expected to feed the known 6-qp $K^{\pi}=22^{-}$ isomer ($t_{1/2}$=43 μs) [13]. A ^{130}Te(^{48}Ca,2n)^{176}Hf reaction was used, with a 194-MeV ^{48}Ca beam from the ATLAS linac at Argonne National Laboratory, and emitted γ–rays detected with 101 Compton-suppressed Ge detectors of the Gammasphere array [17]. Two different beam-sweeping conditions were used. In the first, beam pulses ~1 ns wide were incident at 825-ns intervals on the target. Subsequently, to cleanly select decays of high-spin isomeric states with half-lives of a few tens of μs, an "on-demand" beam switching system was used in which the beam was switched off for 100 μs following a triple-γ coincidence in a beam pulse, with the master trigger switched to singles during the beam-off period. The out-of-beam data from the first part were sorted into a γ–γ matrix and a γ–γ–γ cube for γ–rays in "prompt" coincidence with each other. While the available statistics was insufficient for any evidence of higher-lying isomeric states, a new ΔK=8 decay branch of the 6-qp isomer to a member of the rotational band built on the $K^{\pi}=14^{-}$ isomer was observed [18]. This is the largest ΔK for K-isomer decays observed in this nucleus. While the primary decay branches observed previously from this isomer and all other isomers in ^{176}Hf have canonical f_{ν} values (between 20 and 120), the f_{ν} for this decay was measured to have the unusually low value of 3.2. This suggests Coriolis K-mixing or chance degeneracies in either the initial or final states involved in the transition, since there are no obvious possibilities of speeding up the decay via shape softness in this axially rigid nucleus or a high density of states environment for statistical mixing of this yrast isomer. Mixing amplitudes and interaction strengths were extracted for the different scenarios. An interesting feature is the observed trend of decreasing f_{ν} with increasing ν [18].

We are continuing the search for higher-qp isomers in ^{176}Hf in two separate recent experiments. The first one was at Jyvaskyla with the same reaction as at Argonne, using the JUROGAM II Compton-suppressed Ge array at the target position and the GREAT spectrometer [19] at the focal plane of the RITU gas-filled recoil separator [20]. The second was at Yale with an array of 10 Compton-suppressed clover detectors, using the original (α,4n) reactions used to study high-spin states this nucleus. Data from both these experiments are currently under analysis.

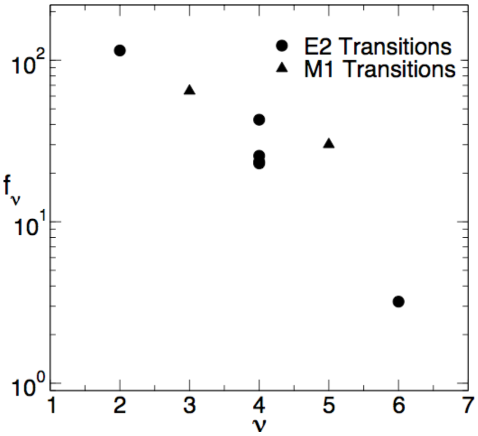

Fig. 3. Reduced hindrance factors f_{ν} as a function of ν for K-isomer decays in ^{176}Hf

4. Neutron-rich Hf

The neutron-rich Hf region has long been identified as one where it is possible for many quasiparticles to unite and form high-K isomers that compete with collective rotation along the yrast line [21]. One of the difficulties in studying neutron-rich Hf nuclei (A≥180) to high spins is that they cannot be populated via fusion-evaporation reactions with beam-target combinations of stable isotopes. It is interesting to note that the $K^{\pi}=8^{-}$ isomer with a 5.5-hr half-life in ^{180}Hf, the heaviest stable isotope of Hf, was observed about 60 years ago via neutron activation of the stable ^{179}Hf isotope [22]. But observation of states feeding this isomer, as well as the population of higher-qp isomers in this nucleus, had to wait another 50 years for new techniques [23]. Advances in using inelastic and transfer reactions to access high-spin states in nuclei have finally allowed this region to be accessed in the past decade.

Over the past decade, we have made significant inroads into both delayed and prompt spectroscopy of neutron-rich Hf nuclei, using heavy beams, such as ^{136}Xe, ^{207,208}Pb, ^{209}Bi and ^{238}U from the ATLAS accelerator at Argonne incident on natural Hf and enriched ^{180}Hf targets, as well as ^{180}Hf incident on a ^{232}Th target.

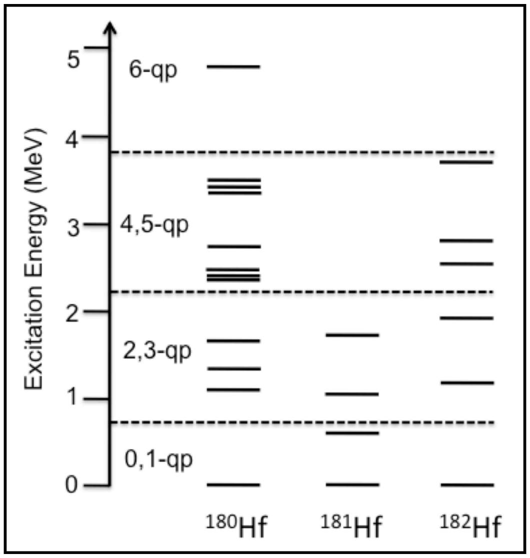

Fig. 4. Multi-qp configurations in neutron-rich $^{180\text{-}182}$Hf nuclei identified in the present work.

The beam energies were typically chosen to be ~15% above the Coulomb barrier, which prior experience had shown to be optimum for mutually exciting both target and beam nuclei to high spins with best peak-to-background for the inelastic and transfer channels. The Gammasphere array was used to detect the gamma-rays and beam sweeping was varied to match the new isomers of interest that were populated [23-25].

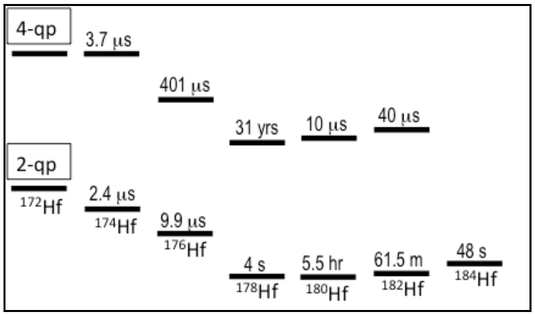

Fig. 5. Systematics of lowest 2-qp and 4-qp high-K configurations in even-even $^{172\text{-}184}$Hf.

The status of our current results on multi-qp high-K configurations and isomers in $^{180\text{-}182}$Hf is shown in Fig.4, and the systematics of 2-qp and 4-qp isomers in the chain of even-even $^{172\text{-}184}$Hf nuclei are shown in Fig.5. Cross-sections drop by approximately 1.5 orders of magnitude for each additional neutron transfer. While advances have been made in pushing into this unstudied region and identifying 4-qp and 6-qp isomers, the progress is slow, and the yrast isomers at the highest spin in neutron-rich Hf nuclei remain elusive. Significant progress in this arena will have to wait for the advent of neutron-rich beams from upcoming rare isotope facilities that could be used for returning to fusion reactions for access to nuclei at high spin at higher N/Z ratios.

5. A~250: superheavies and fusion

The remainder of the talk will focus on our most recent experiments in the A~250 region. The fact that there are only a finite number of elements in the universe is a consequence of long-range repulsive Coulomb interaction between protons winning over short-range nuclear attraction with increasing Z. The tug-of-war between these two forces manifests itself in exquisite fashion in the stability of superheavy elements, where gaps in the shell structure of the nucleons in a mean-field potential formed by the rest of the nucleus provides additional stability against fission, and gives rise to a superheavy island of stability. While this is an active area of current nuclear structure research, extensive experimental effort is necessary to synthesize a few superheavy nuclei at a time [26]. Theoretical models also vary in their predictions of where the next magic spherical shell gap might lie [27-29]. Important input on single-particle energies and residual nucleon-nucleon interactions in this region can come from the spectroscopy of deformed nuclei in the slightly lighter A~250, Z~100 region. This constitutes a frontier region of spectroscopy of the heaviest elements, where single-particle orbitals from the highest oscillator shells can be accessed and studied.

The first studies of ^{254}No (Z=102) using fusion-evaporation reactions showed unexpected stability against fission up to high angular momenta [30]. In addition, low-lying high-Ω orbitals lead to K-isomers. As in the A~180 region, the isomers provide information on single-particle energies, pair gaps and spin-spin residual interactions, and also serve as a tag in selecting the nuclei of interest with improved signal-to-noise. It has also been suggested that the orbitals responsible for the meta-stability of K-isomerism may be responsible for the additional shell stability of of these nuclei at high angular momentum [31].

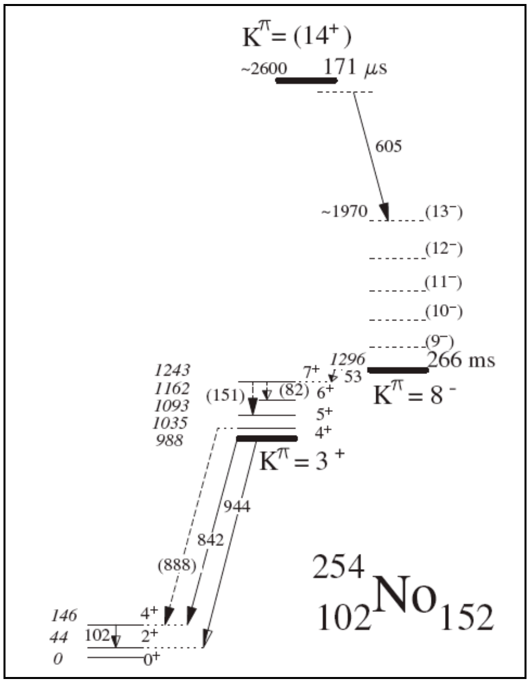

Fig. 6. Level scheme of ^{254}No (from Ref 32).

An excellent example of the quality of spectroscopic information that is obtained from K-isomer data is provided by our study of ^{254}No [32]. This particular experiment was spearheaded by Argonne and the analysis led by the Lowell team. At the outset, the occurrence of K-isomers automatically indicates axial symmetry. An isomer with half-life of 280 ms had been seen in ^{254}No, without any further information on its properties. A ^{208}Pb(^{48}Ca,2n)^{254}No reaction, with 120 pnA of a 217 MeV ^{48}Ca beam from ATLAS at Argonne, was employed to populate high-spin states in ^{254}No, with the goal of identifying γ-rays and conversion electrons emitted in the decay of isomers. The fusion residues were transported to the back of the Fragment Mass Analyzer, implanted into a pixellated double-sided Si strip detector, and identified by their A/Z ratio. An isomer signal required a decay within ~ 1 s in the same pixel as a residue implant. Two K-isomers were identified, and their half-lives and decay pathways measured. The resulting level scheme is shown in Fig.6.

A good understanding of the spectroscopic power of the data can be obtained from an analysis of the 2-qp 3^+ state, which lies in the decay pathway of the higher-lying 2-qp $K^\pi = 8^-$ isomer. The unusually low excitation energy of the 3^+ state, at around the pair-breaking energy, indicates that the energies of the constituent particles lie very close to, and on either side of the Fermi surface. The calculations reproduce this feature very well [27]. In addition, this makes the 3^+ excitation energy very sensitive to the pair gap. The fact that the energy of the 3^+ state is well reproduced by the calculations says that the choice of the pair gap is very good.

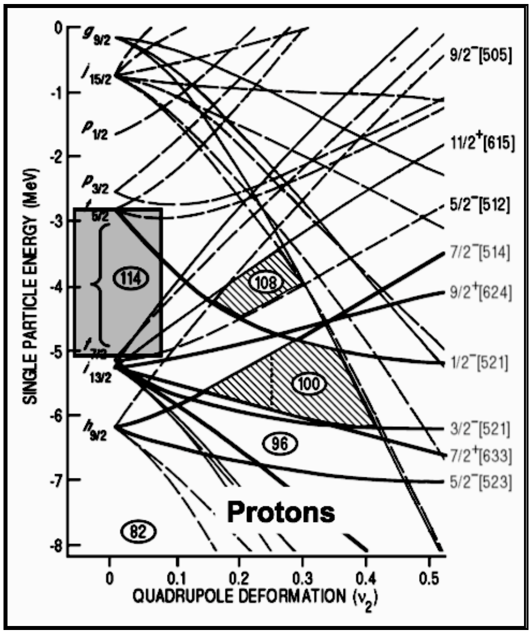

Fig. 7. Proton single-particle energies from Woods-Saxon calculations (from Ref 27).

On a second important note, the 3^+ state has a π^2[514]7/2$^-$[521]1/2$^-$ configuration. The constituent [521]1/2$^-$ orbital has its origin in the spherical $f_{5/2}$ shell above the Z=114 shell gap that occurs in Woods-Saxon calculations (see Fig.7), which also reproduce the 3^+ excitation energy. These seem to validate the Woods-Saxon parameters up to Z=102, and lends faith in its predictions of the next magic shell gap.

6. A~250 region: inelastic and transfer

A systematic exploration of high-spin states and K-isomers in the trans-fermium region of the nuclear chart is in progress using fusion-evaporation techniques [33]. These studies have identified additional sub-shell gaps in the single particle energies, e.g. at N=152 [34]. To follow the evolution and robustness of such a gap with varying Z, an extended isotonic chain of N=150-152 nuclei need to be studied. Since higher-Z nuclei are more difficult to access due to diminishing fusion cross-sections, lower-Z isotones offer a better choice. The spectroscopy of the lower-Z isotones, however, is complicated by the fact that the nuclei get progressively more neutron-rich, and, just as in the neutron-rich Hf region, become inaccessible via fusion of stable beam-target combinations.

Building on our experience in populating high-spin states in the A~180 region using inelastic and transfer reactions [23-25], we have spearheaded a program of spectroscopic investigation of nuclei in the sub-fermium, trans-plutonium region [35-37]. The cross-sections for inelastic excitation and transfer in these Z≤100 region are comparatively higher, and complement the spectroscopy of the heaviest nuclei that are being investigated via fusion-evaporation techniques.

A new challenge in these experiments is that the targets are naturally radioactive. To date, we have utilized ^{246}Cm, ^{249}Cf and ^{244}Pu targets, and have populated and identified K-isomers in the even-even ^{246,248}Cm [35.36] and ^{244}Pu nuclei, as well as carried out prompt spectroscopy of the odd-A ^{247,249}Cm and ^{249}Cf nuclei [37]. A blow-up of the nuclear chart of the region of interest is shown in Fig.8, in which the current experimental status of nuclei being populated for high-spin spectroscopy is marked. The nuclei are differentiated by their mode of population, *viz.*, either fusion-evaporation or inelastic and transfer reactions.

A two-quasineutron 8_ isomer is expected to be present at low excitation energies in all even-even N=150 and 152 nuclei in this region. This is analogous to the two-quasiproton 8^- isomers that are observed in all even-even Z=72 Hf nuclei with 170≤A≤184. The configuration of these 8^- isomers is $\nu^2[734]9/2^-[624]7/2^+$, which involve the two high-Ω neutron orbitals that straddle the N=152 deformed sub-shell gap. The evolution and robustness of this sub-shell gap as a function of Z is one of the aims of these studies. We have chosen to study the N=150 and 152 isotones of Cf (Z=98), Cm (Z=96) and Pu (Z=94), to complement the results obtained in the Fm (Z=100) and No (Z=102) nuclei, with the Rf (Z=104) nuclei at the current spectroscopic frontier being pursued via fusion reactions.

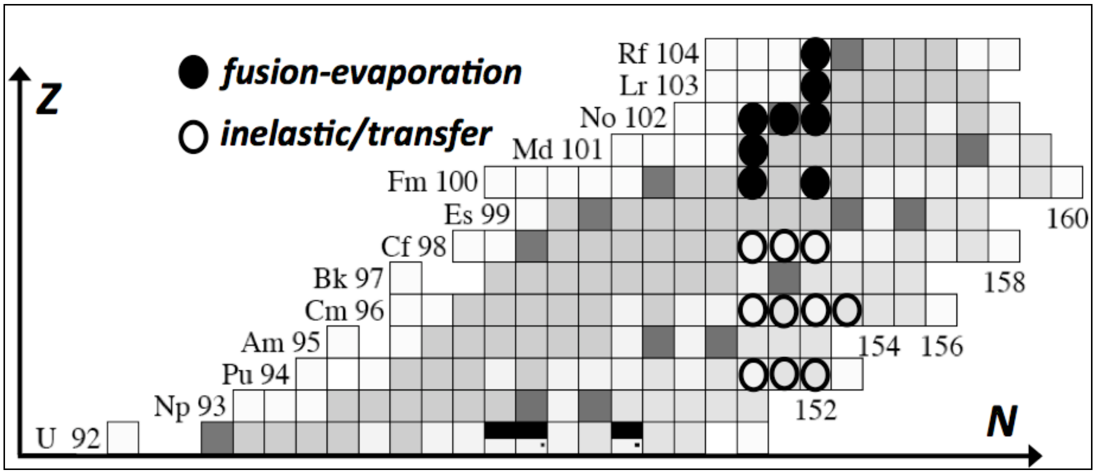

Fig. 8. Recent γ-ray spectroscopy in the A~250 region using different reaction techniques.

^{246}Cm (Z=96, N=100)

The 8^- isomer in ^{246}Cm had been previously populated in the β-decay of ^{246}Am. While the decay scheme had been deduced, the half-life had not been measured. For our experiment, a 1450 MeV ^{209}Bi beam was incident on a thin ^{248}Cm target backed by ^{197}Au. The activity of the target was 0.8 μCi. A series of beam sweeping intervals, ranging from microseconds to seconds, were used to zero in on the half-life of the 8^- isomer in ^{246}Cm.

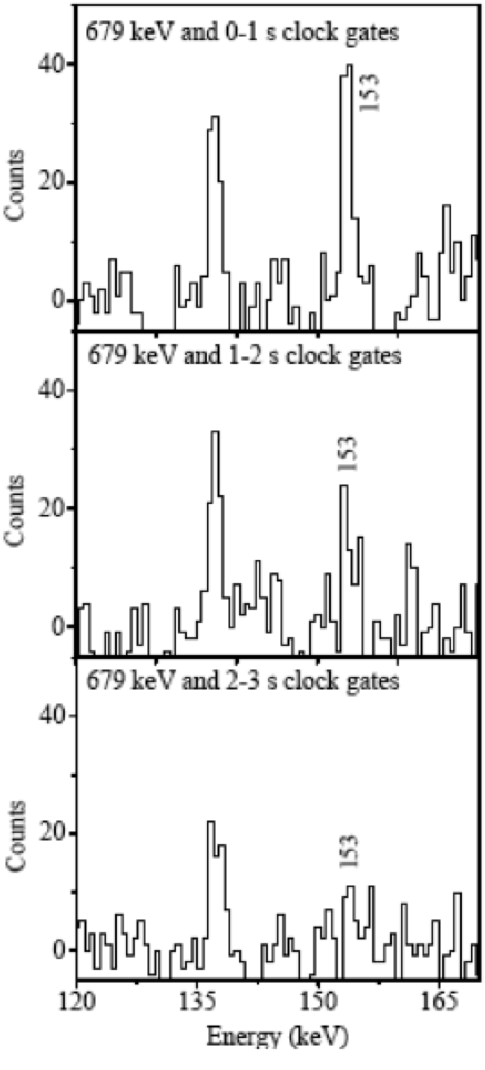

Fig. 9. Time-gated spectra from the decay of the 8^- isomer in ^{246}Cm (see text).

The spectra in Fig.9 show the quality of the data obtained in these measurements for a two-neutron transfer reaction. Although the activity of the target is significant, the out-of-beam spectra are of good spectroscopic quality. The spectra in Fig.9 have been gated on a coincident 679-keV γ-ray in addition to the specific 1-sec intervals marked, as measured by an external clock. From the intensity drop of the 153-keV transition, a half-life of ~1 s is deduced for the 8^- isomer [35,36]. Using the measured half-life, the deduced f_ν value for the K-isomer decay via a ΔK=8 transition is 212. This value is almost identical to that obtained for the N=150 isotone ^{250}Fm (see discussion later). This continues to validate the robustness of axial symmetry in these nuclei, and the associated conservation of the K quantum number in this region.

^{248}Cm (Z=96, N=102)

While the ^{246}Cm nucleus is populated by a 2-neutron transfer reaction, the inelastic channel leading to excitations in the ^{248}Cm target also revealed a new 2-qp isomer with a half-life of the order of a hundred microseconds [35,36]. The spectrum shown in Fig.10 is a sum of double-coincidences of all strong gamma rays in the decay of the isomer, and again shows the cleanliness of the data. An interesting feature of the decay of the isomer in ^{248}Cm is that it proceeds through the gamma-vibrational band, while most of the 2-qp isomers in this region seem to prefer the low-lying octupole bands.

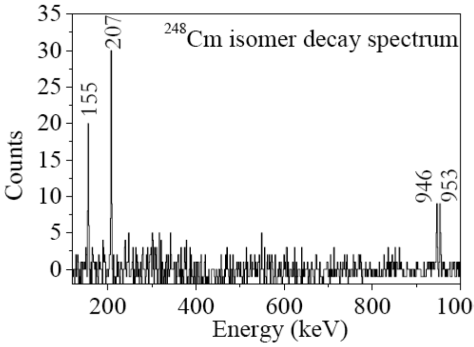

Fig. 10. Sum of double coincidences in the decay of a 2-qp isomer in ^{248}Cm.

^{244}Pu (Z=94, N=100,101)

The ^{244}Pu nucleus was populated via inelastic excitations using ^{47}Ti and ^{208}Pb beams approximately 15% above the Coulomb barrier, incident on a Au-backed ^{244}Pu target. The first experiment, which focused on a search for K-isomers, utilized a ^{47}Ti beam. A subsequent experiment, using a ^{208}Pb beam, was used to look for collective structures feeding the K-isomer observed in the first experiment on ^{244}Pu, as well as look for collective band structures built on single-particle states in ^{245}Pu via one-neutron transfer. Delayed and prompt gamma rays in the two experiments were detected with ~100 Ge detectors in Gammasphere.

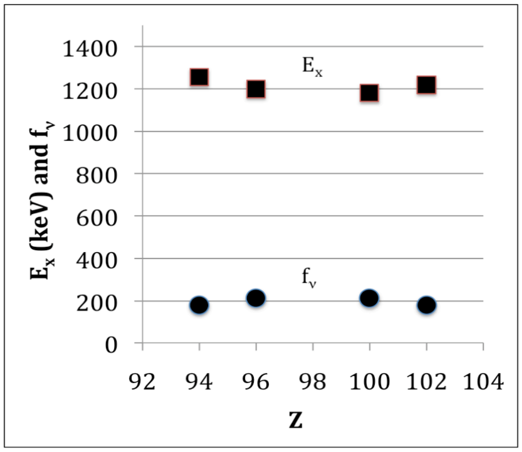

Fig. 11. Excitation energies of 2-quasineutron 8$^-$ K-isomers and reduced hindrance factors for their decay via ΔK=8 transitions to the ground state band in even-even N=150 isotones.

A new K-isomer in ^{244}Pu was identified in the initial experiment that [38] focused on out-of-beam isomer decays, and its measured half-life is measured to be ~2 s. The excitation energy and decay pattern of this isomer is similar to previously observed 2-quasineutron 8$^-$ isomers in heavier N=150 neighbors. In fact, the growing systematics exhibit a remarkable similarity in the properties of these 2-quasiparticle N=150 isomers. The similarity extends to the reduced hindrance factors f_v. The excitation energies and f_v values for the ΔK=8 E1 decay branches of the 8$^-$ isomers to the respective 8$^+$ members of the ground state band, for all 2-quasineutron isomers identified in N=150 nuclei, are shown in Fig. 11.

A candidate band structure possibly feeding the 2-qp isomer in ^{244}Pu, as well as a collective band possibly built on the 1-qp ground state in ^{245}Pu has very recently been identified [38] in the second experiment focused on prompt spectroscopy, and the data are currently under analysis.

Summary

K-isomers provide a versatile and powerful platform for probing the structure and symmetries in deformed nuclei. In the A~180 region, the unresolved physics questions reside at high angular momentum, e.g. the effect of broken pairs on the eventual disappearance of pairing correlations (the spin frontier), and the associated quest for reaching such high-K configurations long-predicted to exist in neutron-rich hafnium nuclei beyond the line of beta-stability (the isospin frontier). In the A~250 region, the spectroscopy of the heaviest elements provides critical information on single particle levels and their interactions, which directly test theories that attempt to describe the structure and stability of superheavy nuclei (the heavy frontier).

Acknowledgments

The experiments presented here were performed in collaboration with students and scientific colleagues from multiple institutions, with the most recent ones primarily from the University of Massachusetts Lowell and Argonne National Laboratory. The work is funded in part by the U.S. Department of Energy under grant DE-FG02-94ER40848.

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