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First observation of excited states in ^{182}Pb

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Excited states in the light lead nucleus, ^{182}Pb, have been observed for the first time, by means of the recoil-decay tagging technique. A rotational band has been observed which has features in common with bands attributed to a prolate configuration in the heavier neutron deficient lead nuclei, $^{184-188}$Pb. A variable moment of inertia fit to the states in this band suggests that the prolate minimum has risen significantly in energy compared to the next even lead nucleus, ^{184}Pb. This constitutes firm evidence for the minimization of this configuration with respect to the spherical ground state around $N=103$.

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The light lead nuclei ($A \leqslant 192$) provide textbook examples for the phenomenon of nuclear shape coexistence [1]. Indeed, such behavior was explicitly predicted by early Nilsson-Strutinsky calculations [2]. Being far from the line of β stability, the peculiar combinations of proton and neutron numbers may lead to the occurrence of several minima in the potential energy surface, corresponding to very different nuclear shapes. This instability with respect to shape change means that increasing the angular momentum of the nucleus may make it favorable for the nucleus to adopt a more deformed over a less deformed shape. For example, in the neutron deficient lead and mercury nuclei, a common feature is the transition from a ground state, which is spherical in the case of the lead nuclei and oblate in the mercury isotopes, to a prolate shape at low spin [1].

In keeping with the behavior of the heavier neutron deficient lead nuclei, ^{182}Pb is predicted to be spherical in its ground state [3]. The transition from a spherical to a prolate deformed shape should occur at the same spin as previously observed in ^{184}Pb ($I=2$) [4] but at a higher excitation energy since the prolate configuration is predicted to minimize with respect to the ground state around $N=102$ [5]. This is not the only incidence of shape coexistence known in the light lead nuclei. Indeed, normal deformed oblate states ought to be present in ^{182}Pb at low excitation energy, while at higher excitation energies, $E \geqslant 2.5$ MeV, strongly deformed oblate states ($\beta_2 \sim -0.35$) are expected [5], a fairly rare prediction for a heavy nucleus [5]. In summary, ^{182}Pb is expected to be an interesting testing ground for the phenomenon of shape coexistence with all three shapes, spherical, prolate, and oblate, predicted to be manifested within a limited range of excitation energy.

There are two distinct but complementary methods which have proven to be successful in tracing the shape-coexisting states in the light lead nuclei. Firstly, these states may be populated via alpha decay from the polonium nuclei; the energies and relative intensities of these alpha decays supply an indication of the location and nature of low-lying states in the daughter lead nucleus [6,7]. Secondly, higher-lying excited states may be populated directly by means of fusion-evaporation reactions. The principal difficulty in studying the very light lead nuclei by this latter technique arises from the increasing dominance of fission on approaching the proton drip line. Nevertheless, it has been possible to study the high spin states of lead nuclei down to ^{186}Pb either by correlating their gamma decay with the detection of their evaporation residues in a recoil filter detector [8] or by using a fragment mass analyzer [9]. However, in order to study the lighter lead nuclei it is necessary to use a channel selection technique which uniquely discriminates the gamma rays associated with their decay from the overwhelming fission background. One such technique is recoil decay tagging (RDT) [10]. This method correlates the prompt gamma decay of a recoiling nucleus with its alpha (or proton) decay following its implantation in a silicon strip detector. The RDT technique has been particularly successful when used as a means of studying nuclei which decay by α emission with a lifetime in the range of ms to hundreds of ms. Recent successful applications of this technique include studies of the light lead nucleus ^{184}Pb [4], as well as ^{176}Hg [11,12] and ^{178}Hg [11,13]. The principal limiting factor in such experiments is the implantation rate in the silicon detector which determines the observed rate of random coincidences. In an earlier RDT study of ^{184}Pb, which has a half-life of 480(25) ms [14], this high background from random coincidences meant that only states up to the (8^+) level could be identified. In contrast, the half-life of ^{182}Pb is known to be of the order of 50 ms

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[14], rendering it eminently suitable for an RDT study, since the probability of false correlations will be low due to the short search time required between implantation and subsequent decay. This has been borne out in the present Rapid Communication, by the clear identification of yrast levels up to the (12^+) state by means of the RDT technique.

Since ^{182}Pb is very far from stability and the competing fission channels completely dominate any particle evaporation channel, it was essential to determine in advance an appropriate beam energy which would maximize the production rate for ^{182}Pb. Accordingly, an excitation function measurement was performed at the Accelerator Laboratory of the University of Jyväskylä. A ^{42}Ca beam accelerated by the $K = 130$ MeV cyclotron was incident on a thin target of 500 μg/cm^2 thickness of ^{144}Sm, producing ^{182}Pb via the four neutron evaporation channel. The recoiling nuclei passed through the RITU gas-filled separator [15] and were implanted in a silicon strip detector. The ^{182}Pb alpha decays observed at the focal plane allowed the production cross section to be determined. The beam energy was increased from 203 MeV to 215 MeV in steps of 2 MeV by successively removing a series of degrader foils. Maximum production of ^{182}Pb, corresponding to a cross section of around 300 nb, was found to occur for a beam energy of 213 MeV.

Using this information, a subsequent RDT experiment was conducted at the Accelerator Laboratory of the University of Jyväskylä. This made use of a ^{42}Ca beam at the predetermined energy of 213 MeV, incident on a ^{144}Sm target. A target consisting of a thin foil of 500 μg/cm^2 thickness was used for the first 30 hours. The target was subsequently changed to two stacked 500 μg/cm^2 thin foils for the remaining 120 hours of the experiment.

The target was situated at the center of the Jurosphere II array, consisting of seven TESSA [16], five NORDBALL [17], and 15 Eurogam Phase I [18] escape-suppressed germanium detectors, providing an absolute efficiency of around 1.8% at 1.3 MeV. The array was used to detect prompt γ rays emitted by the recoiling evaporation residues. These recoiling nuclei then traveled through the RITU gas-filled separator [15], where they were magnetically separated from both the primary beam and from fission products. On exiting RITU, the recoils passed through a gas detector, which, as a ΔE detector, served to assist in discriminating both alpha decays from low energy scattered beam particles and fusion products from high energy scattered beam events. This device afforded an efficiency of around 99% for the discrimination of recoils from scattered beam particles. On exiting the gas detector chamber, the recoils were embedded in an 80 mm (horizontal) $\times 35$ mm (vertical) 16-element Si strip detector, covering approximately 70% of the image, positioned at the focal plane of the separator, 110 mm downstream of the gas detector. Each strip was 5 mm in width and position sensitive in the vertical direction with a resolution of 400 μm. Thus the total information available in the off-line analysis consisted of γ-ray energies from the Jurosphere II array, timing information relative to the rf signal from the cyclotron, the positions, energies, and times of implanted residues and of subsequent decays in the silicon strips.

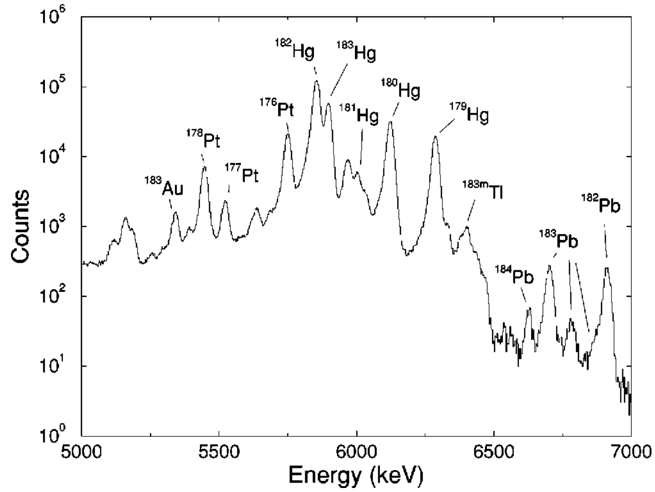

FIG. 1. Alpha-particle energy spectrum obtained during the RDT experiment. This spectrum has been calibrated using known alpha peaks from the literature: ^{178}Pt, $E = 5446(3)$ keV; ^{177}Pt, $E = 5517(4)$ keV; ^{176}Pt, $E = 5751(20)$ keV; ^{180}Hg, $E = 6119(5)$ keV; ^{179}Hg $E = 6285(5)$ keV [23].

Alpha decay events in the silicon strip detector, which were correlated with the prior implantation of a recoil, under the further condition that the gas detector did not fire simultaneously with the detection of the alpha particle, were accepted and incremented into an alpha-particle energy spectrum (see Fig. 1). The veto signal from the gas detector dramatically reduces the background from low energy scattered beam particles in the alpha-particle energy spectrum. The peak in the alpha-particle energy spectrum, identified with the alpha decay of ^{182}Pb, has an energy of 6911(10) keV, measured from around 2300 decays. The observed value is consistent within errors with a recent measurement of $E_\alpha = 6895(10)$ keV for the ^{182}Pb alpha decay [14]. Following the procedure outlined in Ref. [19], a half-life of 68(7) ms was deduced for ^{182}Pb, which is consistent with a recent measurement of 55(5) ms for the ^{182}Pb half-life [14].

Prompt gamma rays emitted by ^{182}Pb evaporation residues were extracted from the overwhelming background due to fission and other reaction channels using the RDT technique. This was achieved by correlating the gamma rays with implants in the strip detector which were succeeded within a search time of 210 ms, corresponding to approximately three half-lives, by a ^{182}Pb alpha decay. It should be noted that a very weak ($\sim 2.5\%$ branch) alpha decay from ^{183}Pb [6873(8) keV] lies on the low-energy side of the ^{182}Pb peak (just visible in Fig. 1). The contribution of this contaminant to the RDT spectrum is not significant due both to its strength and its half-life which is around five times longer than ^{182}Pb [20]. When selecting alpha decay events for the correlation, a further condition was applied as before, namely, that the gas detector should not have fired at the time when the alpha particle was detected. Around 25% of the alpha decays were found to have an associated γ ray. The Jurosphere II array was also operational during the excitation function experiment. Correlated γ rays from these data have been included in the present analysis. An RDT spectrum for ^{182}Pb has been produced by the procedure described above

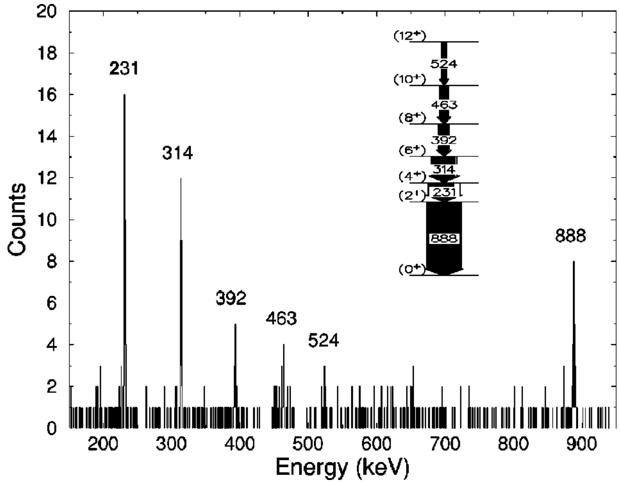

FIG. 2. γ-ray energy spectrum for ^{182}Pb obtained by correlating the 6911 keV alpha peak with its implant within a 210 ms search time. Peaks assigned to ^{182}Pb are labeled with their energy in keV. The inset shows the partial level scheme for ^{182}Pb obtained in the present work. The width of the arrows is proportional to the intensity of the transitions.

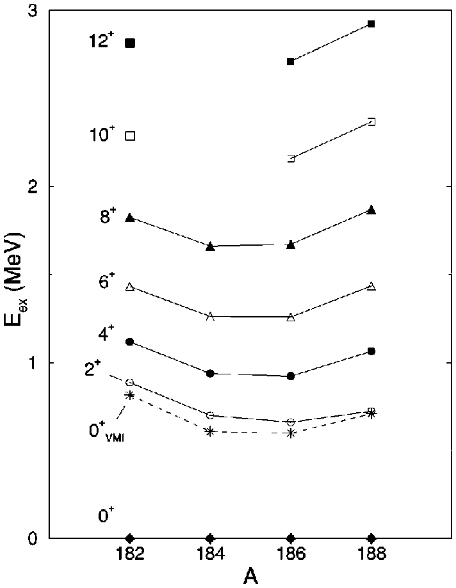

FIG. 3. The position of the known yrast levels for the chain of lead nuclei, $^{182-188}$Pb. The asterisks indicate the location of the (unmixed) prolate bandheads as deduced from a VMI fit to the prolate band in the respective nuclei (see text). No states are known in ^{184}Pb above (8^+).

(see Fig. 2). As well as lead x-ray lines, six γ-ray transitions are observed in ^{182}Pb for the first time. The γ-ray energies, intensities, and proposed assignments are presented in Table I.

Owing to the very low production cross section for ^{182}Pb, it was not possible to observe coincidence relationships between the six γ-ray transitions and it is therefore necessary to make the assumption that they constitute a single cascade. On the basis of intensity, the 888 keV transition is identified with the $(2^+)\rightarrow(0^+)$ transition. The remaining five transitions have been ordered such that they comprise a rotational band (see inset to Fig. 2), analogous to those bands observed in the heavier lead isotopes $^{184-188}$Pb. Furthermore, the levels in the band have been assigned tentative spins in accordance with systematics, a similar procedure to that previously applied in the case of ^{184}Pb [4]. The proposed ordering is consistent with the measured relative intensities of the transitions and implies a pattern of alignment in ^{182}Pb nearly identical to that previously seen in ^{184}Pb [4]. Furthermore, above spin (6^+), the observed rotational band in ^{182}Pb has a nearly identical moment of inertia to the known prolate band in the isotone, ^{180}Hg, the transition energies being typically 10–15 keV larger in the mercury band [21]. Taken together, the evidence from the similarity of the ^{182}Pb band to those bands observed both in the heavier lead nuclei and in the mercury isotones, is compelling and allows the firm conclusion that an analagous prolate configuration is responsible for the band in ^{182}Pb.

TABLE I. Energies and intensities relative to the 888 keV γ ray of the newly discovered transitions in ^{182}Pb. The tentative assignments are made on the basis of intensity and systematics (see text).

E_γ (keV)	I_γ (%)	Assignment
231.2(2)	73(17)	$(4^+)\rightarrow(2^+)$
313.7(2)	68(12)	$(6^+)\rightarrow(4^+)$
392.3(3)	29(5)	$(8^+)\rightarrow(6^+)$
462.7(4)	24(4)	$(10^+)\rightarrow(8^+)$
524.0(4)	14(3)	$(12^+)\rightarrow(10^+)$
888.3(3)	100(7)	$(2^+)\rightarrow(0^+)$

A variable moment of inertia (VMI) fit [22] has been applied to the (6^+) to (12^+) levels on the assumption that they comprise a prolate rotational band. Extrapolating the fitted values indicates that the bandhead of this prolate configuration would be expected to lie at an excitation energy of 817 keV in the absence of mixing with other configurations (see Fig. 3). The extrapolation from the higher spin states strongly suggests that the (4^+) state is, in fact, also a member of the prolate band but has been pushed down in energy by 3–4 keV. Furthermore, the (2^+) level is almost certainly also a member of the prolate band but has been depressed in excitation energy more strongly than the (4^+) state by mixing with other (as yet) unobserved states. It should be noted that, on the basis of the evidence collected in the present Rapid Communication, the possibility that the (2^+) state is spherical cannot be completely excluded. However, if a revised fitting procedure is applied, on the assumption that the (2^+) level is spherical, then it is not possible to reach a consistent interpretation of the observed levels, giving confidence to the assignment of the (2^+) level to the prolate band.

It is interesting to compare the deduced excitation energy of the prolate bandhead in ^{182}Pb with those derived for the heavier lead nuclei, ^{184,186,188}Pb, and to assess the implications for the belief that the minimum of this configuration occurs at $N=103$. Certainly, the excitation energy of the prolate bandhead deduced in the present Rapid Communication is significantly larger than the next heaviest even lead isotope, ^{184}Pb, for which a bandhead excitation energy of 615 keV was deduced [4]. A plot of the yrast levels for the light lead nuclei clearly demonstrates the upturn in the excitation energy of the prolate bandhead on going from ^{184}Pb to ^{182}Pb (Fig. 3). One can conclude, that while the earlier ^{184}Pb result [4] strongly suggested that the prolate minimum was at $N=103$, the addition of the present result clearly delineates this minimum.

In summary, six γ-ray transitions have been observed in ^{182}Pb for the first time by means of the RDT technique. Five of these transitions comprise a prolate rotational band. An extrapolation of a VMI fit to these states suggests that the bandhead of the prolate band has risen significantly in excitation energy from the adjacent even mass lead nucleus, ^{184}Pb, confirming the presence of the prolate minimum at $N=103$.

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