 (1965).

[15]See, for example, J. J. Quinn and S. Rodriguez, Phys. Rev. 128, 2487 (1962).

[16]See, for example, E. J. Johnson and D. H. Dickey, Phys. Rev. B 1, 2676 (1970).

Observation of $T = 23$ Double Analog States in ^{210}Po†

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The T 23 states in $^{210}_{84}\mathrm{Po}_{126}$ ($T_3 = 21$) which are the isobaric analogs of the $T = T_3 = 23$ ground state and low-lying states in $^{210}_{82}\mathrm{Pb}_{128}$ have been observed as enhancements in the excitation function for the reaction $p + {}^{209}_{83}\mathrm{Bi}_{126} \to {}^{208}_{82}\mathrm{Pb}_{126} + 2p$. The experimentally observed enhancements in the two-proton coincidence excitation function correlate with the known level structure of ^{210}Pb and occur at the incident proton energies predicted by Coulomb energy formulas, thus establishing that these enhancements are due to the population of double analog levels in ^{210}Po.

For the neutron-rich, heavy nuclei $[T_3 = (N-Z)/2 \gtrsim 10]$ the experimental observation of double analog states—states with isospin T greater by 2 than T_3—has not been previously reported. In lighter nuclei such states have been strongly excited by direct reactions such as the (p, t) reaction.[1] However, in the (p, t) reaction the $T = T_3 + 2$ states are excited by a factor approximately proportional to $1/T^2$ compared with the $T = T_3$ states in the same nucleus.[2] For nuclei around ^{208}Pb $T \simeq 22$, so that the excitation of double analog states by direct reactions such as (p, t) is greatly inhibited.

In the present experiment the $T = 23$ double analog states in $^{210}_{84}\mathrm{Po}_{126}$ are reached via the entrance channel $p + {}^{209}_{83}\mathrm{Bi}_{126}$ ground state. Since the isospin of the ^{209}Bi ground state is only $\frac{43}{2}$, the entrance channel has a maximum isospin of $T = 22$; and thus the $T = 23$ states in ^{210}Po can only be reached via isospin mixing due to the isospin-nonconserving parts of the Coulomb force. In turn, this means that the cross section for the formation of double analog states in ^{210}Po via the $p + {}^{209}$Bi entrance channel is expected to be very small. For the incident proton energies at which the double analog states are excited ($E_{p\,\mathrm{in}} \simeq 33$ MeV) the total reaction cross section is approximately 2 b. Thus, the observation of the double analog states depends on the existence of a very unique signature for their decay.

Previous experiments on $T_> = T_3 + 1$ isobaric analogs in the lead region have shown that isospin-allowed proton emission accounts for at least 60–70% of the total decay width for these states.[3,4] Correspondingly, a double analog state would be expected to decay preferably by isospin-allowed two-proton emission, with the first proton decay proceeding to $T_>$ states in the intermediate nucleus, and the second proton decay proceeding to the ground state and the low-lying states in the residual nucleus. On the other hand, the other levels with $T = T_3$ and $T_3 + 1$ at the same excitation energy would not be expected to decay by two-proton emission, since in their case neutron emission is isospin allowed, and it is well known that (p, xn) reactions constitute almost entirely the total reaction cross section for proton-induced reactions on heavy nuclei.[5] Hence, the detection of two protons in coincidence should provide a rather unique signature for the population of double analog states.

Our program, then, is to measure the two-proton coincidence excitation function and observe the formation of double analog states as enhancements in the yield of two decay protons in coincidence as the incident proton energy varies over the thresholds for the formation of the double analog levels. The two-proton coincidence excitation function will include contributions from processes other than the decay of double analog levels. Such processes would include $(p, 2p)$ direct knockout reactions and (p, p') excitation of $T_>$ $(T = T_3 + 1)$ levels with the subsequent proton decay of these $T_>$ levels. However, such processes, which produce two protons in the exit channel, would not be expected to resonate as a function of the incident proton energy.

We have now completed such an excitation function measurement for $T = 23$ levels in ${}^{210}_{84}\mathrm{Po}_{126}$ ($T_3 = 21$) which are the analogs of the low-lying levels of ${}^{210}_{82}\mathrm{Pb}_{128}$ ($T_3 = 23$). Figure 1 shows the energetics involved for the first three members of the $T = 23$ multiplet. The excitation energies of the ${}^{210}\mathrm{Po}$ $T = 23$ levels may be calculated from the known ${}^{210}\mathrm{Pb}$ and ${}^{210}\mathrm{Po}$ masses[6] by the formula

$$E_x({}^{210}\mathrm{Po}(23, 21)) = M({}^{210}\mathrm{Pb}_{\mathrm{g.s.}}(23, 23)) - M({}^{210}\mathrm{Po}_{\mathrm{g.s.}}(21, 21)) + \Delta E_C + \Delta E_C' - 2\delta_{n\mathrm{H}},$$

where $\delta_{n\mathrm{H}}$ is the neutron-hydrogen atom mass difference and ΔE_C and $\Delta E_C'$ are the Coulomb energies for the respective Pb-Bi and Bi-Po $A = 210$ systems, which may be extracted—using an A^{-1} $A^{-1/3}$ dependence—from known Coulomb energies.[3,7] Formula (1) predicts an excitation energy of 37.36 MeV in ${}^{210}\mathrm{Po}$ for the $T = 23$ analog of the ${}^{210}\mathrm{Pb}$ ground state. An incident proton energy of 32.53 MeV on ${}^{209}\mathrm{Bi}$ will then excite the centroid of this double analog level. The ${}^{210}\mathrm{Po}$ $T = 23$ analogs of other low-lying states in ${}^{210}\mathrm{Pb}$ will be populated as the incident proton energy is increased. These $g_{9/2}{}^2$ states in ${}^{210}\mathrm{Pb}$ are well known,[8] and their analogs in ${}^{210}\mathrm{Pb}$ are suggested in Fig. 1.

Where isospin allowed, the neutron, deuteron, and triton decays of these $T = 23$ analog states are forbidden by energetics, while proton decay is energetically and T allowed. In the simplest picture the (23, 21) ground-state analog could undergo proton decay to the ground-state analog $(\frac{45}{2}, \frac{43}{2})$ in ${}^{209}\mathrm{Bi}$ of ${}^{209}\mathrm{Pb}(\frac{45}{2}, \frac{45}{2})$ with the emission of a 13.7-MeV proton. This $(\frac{45}{2}, \frac{43}{2})$ state could then undergo proton decay to the ground state of ${}^{208}\mathrm{Pb}$ (22, 22) by emitting a 14.9 proton. This sequential decay can be seen in Fig. 1.

In the isospin-allowed two-proton decay of the ${}^{210}\mathrm{Po}$ double analog levels the structure of three groups of levels are involved: the $T = 23$ double

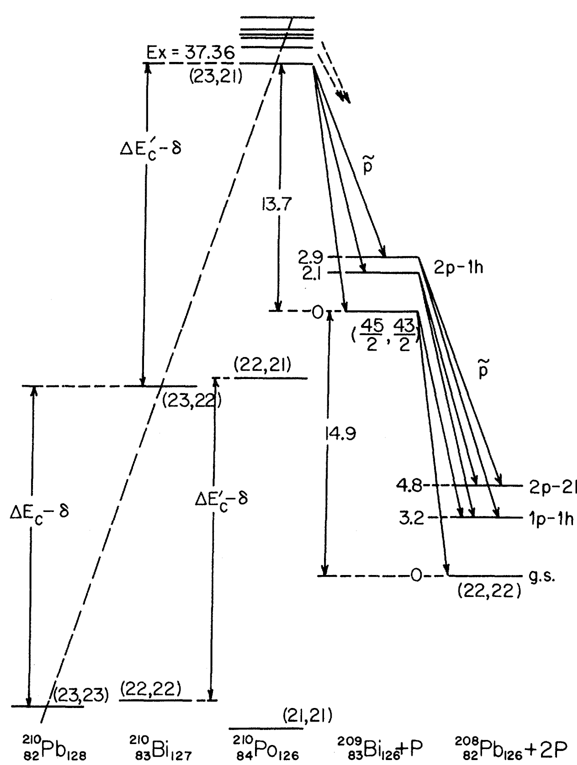

FIG. 1. Level diagram of the $T = 23$ multiplet. The energetics for the isospin-allowed two-proton decay of the $T = 23$ analog in ${}^{210}\mathrm{Po}$ of the ${}^{210}\mathrm{Pb}$ ground state is indicated, as discussed in the text.

analog levels in ^{210}Po, the $T=\frac{45}{2}$ analog levels in ^{209}Bi, and the $T=T_z=22$ levels in ^{208}Pb. By use of the isospin lowering operator $(T_-)^2$ on the low-lying two-particle, zero-hole (2p-0h) levels of ^{210}Pb,[8,9] one obtains the configurations in the ^{210}Po double analog levels. These configurations can undergo proton decay to $T=\frac{45}{2}$ levels in ^{209}Bi which are analogs of 1p-0h or 2p-1h levels in ^{209}Pb. The positions of the low lying 1p-0h and 2p-1h levels in ^{209}Pb are known.[10,11] In turn the $T=\frac{45}{2}$ levels of ^{209}Bi reached in the first proton decay can then experience proton decay to low-lying 0p-0h, 1p-1h, and 2p-2h levels in ^{208}Pb whose positions are known.[12,13] In both proton decays the emission of $3p_{3/2}$ and $3p_{1/2}$ protons is particularly favored because of the angular momentum barrier.[3,14] Thus, the strongest decay mode of the $(g_{9/2})^2$ double analogs in ^{210}Po should proceed to $T=\frac{45}{2}$ analogs in Bi^{209} of the $(p_{3/2}^{-1})g_{9/2}^2$ and $(p_{1/2}^{-1})g_{9/2}^2$ levels in ^{209}Pb. These levels are known to be 2.5 ± 0.5 MeV above the ground state in ^{209}Pb. In turn, the second proton decay should proceed primarily to 2p-2h states in ^{208}Pb at excitations of 4.8 ± 0.5 MeV. This favored mode of two-proton decay is indicated in Fig. 1.

In the coincidence experiment it is not possible to distinguish the first decay from the second. The sum of the decay energies for the most prominent decay mode is 24 ± 1 MeV (see Fig. 1). It is expected that the coincidence summed proton energy spectrum should show enhancements in this energy region as the double analog levels become populated.

The experimental geometry consists of two E-veto telescopes, E_L and E_R, positioned along a straight line perpendicular to the direction of the beam. The solid angle subtended by each telescope is approximately 0.31 sr. The 15.6-mg/cm^2 ^{209}Bi target was at an angle of 45 degrees to the beam direction, so that the target was 170 keV thick at the beam energies of this experiment ($\simeq 33$ MeV).

An SDS 925 on-line computer is used to store the data event by event on magnetic tape. Each event consists of a linear energy signal from each of the two E detectors and the relative time of flight between the two particles. Because of the 33-nsec time structure of the University of California at Los Angeles cyclotron, the electronics are set so that the computer is presented a time-of-flight spectrum consisting of a "real" coincidence region with two or three "accidental" coincidence regions on each side. With our experimental geometry it is found that with beam currents of ≈ 0.7 nA the "real" coincidence time of flight is two to three times the magnitude of the "accidental" peaks.

The data are analyzed off-line on the SDS 925 computer. The events are processed one by one. If the event is a "real," then both proton energies are stored in a two-dimensional (64×64) energy array. If the event is an "accidental," then a corresponding "accidental" two-dimensional energy array is updated. When all events for a given beam energy are processed, the program divides the accidental array by the number of accidental beam bursts in the spectrum and subtracts this array from the real array. Experimental studies, both in this experiment and in previous experiments at the University of California at Los Angeles cyclostron, have produced no evidence for short (0.03–10 μsec) fluctuations in the beam structure. We are therefore quite confident of the procedure used in subtracting the "accidental" spectra from the "real" spectra.

The energy calibration for the array is determined by using the position of the 11.41-MeV protons ($\tilde{p}$) which appear prominently in the accidental spectrum due to the reaction[7] ^{209}Bi$(p,n\tilde{p})^{208}$Bi (the cross section is $\simeq 10^3$ larger for this process). Lines of constant sum (energy left plus energy right) are determined for the array. The events of interest appear as a small peak in the array in the vicinity of $E_L=E_R\simeq 12$ MeV. A contour plot of the sum of the arrays obtained while taking a 19-point excitation function between 32.1 and 33.6 MeV is shown in Fig. 2(a). Figure 2(b) shows the number of counts per unit channel versus E_L+E_R in the vicinity of the peak for a typical run (bombarding energy = 33.0 MeV). A smoothly extrapolated background such as that shown in Fig. 2(b) is subtracted off, leaving the net yield of double decay protons from ^{210}Po(23, 21). In the region of incident proton energies between 32 and 34 MeV, the ratio of this net yield to the subtracted background varies between 0.6 and 1.3.

Figure 2(c) shows the excitation-function data obtained in two separate runs. In Fig. 2(d) the low-lying levels in ^{210}Pb are illustrated.[8,9] The appearance of the minimum at 32.7 MeV and the rapid rise of the cross section to 33.8 MeV is consistent with the ^{210}Pb spectrum; i.e., the ground state is located about 1 MeV below the closer lying $(g_{9/2})^2$ configurations with $J>0$. The gap between the $(g_{9/2})^2$ configuration and the $(g_{9/2}i_{11/2})$ configuration is suggested in the region near 34 MeV. The two-proton coincidence excitation function presented in Fig. 2(c) does not, in gener-

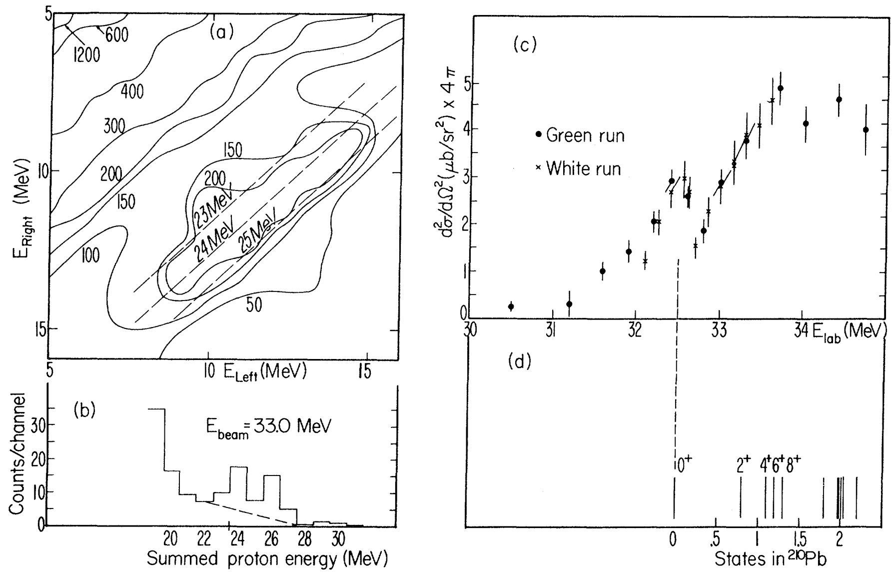

FIG. 2. (a) Contour plot of the sum of the E_L-vs-E_R arrays obtained from a 19-point excitation function between $E_{p\,\text{in}}$= 32.1 and 33.6 MeV. (b) Number of real coincident events per unit channel for a typical run ($E_{p\,\text{in}}$=33.0 MeV) plotted as a function of $E_L + E_R$. (c) Excitation function, obtained from two separate runs, for the coincident events whose summed energy was 24 ± 2.5 MeV. (d) The low-lying levels of ^{210}Pb with the 0^+ ground state placed beneath the resonance at ~ 32.5-MeV incident proton energy in (c).

al, represent the relative excitation of the various double analog levels since the experimentally observed coincidence rate depends upon angular correlation factors between the two decay protons which are presently unknown.

In summary, the increase of the coincidence counting rate for events in the region near $E_R = E_L \simeq 12$ MeV provides an effective signature for the observations of the double analogs in ^{210}Po(23, 21) of the ground and low-lying states of ^{210}Pb(23, 23). The energy dependence of the excitation function for such events correlates well with the behavior expected on the basis of the positions and multiplicities of the low-lying states of ^{210}Pb.

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[1]G. T. Garvey, J. Cerny, and R. H. Pehl, Phys. Rev. Lett. 12, 726 (1964).

[2]J. P. Schiffer, in *Isospin in Nuclear Physics*, edited by D. H. Wilkinson (North-Holland, Amsterdam, 1969), p. 667.

[3]G. H. Lenz and G. M. Temmer, Nucl. Phys. A112, 625 (1968).

[4]T. J. Woods, G. J. Igo, C. A. Whitten, Jr., W. Dunlop, and G. W. Hoffmann, Phys. Lett. 34B, 594 (1971).

[5]E. K. Hyde, I. Perlman, and G. T. Seaborg, *The Properties of Heavy Elements* (Prentice-Hall, Englewood Cliffs, N. J., 1964), Vol. I, pp. 310–339.

[6]J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. 67, 1 (1964).

[7]G. M. Crawley, W. Benenson, P. S. Miller, D. L. Bayer, R. St. Onge, and A. Kromminga, Phys. Rev. C 2, 1071 (1970).

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

[9]C. Ellegaard, P. D. Barnes, E. R. Flynn, and G. J. Igo, Nucl. Phys. A162, 1 (1971).

[10]E. R. Flynn, G. J. Igo, P. D. Barnes, and D. Kovar, Phys. Rev. Lett. 22, 142 (1969).

[11]G. J. Igo, E. R. Flynn, G. J. Dropesky, and P. D. Barnes, Phys. Rev. C 3, 349 (1971).

[12]J. H. Bjerregaard, Ö. Hansen, O. Nathan, and S. Hinds, Nucl. Phys. 89, 337 (1966).

[13]G. J. Igo, P. D. Barnes, and E. R. Flynn, Ann. Phys. (New York) 64, 655 (1971).

[14]G. J. Igo, C. A. Whitten, Jr., J.-L. Perrenoud, J. W. Verba, T. J. Woods, J. C. Young, and L. Welch, Phys. Rev. Lett. 22, 724 (1969).