Spherical and deformed isomers in ^{188}Pb

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Several isomers in ^{188}Pb have been identified using pulsed beams, the recoil-shadow technique, and the ^{164}Er(^{28}Si,4n)^{188}Pb reaction. Two of the isomers feed the 10^+ state of the yrast sequence and are suggested to be the 11^- and 12^+ states from oblate and spherical configurations, respectively. The 12^+ isomer is fed weakly by another isomer with a relatively long lifetime, but it has not been characterized. A fourth isomer with a lifetime of about 1.2 μs leads via a complicated path to the 8^+ and lower spin yrast states. It is a candidate for the $K^\pi=8^-$, two-quasineutron state which occurs systematically in $N=106$ prolate-deformed nuclei, supporting the assumption that the intruding collective well is prolate. [S0556-2813(99)00407-0]

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Shape coexistence is less well established in the neutron-deficient lead nuclei than in the mercury isotopes ($Z=80$), where archetypal cases are found [1,2]. This is because of experimental limitations in producing very neutron-deficient heavy nuclei, and the nuclear structure complications implied by the presence of three, rather than two, minima in the nuclear potential well at low spin [3,4]. As well as the corresponding oblate—and prolate—deformed minima familiar from the mercury cases, the $Z=82$ closed shell should produce a low-lying spherical minimum [4], leading to a complicated competition between different structures to form the yrast line.

Consistent with theoretical predictions on the mass dependence of these minima [5], the prolate band apparently dominates in the lightest isotopes, minimizing with respect to the spherical ground state near $N\sim104$, as evidenced by the rotational-like (though limited) sequences observed at spin $4\hbar$ and above in the level schemes of ^{184}Pb [6], ^{186}Pb [7,8], and ^{188}Pb [7]. The recent [10] identification and characterization of long-lived isomeric states from the spherical and oblate configurations as well as a weakly populated candidate for the prolate sequence, confirms that all three minima occur in ^{190}Pb — the prolate states becoming nonyrast because the prolate minimum rises with increasing neutron number.

If these interpretations are correct and the spherical and oblate states behave as predicted, the complementary situation should occur in ^{188}Pb. That is, while the prolate collective states may be lowest, structures characteristic of the spherical and oblate configurations, and specifically, isomeric states such as the 12^+ state from the $\nu i_{13/2}^{-2}$ multiplet, should also be present, although they may be nonyrast.

We report here the results of experiments designed to identify such long-lived states. The experiments used ^{28}Si beams from the ANU, 14UD pelletron accelerator, incident on an enriched 0.9 mg/cm^2 target of ^{164}Er. A ''recoil-shadow'' arrangement was employed with the target 5.3 cm upstream of the center of the γ-detector array, CAESAR. In this arrangement the six Compton-suppressed detectors, and the two LEPS detectors which make up the array are shielded from direct radiation from the target. Recoiling nuclei were stopped in a bismuth catcher foil at the center of the array. The foil had a central hole to allow passage of the beam.

The flight time from the target to catcher was about 10 ns so that only transitions from states which were fed by isomers (of at least a few nanoseconds) were observable. In addition to these geometrical constraints, the beam was pulsed with ~1 ns pulses at 1.7 μs intervals to allow additional selection of delayed transitions, and the direct measurement of lifetimes. All time relationships with respect to the pulsed beams are recorded in this system, thus facilitating establishment of decays associated with isomers.

In the primary work on ^{188}Pb, Heese *et al.* [7] identified several delayed transitions feeding the yrast 10^+ state of the prolate band, but did not characterize them because they were too weak. The same transitions, at 335 and 344 keV, are evident in the γ-γ-coincidence spectrum shown in Fig. 1(a). This spectrum is constructed by combining gates on the yrast transitions from the decay of the 10^+ state and those below it, but excluding the 340 keV, $4^+\rightarrow2^+$ transition, with the intention of showing the feeding intensity. The matrix from which the spectra were projected has an additional time condition that the transitions occur only in an interval of 10 to 235 ns after the beam pulses. As well, to further isolate isomers with relatively short lifetimes, a matrix of transitions occurring in the subsequent period between beam pulses has been subtracted, after appropriate normalization, and before the gating on individual transitions was performed. As can be seen from the gate on the 335 keV transition shown in Fig. 1(b), the 335 and 344 keV transitions are not in coincidence, hence they correspond to feeding from two independent states. Those states both have relatively short, but different lifetimes as can be seen from the time curves in Figs. 2(a) and 2(b). As indicated in the level scheme of Fig. 3, these and other results establish two states at 2701 and 2709 keV with lifetimes of 38(6) ns and 136(20) ns, respectively, directly depopulated by the 335 and 344 keV transitions. These account for the majority of the delayed population. The two lifetimes are reflected in more complex time curves for the 499 and 370 keV yrast transitions [Figs. 2(c) and 2(d)], but there are also longer lifetime components in these spectra.

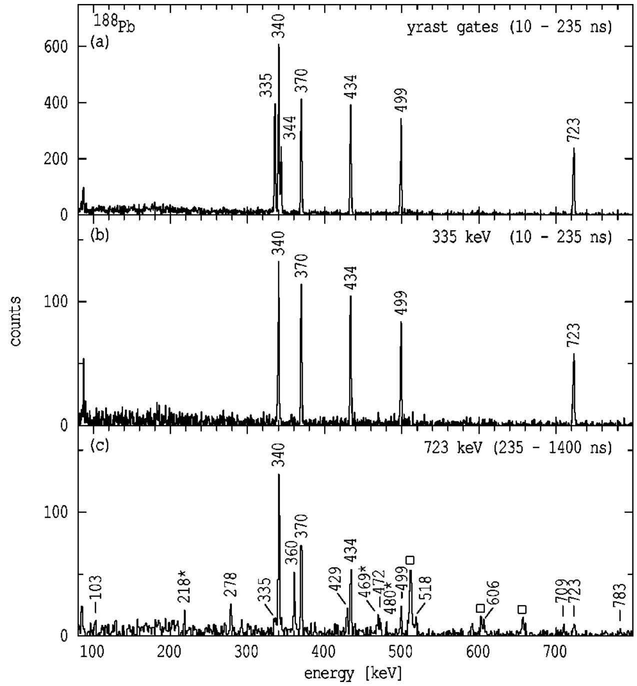

FIG. 1. γ-γ coincidence spectra with different absolute time constraints to separate the main isomeric decays: (a) combining gates on the $723(2^+\rightarrow0^+)$ $370(4^+\rightarrow2^+)$ $434(6^+\rightarrow4^+)$ and $499(10^+\rightarrow8^+)$ yrast transitions with both a ±120 ns time-difference window and the condition that transitions occur in a 10 to 235 ns interval after the beam pulse; in addition, transitions which occur in the subsequent time region between beam pulses have been removed. (b) Projecting transitions in coincidence with the 335 keV transition with the same time conditions as in (a). (c) Gate on the 723 transition in the 235 to 1400 ns time interval after the beam pulse. The γ rays indicated with an asterisk feed the 12^+ isomer.

One component has been associated with several transitions including γ rays at 218 and 469 keV, among others, which are not shown on the level scheme but which feed the 2701 keV, 38 ns isomer, as established from time-correlated coincidences. In the recoil-shadow geometry, such transitions could only have been observed if they follow a higher-lying isomer. Unfortunately, population of that isomer was too weak to enable us to place the transitions more precisely from individual γ-γ coincidence spectra, or to measure the lifetime accurately, although it must be in the region of ~1 μs, as indicated schematically in the level scheme (Fig. 3).

The isomeric state at 2576 keV whose lifetime is measured as $1.2(3)$ μs is more strongly populated but has a fragmented path leading to the 723 keV, 2^+ state, as shown in the level scheme in Fig. 3. The main transitions can be seen in the 723 keV gate in Fig. 1(c). In contrast to the other spectra shown in Fig. 1, the time gate selects a later region, from 235 to 1400 ns after each beam pulse. The 2576 keV state decays by a 709 keV transition to the 8^+ state of the prolate band, and by a number of transitions which establish other (presumably nonyrast) states. All decays are independently confirmed by appropriate γ-γ coincidences except for the 103 keV transition which connects the isomer to the 2473

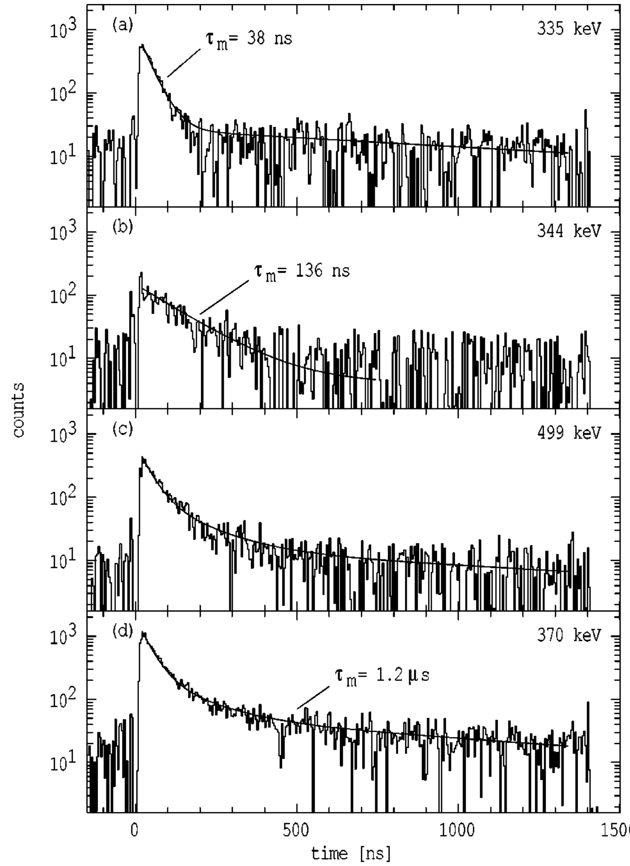

FIG. 2. Time spectra with respect to the pulsed beam with gates on individual transitions (collected in γ-γ coincidence) as indicated.

keV state. Its intensity is low but such a transition is required to explain the delayed feeding to the 2473 keV state without invoking another isomer for which there is no other evidence. Furthermore, the lifetime observed is in agreement with a recent result for ^{188}Pb from a measurement which utilized a recoil separator to search principally for delayed states in ^{187}Pb [9] and also identified a single isomer in ^{188}Pb with a lifetime of $1.1(1)$ μs.

The spins and parities of the isomeric states established can be limited through a number of considerations. Considering first the 2709 and 2701 keV states: these do not decay to each other, and only to the 10^+ state of the prolate band. The absence of even weak branches to the yrast 8^+ state suggests spins greater than $10\hbar$ for both, but the lifetimes are too short for the 344 and 335 keV transitions to be of $M2$ or higher multipolarity, leaving only $E1$, $M1$, or $E2$ as possibilities. The spectrum in Fig. 1(a) was constructed to allow a further restriction on the basis of the differences in the total conversion coefficient, α_T deduced from intensity balances with the 340 keV $E2$ transition. The fact that the 344 and 335 keV paths are parallel requires that

$$I_\gamma^{340}\times1.081=I_\gamma^{335}[1+\alpha_T(335)]+I_\gamma^{344}[1+\alpha_T(344)].$$

The results of the intensity measurement and the differing multipolarity combinations for the 335 and 344 keV transi-

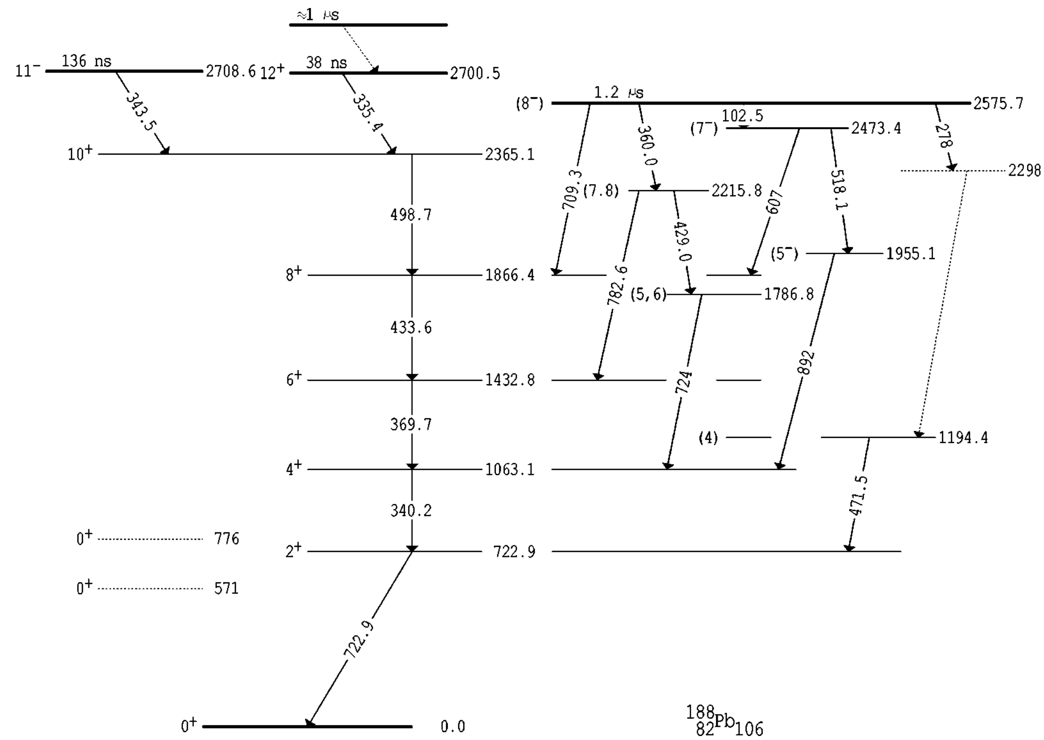

FIG. 3. Proposed level scheme for delayed transitions in ^{188}Pb. [A group of transitions with energies 218, 469, (479), 527, 914, 947, and 977 keV which are delayed with respect to the beam but feed the 2701 keV, 12^+ isomeric state are not shown.] Known excited 0^+ states [18] are shown for completeness.

tions are indicated in Fig. 4, where the shaded area represents the normalized and conversion-corrected intensity, with error, for the 340 keV transition, the left-hand side of the above equation. Of the four combinations which cannot be excluded, only the combination of $E2$ for the 335 keV transition and $E1$ for the 344 keV transition is also consistent with the indication of higher spin for the 2701 keV state, as implied by its stronger population. This argument (which assumes stretched transitions) leads to the proposed assignments of 12^+ for the 2701 keV isomer and 11^- for the 2709 keV isomer.

The relatively weak population of the 1.2 μs isomer at 2576 keV indicates that it and the states to which it decays are nonyrast, and therefore its spin must be $\leqslant 9\hbar$. The absence of direct decays to the 6^+ yrast state says it is unlikely to be 8^+ (or lower spin) leaving 8^-,9^+, or 9^- as the most likely alternatives. There are no strong arguments to make further restrictions although spin 9 would be marginal on the basis of the weak population, at least. For the present, the first alternative, $J^\pi = 8^-$ has been adopted as a tentative assignment. That would in turn imply 7^- for the 2473 keV state since the low γ-ray intensity of the 103 keV transition would argue against $E1$ multipolarity, while $E2$ or $M1$ are possible. The tentative spins suggested for the lower states on the bases of their branches and connections are indicated in Fig. 3. The order of some of the transitions remains ambiguous giving several alternative possibilities for the energies of excited states. The spins and parities will be discussed further below in terms of the systematics.

The presence of the isomers established can be interpreted as good evidence for shape co-existence. The 11^- and 12^+ isomers can be identified with the $\pi i_{13/2} h_{9/2}$ two-proton (oblate) intruder and $\nu i_{13/2}^{-n}$ spherical configurations, respectively, as indicated in the systematics shown in Fig. 4. The $E1$ strength of the 344 keV transition corresponds to $5.3(8) \times 10^{-8}$ W.u., which compares with $\sim 4 \times 10^{-8}$ W.u. for the 43 keV transition from the 11^- isomer in ^{190}Pb, the much longer lifetime in ^{190}Pb being largely a consequence of

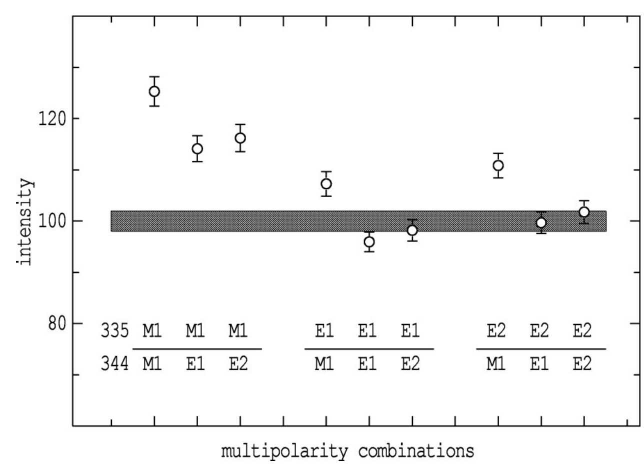

FIG. 4. Intensity balance between the conversion-corrected intensities for the 340 keV $E2$ transition (shaded area) and the sum of the 335 and 344 keV transitions, as a function of their multipolarities. Gamma-ray intensities are from the coincidence spectrum of Fig. 1(a).

the higher excitation energy of the prolate 10^+ state to which it can decay. In contrast the relatively short lifetime (38 ns) of the 12^+ isomer compared to the 36 μs lifetime of the 12^+ isomer in ^{190}Pb, arises because the configurations of the lower states in the two nuclei are different. In ^{190}Pb the absence of a low-lying 10^+ state means that the 12^+ state is forced to decay by a low-energy (in fact unobserved) $E2$ transition to the 10^+ state from the same $\nu i_{13/2}^{-n}$ spherical configuration. However, as well as having a low energy which reduces the transition probability, the absolute strength of that $E2$ is low because of midshell (seniority) cancellation, as noted in Ref. [10], hence the particularly long lifetime (36 μs). The retardation of the $E2$ in ^{188}Pb, which has a strength of $3.7(5)\times10^{-2}$ W.u., can therefore be attributed to factors unrelated to those pertaining to ^{190}Pb, and specifically to the difference between the two configurations, the upper state being a spherical (mainly two-hole) neutron configuration, the lower a collective state in the prolate-deformed well, thus requiring both orbit and shape changes for the transition to proceed.

A complementary element in the shape coexistence framework is provided by the presence of the proposed 8^- isomer, which we would associate with an *intrinsic* state in the prolate well. A feature of $N=106$ *prolate deformed* nuclei is a low-lying $K^\pi=8^-$ state from the $9/2^+[624]\otimes7/2^-[514]$, two-quasineutron configuration which decays by a retarded $E1$ transition to the 8^+ state of the prolate ground state band in all the $N=106$ isotones (see, for example Refs. [11,12]), from ^{176}Yb to ^{184}Pt, and to the prolate-deformed intruder band in ^{186}Hg, with energies which vary from 93 keV in ^{176}Yb to 628 keV in ^{186}Hg. The presence of the isomer in ^{186}Hg was noted as a key sign that there were coexisting shapes in that nucleus [14,15]. The connecting $E1$ transition has hindrance values which range from about 10^{13} to about 10^{11} along the chain.

The lifetime in the present case is comparatively short due, presumably, to the availability of decay paths which do not occur in the other $N=106$ isotones. The proposed 709 keV $E1$ transition is only a 20% branch from the isomer, which gives a partial lifetime of about 8 μs or an $E1$ hindrance of about 10^{10}, less than in ^{186}Hg but roughly following the trend of a hindrance diminishing with increasing Z through the $N=106$ isotones.

The energy systematics of the 8^- isomers relative to the 8^+ state of the prolate band in each nucleus are shown in the lower part of Fig. 5. Note that the energy difference in the ^{178}Hf case ($Z=72$) has been corrected for the perturbation due to strong mixing with an alternative two-quasiproton configuration which is known to interfere in that case [13]. Recent calculations [16,17] of equilibrium shapes constrained to high-K configurations predict a static deformation of $\beta_2=0.26$ for the $K^\pi=8^-$, 2-quasineutron state in ^{188}Pb, similar to that of the prolate minimum, and hence a low energy for such a state in ^{188}Pb. Assuming the same deformation, we have calculated the multiquasiparticle spectrum and confirm that no other two-quasineutron or two-quasiproton states are likely to be low in energy, albeit within the uncertainties of the pairing strength which largely

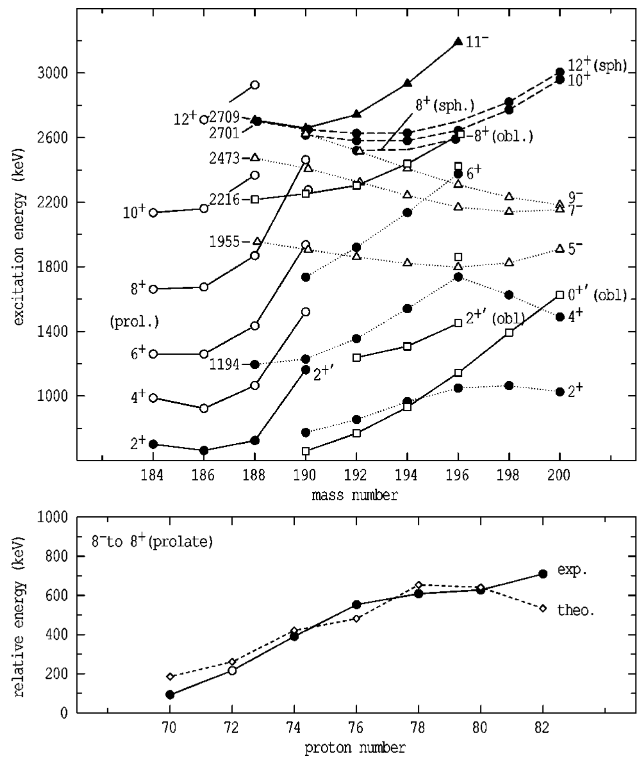

FIG. 5. Partial energy systematics for selected states in the lead isotopes (upper panel) obtained by including the states here in the systematics of Ref. [10], and for the 8^- two-quasineutron isomers in the $N=106$ isotones (lower panel) relative to the 8^+ states of their prolate bands. Note that energy of the 8^- state in ^{178}Hf (shown as an open circle) has been adjusted to correct for two-state mixing. The points marked ''theory'' correspond to the difference between energies of the prolate 8^- states calculated by Xu *et al.* [17] and the *experimental* 8^+ prolate states.

controls these excitation energies. It should also be noted that the potential energy surface calculations of Ref. [17] would not be expected to reproduce precisely the energies of both the (0^+) prolate minimum, and the $K=8^-$ minimum, as is evident from the discussion in Ref. [17]. Hence, the level of agreement in Fig. 5, which shows the calculated 8^- energies relative to *experimental* 8^+ energies, is reasonable.

Finally, a comment on some of the non-yrast states exposed in the decay of the 8^- isomer is appropriate. Their inclusion in the energy systematics of Fig. 5 shows that the 2473 keV state falls on a smooth extension of the locus of the 7^- states which appear in all heavier isotopes, although if it is 7^-, the absence of a branch to the yrast 6^+ state is surprising. A similar match is seen between the 1955 keV state and the 5^- states, and perhaps the 2216 keV state with the 8^+ (oblate) states, lending indirect support to the assignments. The 1194 keV state which was also assigned (4^+) in Ref. [7] fits well into the systematics, although the connecting path to the 1.2 μs isomer (involving the 278 keV transition) is yet to be delineated, being at the limit of the present statistics. Most (but not all) of these states are from spherical configurations which would not occur in the lower $Z,N=106$ isotones hence the 8^- isomer in those decays predominantly to the 8^+ state of the prolate band. The exception is ^{186}Hg in which [15] a 242 keV branch is also observed to the 7^- member of a $\Delta J=2$ sequence based on a 3^- state, a sequence which could have counterparts in ^{188}Pb (7^- and 5^- members being the 2216 and 1787 keV states, for example). The configuration of the band in ^{186}Hg, however, and whether it is of prolate or oblate character, remains uncertain [15].

In summary, isomers have been identified in ^{188}Pb and their presence interpreted as evidence for shape coexistence, complementing previous identifications of the rotational band associated with the prolate minimum [7]. As well as the 11^- and 12^+ oblate and spherical isomers, a candidate for the $K=8^-$ isomer, typical of the prolate well, has been identified. There is also evidence of a higher-lying isomer which feeds through the 12^+ isomer but it has not been placed. Further characterization of all these structures could be through identification of the states which feed them, especially the 8^- isomer, above which should be a rotational band with properties characteristic of the proposed two-quasineutron configuration. Being nonyrast, such states would not be strongly populated, and might be difficult to identify, but the present results lay the foundation for studies in the future, particularly studies which exploit the time correlations.

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