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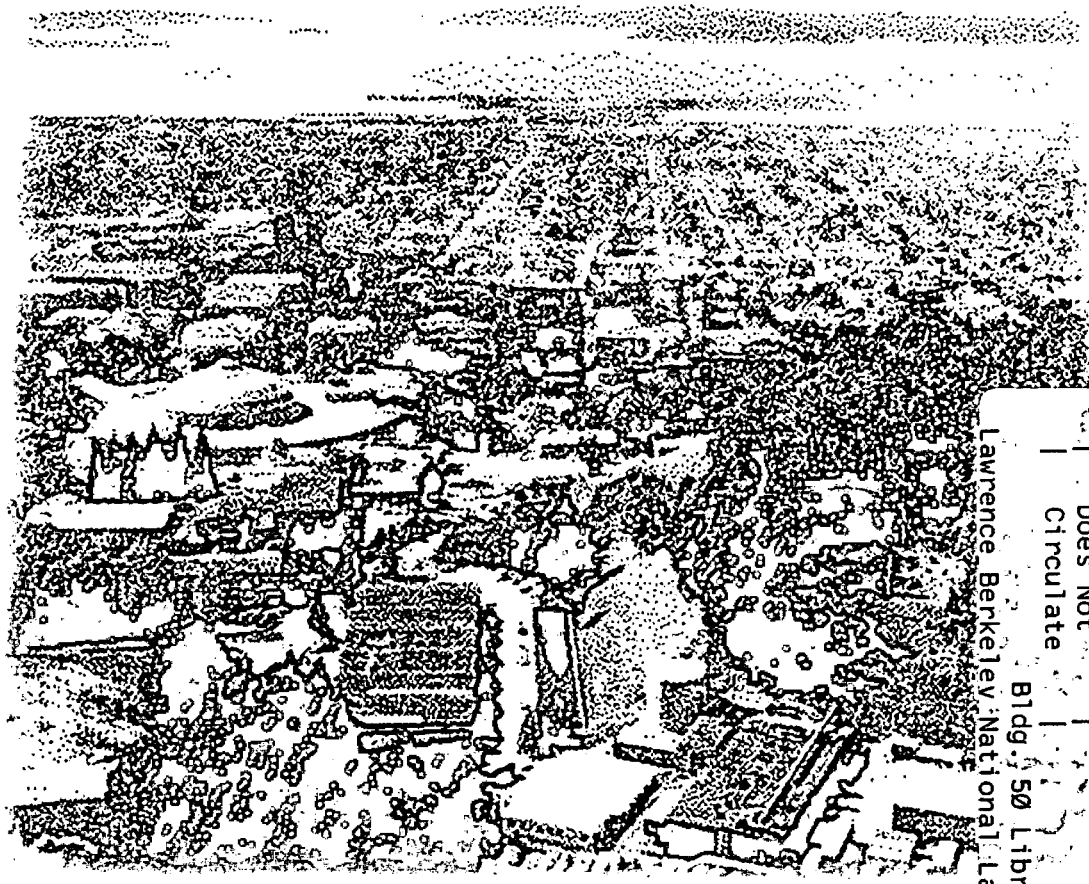

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Search for Proton Decay from a Predicted Isomer of ^{77}Rb

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A search for proton decay from a predicted $\frac{19}{2}^-$ isomer of ^{77}Rb has been performed. Products of the ^{40}Ca + ^{40}Ca reaction at average laboratory bombardment energies of 145 and 160 MeV were transported by helium jet to an array of particle-identification telescopes. No evidence of proton emission from the predicted isomer was observed. In a second measurement, mass 77 residues of the ^{40}Ca + ^{nat}Ca reaction at an average laboratory bombardment energy of 132 MeV were separated using the on-line mass separator RAMA. The yields of ^{77}Rb and ^{77}Sr were monitored by observation of beta-delayed gamma rays; 1.6×10^6 atoms of ^{77}Rb were transported to the detectors. A single particle-identification telescope subtending 23% of 4π sr again showed no evidence of proton emission from the predicted isomer.

PACS number(s): 23.50.+z, 07.75.+h, 21.10.-k, 27.50.+e

I. INTRODUCTION

Direct proton emission was first observed [1-3] from an isomeric state of ^{53}Co. The isomer decays primarily by positron emission to a 2.5 min, $J^\pi = \frac{19}{2}^-$, isomer of ^{53}Fe with a half-life of 247 ms. However, 1.5% of the decays proceed to the ^{52}Fe ground state by emission of a 1.59 MeV (c.m.) proton. Decay energetics, the observed half-life, and shell-model calculations strongly suggest that the ^{53}Co isomer is the isobaric analog of the ^{53}Fe isomer and thus has a spin and parity of $\frac{19}{2}^-$. The observed proton branching ratio from ^{53m}Co leads to an estimated proton-decay partial half-life of ~17 s. This is longer than is typical in proton decay, in part because of the large centrifugal barrier

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between the initial and final states. In addition, major differences between the initial- and final-state wave functions further retard proton emission. Shell model calculations suggest the emitting state is formed by coupling between an $f_{7/2}$ proton hole and a pair of $f_{7/2}$ neutron holes. ^{53}Co remains the only nuclide observed to date that is bound to proton emission from its ground state but emits protons from an isomeric state. (Although proton emission has been observed [4,5] from isomers of ^{165}Ir, ^{171}Au and ^{185}Bi exclusively, all three of these nuclides are also predicted to be unbound to proton emission from their ground states.)

Shortly after the discovery of ^{53m}Co, Peker *et al.* [6] published a paper in which they used the shell model to predict the existence of several three- and four-particle high-spin ($J \geq \frac{17}{2}$) isomers of medium-mass nuclides that would be unbound to proton emission, including the ^{53}Co isomer. Among the predictions is a $\frac{19}{2}^-$ isomer of ^{77}Rb, formed by the coupling of an $f_{5/2}$ hole state with a pair of $g_{9/2}$ neutrons. The predicted excitation of this isomer is ~6.07 MeV, which leaves it unbound to proton emission in the center of mass by 2.93 MeV. Bugrov *et al.* [7] have predicted partial half lives for proton decay from many of these isomers. For this $l = 9$ proton decay, they predict a partial half-life of 240 ms, significantly longer than is typical for proton decays of this energy. Relative to the ground-state proton emitters that have been observed [5,8-13], ^{77}Rb may be produced in high yield via the ^{40}Ca(^{40}Ca, 3p) reaction. Thus it could represent a more experimentally-accessible example of direct-proton emission.

The region of the chart of the nuclides surrounding ^{77}Rb has generated much interest because collectivity in this region has been shown to change very rapidly with changes in microscopic structure. Among the light Kr, Rb, Sr and Y isotopes, various nuclides have been shown to be prolate, oblate and triaxial [14-17]. Shape coexistence has also been observed in this region [18]. Prediction of the isomer's existence is based on the assumption of a spherical collective shape with high spin due to the coupling of a few valence nucleons

residing in high-spin orbitals. However, the ground state of ^{77}Rb is known to be highly prolate from measurements of its spin and magnetic moment [19,20]. This does not *a priori* preclude the possibility that spherical excited configurations could exist, stabilized by the minimization of the surface energy.

In order for proton decay from an isomer to be observed, gamma decay must be strongly hindered. There are many states known in ^{77}Rb at lower excitations than the predicted isomeric state. A few excited states of ^{77}Rb were observed at low excitation energies in the beta-delayed gamma decay of ^{77}Sr [21]. Additionally, in-beam gamma-decay studies of ^{77}Rb [21,22] have reported three rotational bands. These bands include high-spin members to which the predicted isomer could potentially decay via E1 transitions of ~3 MeV. However, differences between the wave functions of these collective-mode states and the many-particle isomeric state may lead to significant gamma-decay suppression. By contrast, the structure of the ^{53}Co-mirror nucleus ^{53}Fe suggests that there are only a few states between the $\frac{7}{2}^+$ ground state and the isomeric state in ^{53}Co [23]. Assuming that these mirror states are present in ^{53}Co, any gamma-ray emission from the isomer must be hexadecapole (l=4) or higher order. This is a significant difference between the cases of ^{77m}Rb and ^{53m}Co.

Two questions are addressed by this work: Will the isomeric state, if it exists, be populated by the decay of the ^{80}Zr compound nucleus and, if so, will its wave function be sufficiently dissimilar from lower-lying collectively-deformed states to allow proton decay to compete with gamma emission?

II. EXPERIMENTAL METHOD

The ^{40}Ca(^{40}Ca,3p) reaction was used to produce ^{77}Rb during three separate bombardments at the Lawrence Berkeley National Laboratory's 88 Inch Cyclotron. During each measurement, a helium-jet system was used to transport the activity away from the target area. When using the helium-jet,

the beam enters (and exits) the target chamber through two HAVAR windows that are cooled by a continuous flow of chilled nitrogen gas. In some cases, the beam energy is further degraded by a thin foil placed upstream of the target(s). The compound-nucleus residues recoil out of the targets and are thermalized in 1.3 atm of helium loaded with KCl aerosols produced by passing the He over KCl heated to ~600°C. Radioactive recoils attach to the aerosols and are swept from the target chamber through a capillary. In the first two measurements, the activity was transported to a detector box approximately 50 cm from the target. For the third measurement, the activity was transported approximately 30 cm to the ion source of the Recoil Atom Mass Analyzer (RAMA) for mass separation prior to counting.

A more complete description of RAMA may be found elsewhere [24-26]; only a brief description will be given here. Figure 1 shows the current configuration of the beam line from the cyclotron and RAMA. The aerosol-loaded helium-jet is fed into an evacuated ion-source region where most of the carrier gas is skimmed away. Since the activity is attached to the surface of high molecular-weight aerosols, it mostly passes through the skimmers into the ion source. RAMA uses a hot hollow-cathode ion source that may be run in either arc mode or surface-ionization mode. Group I elements may be ionized using surface-ionization. In this mode of operation, the tungsten filament is resistively heated to ~2300 °K. In arc mode, a helium plasma is generated from the carrier gas between the anode cap and the hot filament cathode. Ionization of other species is accomplished through charge exchange with the He^{+1} ions. In addition to increasing the ionization efficiency for Group I elements, this permits other elements to be ionized as well. After extraction from the source, the ions pass through a Wien filter optimized for the species of interest. The He^{+1} is deflected, thus minimizing space-charge effects in the rest of the beam optics system. After mass separation, the beam is transported to a neutron-shielded detector station located approximately 10 m from the dipole magnet, where it is implanted for counting.

This was the first measurement to utilize RAMA after several improvements had been implemented [26]. A second skimming stage was added to allow extraction voltages as high as 40 kV to be used, thereby improving extraction and transport efficiencies. The entrance to the ion source is now cooled in an attempt the prevent the explosive breakup of the aerosol clusters prior to entering the source. Most significantly, the entire skimmer/ion source/extraction assembly has been moved so that it sits just above the helium-jet target chamber. By reducing the length of the helium-jet capillary from ~6 m to 30 cm, the transport time has been reduced from several hundred milliseconds to between 15 and 100 ms, depending on whether the space behind the target(s) is swept by one, four or ten small capillaries (which then feed into the single capillary exiting the helium-jet chamber.) The relocation of the ion source has required the addition of ~6 m of beam line and several optical elements, including an electrostatic mirror which redirects the vertically-extracted beam to the horizontal plane. Efficiency tests with the Group I element Na have demonstrated an efficiency of 0.5-1.0%, whereas the efficiency for the Group II element Mg was approximately 10-20 times less [26].

A. Measurements without mass separation

For the first measurement a 245 MeV ^{40}Ca beam was degraded by the HAVAR entrance windows to a mid-target energy of 160 MeV. A 1.9 mg/cm^2 ^{40}Ca separated-isotope target was used. Reaction products were degraded by a 1.7 mg/cm^2 Al foil to increase collection efficiency in the helium gas. After thermalization in the gas, reaction products were swept from the target chamber by a single 1.07 mm inner diameter capillary and transported to a neutron-shielded detector box, as shown in Fig. 2. The activity was deposited onto the tip of a moving tape located at the center of an array of six particle identification telescopes [27], each consisting of two gas-ionization ΔE detectors backed by a 300 μm Si E detector. The catcher tape was slowly moved to prevent the build-up of long-lived activity. Because the tape drive

occludes two of the six telescopes, they were not used; a third telescope became inoperative during the experiment. Each telescope subtended a solid angle of ~4% of 4π sr and was capable of observing protons with energies from 200 to 6000 keV. To calibrate the detectors *in situ*, a separate ^{3}He bombardment on ^{nat}Mg was performed to produced the beta-delayed proton emitter ^{25}Si [28].

Figure 3 shows the results of the 30 mC $^{40}Ca^{11+}$ bombardment, during which the average beam current was 30 enA. The spectrum is dominated by a broad continuum due to the beta- and EC-delayed proton decays of ^{77}Sr and ^{69}Se [29]. A scattering of proton events up to ~5 MeV was also observed, probably due to the decays of one or more weak proton emitters produced in this reaction whose decays have yet to be studied. It is known from other work that products made in the entrance windows of the helium-jet chamber are stopped in the target and do not introduce significant contamination. There is no compelling evidence for the ^{77m}Rb decay group near the predicted proton energy of 2.93 MeV.

A second bombardment of 70 mC was performed using a 260 MeV $^{40}Ca^{11+}$ beam; the helium-jet windows, a 2.4 mg/cm^2 Al degrader and two ^{40}Ca targets of 1.9 and 1.2 mg/cm^2 degraded the beam to a mid-target energy of 145 MeV. Few reaction products made in the second target were stopped in the helium gas; this target acted primarily as a degrader for products made in the first target. The helium-jet transport and the detection system were identical to those used in the previous measurement. Although there were fewer high-energy events, there was again no evidence of a peak due to the decay of the predicted isomer that could be clearly identified in the presence of the other reaction products.

B. Measurement utilizing RAMA

The measurements discussed in the previous section precluded the possibility of a large branching ratio for the isomeric state. Simultaneous production of beta- and EC-delayed protons prevented observation of a weak

branch. Mass separation was employed for the third measurement in an attempt to improve the sensitivity by eliminating all or most of the proton background shown in Fig. 3. Two target configurations were utilized. During the first 24 hours of the experiment, the beam was first degraded by a 0.9 mg/cm^2 ^{nat}Ni foil before impinging on a 4.4 mg/cm^2 ^{nat}Ca target. With this configuration, approximately 40% of the target thickness was sampled; the on-target beam energy over this thickness ranged from 110 to 140 MeV. On-target beam currents of 35 to 90 enA were employed. In the second configuration, the degrader and thick Ca target were replaced by two 2.8 mg/cm^2 ^{nat}Ca targets. The first of these targets acted primarily as a degrader. Approximately 60% of the second target was sampled; over this thickness the beam energy ranged from 125 to 145 MeV. The four-capillary helium-jet system was used to transport the activity to RAMA. This helium-jet arrangement has a transport time of ~50 ms, which is a factor of ~4 longer than the single-capillary configuration. It was reasoned that the improved collection efficiency using this arrangement would more than compensate for half-life losses.

The presence of the beta-delayed proton continuum from ^{77}Sr limited the sensitivity of the earlier measurements. RAMA cannot separate ^{77}Sr from ^{77}Rb by mass, but the different chemical properties of the two isotopes affect their ionization efficiencies. Rb and Sr belong to Groups I and II of the periodic table, respectively. Tests have shown [26] that running the ion source in the arc mode ionizes both Group I and Group II elements, but the efficiency for ionizing Group II elements is a factor of 20 less. Alternatively, when run in surface-ionization mode Group II elements are not ionized. However, the yield of Group I elements is also reduced relative to the arc mode by a factor of two. Arc mode was chosen for this experiment since the absolute ^{77}Rb yield would be better; although not eliminated, the level of contamination from ^{77}Sr would be about twenty times less than in the helium-jet measurements.

The detector configuration for this experiment is shown in Fig. 4. After separation, the mass 77 beam was deposited onto a ~20 μg/cm^2 carbon foil

placed directly in front of a gas-ΔE/gas-ΔE/Si-E particle-identification telescope. The square Si E detector was 50 mm on a side by 300 μm thick; it was placed at a distance of 17 mm from the catcher foil. Using a Monte Carlo simulation of the distributed source, the solid angle for the telescope was calculated to be 23.0 ±0.5% of 4π sr. Two high purity germanium (HPGe) γ-X detectors, with relative efficiencies of 28% and 50%, were placed upstream and to either side of the catcher foil; a gap of 2 cm between the gamma detectors permitted the RAMA beam to pass through.

The RAMA-beam transport optics were tuned on the stable isotopes ^{39}K and ^{85}Rb, which were introduced into the helium-jet as chloride salts. Fine tuning was accomplished by monitoring the rate of 66.5 keV beta-delayed gamma rays from the 3.70 min decay of the ^{77}Rb ground state. Based on the intensities of the ^{77}Rb 66.5 and 178.8 keV gamma-ray peaks observed in the two HPGe detectors, 1.58 ±0.08 × 10^6 atoms of ^{77}Rb were transported to the detector station during the bombardment. Figure 5 shows the gamma-ray spectrum collected with the 28% efficiency detector after subtraction of long-lived background events. This yield is at least 10 times less than had been expected based on the previously observed efficiency for ^{20}Na, though it is difficult to estimate the absolute efficiency due to uncertainties in the production cross section and the helium-jet transport efficiency for this symmetric heavy-ion production reaction.

Three proton events were observed during this measurement, with energies of 1674, 2725 and 4420 keV. Calibration was performed with a ^{148}Gd/^{241}Am alpha source; corrections were made for energy losses [27] in the inactive entrance components (window, gas and silicon dead layer) of the detector telescopes. The 2725 keV event could be from the decay of the predicted ^{77}Rb isomer but the observation of only a single event prevents a positive assignment. More importantly, both this event and the 1674 keV event could be beta-delayed protons from ^{77}Sr, since protons with energies from ~1 - 3.5 MeV are observed in this decay. It should be noted that the

scarcity of proton events from ^{77}Sr is consistent with the number of ^{77}Sr gamma decays detected, based on the known beta-delayed proton branching ratio. Thus suppression of Sr relative to Rb by selective ionization was successful. The origin of the event at 4420 keV is unknown.

III. RESULTS AND DISCUSSION

In order to choose an appropriate beam energy and to interpret the results of the measurements, it has been important to estimate the production cross-sections for the ^{40}Ca + ^{40}Ca compound-nuclear reaction. Two different statistical codes were used for this purpose: ALICE [30] and PACE2 [31]. Whereas ALICE calculates the evaporation probabilities analytically, PACE2 uses a Monte Carlo approach to assess the likelihood of producing the various reaction residues. ALICE predicts a maximum cross-section for production of ^{77}Rb of ~240 mb at a laboratory beam energy of ~140 MeV; the excitation function is predicted to be rather flat from ~120 to ~200 MeV. PACE2 predicts that the peak cross-section is ~130 mb at 125 MeV and that the excitation function is more sharply peaked, falling off rapidly above ~140 MeV. An experiment using the velocity filter SHIP [32] measured a cross section of 29.0 mb at a bombardment energy of 145 MeV [33]. This agrees closely with the prediction of PACE2 of ~32 mb at this energy, suggesting that this is the more accurate of the two codes. The codes predict ^{77}Rb/^{77}Sr relative yields of ~20 and ~15 for ALICE and PACE2, respectively.

Prediction of the yield of the ^{77}Rb isomer relative to its ground state is more difficult. To estimate this ratio for the case of ^{53}Co, Kochan *et al.* [34] assumed that all high-spin ($J \geq \frac{17}{2}$) excited states above the isomer would eventually decay into the isomer. We do not believe this approach is valid for the present calculation. In ^{77}Rb, excited states which are populated after the evaporation of three protons from the ^{80}Zr compound nucleus will tend to decay into the yrast band if they have high spin but relatively low excitation. PACE2 allows the decay sequences leading to a specific residue to

be examined in detail. To estimate the population of the isomer relative to the ground state, we first determined the percentage of all decays that proceed through $J^{\pi} = \frac{19}{2}^{-}$ excited states at excitations within 2 MeV of the predicted isomer. This feeding was divided by the number of $\frac{19}{2}^{-}$ states in this energy range as estimated by treating the system as a Fermi gas with equidistant level spacings and subtracting the (measured) energy of the $\frac{19}{2}^{-}$ yrast level from the excitation energy. Using this method, the expected population of the isomer relative to the ground state is ~1/1500. This estimate should be taken as an upper limit only since microscopic properties of the intermediate states feeding the isomer have been ignored.

During the measurements without mass separation, no evidence of the decay of a high-spin proton-emitting isomer of ^{77}Rb was observed. Because the radiation flux during the measurement was very high, no gamma decay data were taken which would have indicated the amount of ^{77}Rb produced. However, approximately 1300 proton events were observed, the majority of which may be attributed to the beta-delayed proton decay of ^{77}Sr [29]. The measured branching-ratio limit for this decay mode is <0.25%. If we take the relative yield predicted by ALICE (~20:1) for production of ^{77}Rb relative to ^{77}Sr as an upper limit, then the number of ^{77}Rb atoms whose proton decays could have potentially been measured is approximately 1.0×10^{7}. The presence of the ^{77}Sr protons in the spectrum in the energy range predicted for the isomeric decay protons reduces the sensitivity by a factor of ~50. This implies a sensitivity to proton emission of $1{:}2 \times 10^{5}$ relative to the yield of the ^{77}Rb ground-state atoms. The transport time for these measurements was ~15 ms.

More precise limits may be set from the mass-separated data. Based on the number of ground-state beta-delayed gamma-ray decays observed and gamma detector efficiencies, 1.6×10^{6} atoms of ^{77}Rb were transported to the shielded detector station. The solid angle of the particle-identification telescope was 23.0 ±0.5% of 4π sr. If, somewhat arbitrarily, it is assumed that 4 proton events of the same energy would have been sufficient to conclude that

the decay had been observed (given the extremely low background), one can estimate that this measurement had a sensitivity to proton emission of $1{:}1x10^5$, again relative to the ground state yield. The transport time for this measurement was ~50 ms.

The fact that no evidence for proton emission from the predicted isomer of ^{77}Rb has been observed may indicate that the state does not exist. Alternatively, it may be attributed to a lack of feeding to the isomeric state from the compound nucleus, preferential gamma-ray de-excitation of the state or to a combination of these causes. Figure 6 shows a graphical representation of the limits set by the measurements with and without mass separation. The total half-life plotted along the x-axis assumes that the proton partial half-life is 240 ms, as predicted by Bugrov *et al.* [7]. The region above and to the right of the curves is experimentally accessible; that is, the isomer would have been observed had its half-life and feeding been within this region. The sharp decline in sensitivity for isomer half-lives less than ~25 ms is due to half-life losses during transit. Note that if the half-life of the isomer were longer than predicted, the limits would be the same as shown for the predicted half-life. Although the sensitivity is better for the helium-jet only measurements, the limit set with mass separation is more stringent, since the former limit relies on a ^{77}Rb yield estimated from the approximate ^{77}Sr yield. Also, the RAMA measurements were made at somewhat lower bombardment energies. The PACE2 predictions suggest that the measurements without mass separation may not have sampled the peak of the excitation function as effectively. However, the use of thick targets in all instances caused a range of beam energies to be sampled.

The structure of ^{77}Rb has been studied extensively through atomic beam, beta-delayed gamma-ray and in-beam gamma-ray measurements. Atomic beam experiments [19,20] deduced a ^{77}Rb ground state spin of $\frac{3}{2}$ and magnetic moment 0.652 n.m. from magnetic resonance measurements. Based on this information, the valence proton of the ground state was assigned to the $[312\frac{3}{2}]$ Nilsson level corresponding to a deformation of $\varepsilon_2 \equiv$

0.38. A beta-delayed gamma-ray measurement [21] deduced the existence of a handful of excited states. All of these states are well below the excitation of the predicted isomer. Beta decay from the $\frac{5}{2}^+$ ground state of ^{77}Rb to the $\frac{19}{2}^-$ predicted isomer is highly forbidden and was not observed. Subsequent in-beam gamma decay studies [21,22] of ^{77}Rb have revealed the presence of three rotational bands, built on the $\frac{3}{2}^-$ ground state, the $\frac{5}{2}^+$ second excited state at 147 keV, and upon a $\frac{9}{2}^+$ excited state at 1153 keV; the highest members of these bands measured are at excitations of 1715, 12265 and 18376 keV and have spins of $\frac{15}{2}^-$, $\frac{45}{2}^+$, and $\frac{57}{2}^+$, respectively. The bands based on the 147 keV and 1153 keV states correspond to different deformations, with ε_2 values of ~0.38 and ~0.29, respectively. The highest-energy neutron pair of the former band is thought to occupy the $[422\frac{5}{2}]$ Nilsson level; in the latter band, this pair occupies the $[301\frac{3}{2}]$ level. In both cases, the valence proton is thought to occupy the $[431\frac{3}{2}]$ level.

The presence of many high-spin excited states below the predicted isomer in excitation energy presents several possible pathways for the isomer to de-excite to the ground state. In particular, E1 decays to the $\frac{17}{2}^+$ excited states at 1576 or 2596 keV might be expected. If proton emission is to be a viable decay mode, these gamma transitions would have to be severely hindered due to differences in the wave functions and collective shapes of the initial and final states. If the gamma-ray decay is not hindered, it could in principle have been observed in the in-beam gamma studies discussed above. No evidence for the predicted isomer was noted in these measurements. Since the energy of the decay would likely be ~3 MeV, the efficiency for detection would be poor.

Although the experiment by Hardy *et al.* [29] which first measured the decay of ^{77}Sr could potentially have measured protons from an isomer of ^{77}Rb, such an observation was highly unlikely given the limits set in this paper. First, the transport time for the activity was given as ~2 s, so if the prediction by Bugrov et al. [7] is taken as an upper limit, the activity would have decayed

prior to counting. Second, in that experiment only p-γ, p-X, p-e^+ and X-γ coincidences were recorded; coincident X-rays from EC decay were used to identify the element decaying. Since the isomeric state would be produced directly (rather than being fed by highly-forbidden beta decay), proton emission would not occur in coincidence with X or γ emission unless it populated an excited state of ^{76}Kr rather than the ground state.

A search [33] for proton-unstable isomers in this region that discovered a 3.2 μs isomer of ^{76}Rb also looked at the decay of ^{77}Rb using both gamma and proton detectors. This measurement utilized the velocity filter SHIP [32] and was sensitive to isomers with half-lives of 1 μs to 1 ms. ^{77}Rb was produced via the ^{40}Ca(^{40}Ca, 3p) reaction at an energy of 142 MeV; ~14000 counts were observed in the 66.5 and 178.8 keV gamma peaks. No evidence of the predicted isomer is given. Assuming that the Bugrov estimate for the proton-decay partial half-life is reasonable, the proton branching ratio would have been very small (<0.5%) if the isomer half-life were within the range of sensitivity. Because of this, the cross section for the isomeric state would have had to have been comparable to that of the ground state for the proton decay branch to have been observed. In principle, gamma de-excitation of the isomer could have been measured. The relative efficiency quoted for the germanium detector (12%) suggests that the sensitivity to gamma-rays from the isomer would be rather low. It is interesting to note that the ^{76}Rb isomer observed at SHIP had a large hindrance factor of 3×10^6 for E1 gamma-ray emission, which the authors attribute to a possible change in the core-particle structure between the initial and final states.

IV. CONCLUSION

A search has been made for a predicted many-particle $\frac{19}{2}^-$ isomer of ^{77}Rb. The ^{40}Ca(^{40}Ca,3p)^{77}Rb reaction was utilized at energies from 110 to 160 MeV on target. Two measurements using a helium-jet to transport the

activity to an array of particle-identification telescopes set an upper limit for the production cross section for the isomeric state of ~2 x 10^{-5} relative to feeding of the ground state. The same reaction was used in a third bombardment at lower energies in which reaction products were mass separated using the on-line mass separator RAMA. Gamma-ray and charged-particle decays were measured and used to monitor the yield of ^{77}Rb. This measurement sets a more precise upper limit of 1 x 10^{-5} for production of the isomeric state relative to the ground state. Both of the above limits assume a half-life for the isomer that is longer than the helium-jet transport times of ~15 ms and ~50 ms for the direct and mass-separated measurements, respectively.

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REFERENCES

[1] K. P. Jackson, C. U. Cardinal, H. C. Evans, N. A. Jelley, and J. Cerny, Phys. Lett. **33B**, 281 (1970).

[2] J. Cerny, J. E. Esterl, R. A. Gough, and R. G. Sextro, Phys. Lett. **33B**, 284 (1970).

[3] J. Cerny, R. A. Gough, R. G. Sextro, and J. E. Esterl, Nucl. Phys. **A188**, 666 (1972).

[4] C. N. Davids, P. J. Woods, H. T. Penttilä, J. C. Batchelder, C. R. Bingham, D. J. Blumenthal, L. T. Brown, B. C. Busse, L. F. Conticchio, T. Davinson *et al.*, Phys. Rev. Lett. **76**, 592 (1996).

[5] C. N. Davids, P. J. Woods, J. C. Batchelder, C. R. Bingham, D. J. Blumenthal, L. T. Brown, B. C. Busse, L. F. Conticchio, T. Davinson, S. J. Freeman *et al.*, Phys. Rev. **C55**, 2255 (1997).

[6] L. K. Peker, E. I. Volmyansky, V. E. Bunakov, and S. G. Ogloblin, Phys. Lett. **36B**, 547 (1971).

[7] V. P. Bugrov, V. E. Bunakov, S. G. Kadmenskii, and V. I. Furman, Sov. J. Nucl. Phys. **42**, 34 (1985).

[8] S. Hofmann, in *Particle Emission in Nuclei*, edited by D. N. Poenaru and M. S. Ivascu (CRC Press, Inc, Boca Raton, Florida, 1989), Vol. II, p. 25.

[9] S. Hofmann, Gesellschaft für Schwerionenforschung mbH Preprint No. GSI-93-04, 1993 (unpublished).

[10] P. J. Woods, T. Davinson, N. J. Davis, A. N. James, K. Livingston, R. D. Page, P. J. Sellin, and A. C. Shotter, Nucl. Phys. **A553**, 485 (1993).

[11] R. J. Tighe, D. M. Moltz, J. C. Batchelder, T. J. Ognibene, M. W. Rowe, and J. Cerny, Phys. Rev. **C49**, R2871 (1994).

[12] R. D. Page, P. J. Woods, R. A. Cunningham, T. Davinson, N. J. Davis, A. N. James, K. Livingston, P. J. Sellin, and A. C. Shotter, Phys. Rev. Lett. **72**, 1798 (1994).

[13] R. J. Irvine, C. N. Davids, P. J. Woods, D. J. Blumenthal, L. T. Brown, L. F. Conticchio, T. Davinson, D. J. Henderson, J. A. Mackenzie, H. T. Pentillä *et al.*, Phys. Rev. **C55**, R1621 (1997).

[14] C. J. Lister, P. E. Haustein, D. E. Alburger, and J. W. Olness, Phys. Rev. **C24**, 260 (1981).

[15] C. J. Lister, B. J. Varley, H. G. Price, and J. W. Olness, Phys. Rev. Lett. **49**, 308 (1982).

[16] J. Panqueva, H. P. Hellmeister, F. J. Bergmeister, and K. P. Lieb, Phys. Lett. **98B**, 248 (1981).

[17] J. Panqueva, H. P. Hellmeister, L. Lühmann, F. J. Bergmeister, K. P. Lieb, and T. Otsuka, Nucl. Phys. **A389**, 424 (1982).

[18] R. B. Piercey, J. H. Hamilton, R. Soundranayagam, A. V. Ramayya, C. F. Maguire, X.-J. Sun, Z. Z. Zhoa, R. L. Robinson, H. J. Kim, S. Frauendorf *et al.*, Phys. Rev. Lett. **47**, 1514 (1981).

[19] C. Ekström, S. Ingelman, G. Wannberg, and M. Skarestad, Nucl. Phys. **A311**, 269 (1978).

[20] C. Thibault, F. Touchard, S. Büttgenbach, R. Klapisch, M. de Saint Simon, H. T. Duong, P. Jacquinot, P. Juncar, S. Lieberman, P. Pillet *et al.*, Phys. Rev. **C23**, 2720 (1981).

[21] C. J. Lister, B. J. Varley, D. E. Alburger, P. E. Haustein, S. K. Saha, J. W. Olness, H. G. Price, and A. D. Irving, Phys. Rev. **C28**, 2127 (1983).

[22] A. Harder, F. Dönau, K. P. Lieb, R. A. Cunningham, W. Gelletly, C. J. Gross, F. Hannachi, M. K. Kabadiyski, H. A. Roth, D. Rudolph *et al.*, Phys. Lett. **374B**, 277 (1996).

[23] R. B. Firestone, *Table of the Isotopes, Eighth Edition* (John Wiley and Sons, New York, 1996).

[24] D. M. Moltz, R. A. Gough, M. S. Zisman, D. J. Vieira, H. C. Evans, and J. Cerny, Nucl. Instrum. Methods Phys. Res. **172**, 507 (1980).

[25] D. M. Moltz, J. M. Wouters, J. Äystö, M. D. Cable, R. F. Parry, R. D. vonDincklage, and J. Cerny, Nucl. Instrum. Methods Phys. Res. **172**, 519 (1980).

[26] T. J. Ognibene, Ph.D. Thesis, University of California, Berkeley, 1996, (Report No. UC-413/LBNL-38848, unpublished).

[27] M. W. Rowe, D. M. Moltz, J. C. Batchelder, T. J. Ognibene, R. J. Tighe, and J. Cerny, Nucl. Instrum. Methods Phys. Res. **A397**, 292 (1997).

[28] J. D. Robertson, D. M. Moltz, T. F. Lang, J. E. Reiff, J. Cerny, and B. H. Wildenthal, Phys. Rev. **C47**, 1455 (1993).

[29] J. C. Hardy, J. A. MacDonald, H. Schmeing, T. Faestermann, H. R. Andrews, J. S. Geiger, R. L. Graham, and K. P. Jackson, Phys. Lett. **63B**, 27 (1976).

[30] M. Blann and J. Birplinghoff, Lawrence Livermore National Laboratory Report No. UCID-19614, 1982 (unpublished).

[31] A. Gavron, Phys. Rev. **C21**, 230 (1980).

[32] G. Münzenberg, W. Faust, S. Hofmann, P. Armbruster, K. Güttner, and H. Ewald, Nucl. Instrum. Methods Phys. Res. **161**, 65 (1979).

[33] S. Hofmann, I. Zychor, F. P. Hessberger, and G. Münzenberg, Z. Phys. **A325**, 37 (1986).

[34] S. Kochan, B. Rosner, I. Tserruya, and R. Kalish, Nucl. Phys. **A204**, 185 (1973).

FIGURE CAPTIONS

FIG. 1. A schematic diagram of the cave 2 external beam line at the 88 Inch Cyclotron and the Recoil Atom Mass Analyzer (RAMA). The beam line exiting the main dipole magnet lies in the horizontal plane (not in the vertical plane as shown.) Inset: Detail of the RAMA helium-jet target, skimmers, ion source and extraction box.

FIG. 2. Diagram showing the helium-jet target chamber, capillary and detector station used in the initial measurements.

FIG. 3. Proton spectrum resulting from activity produced in a 30 mC $^{40}Ca^{11+}$ bombardment of a ^{40}Ca target at a laboratory energy of 160 MeV. The broad proton continuum is due primarily to the beta-delayed proton decay of ^{77}Sr.

FIG. 4. Detector configuration used at the shielded detector station of RAMA in the mass-separated measurement. Activity is stopped in a carbon catcher foil mounted on the front face of the detector telescope housing.

FIG. 5. Gamma ray spectrum resulting from the decay of mass 77 residues of a ^{40}Ca bombardment of ^{nat}Ca targets at an average laboratory energy of 132 MeV. The spectrum of long-lived background species has been subtracted.

FIG. 6. Experimental limits on the population of the isomer relative to the ground state of ^{77}Rb and on the isomer half-life, based on the results of the measurements made with helium-jet transport only and with subsequent mass separation by RAMA. The relative population, as estimated using PACE2, is also shown.

Figure 1

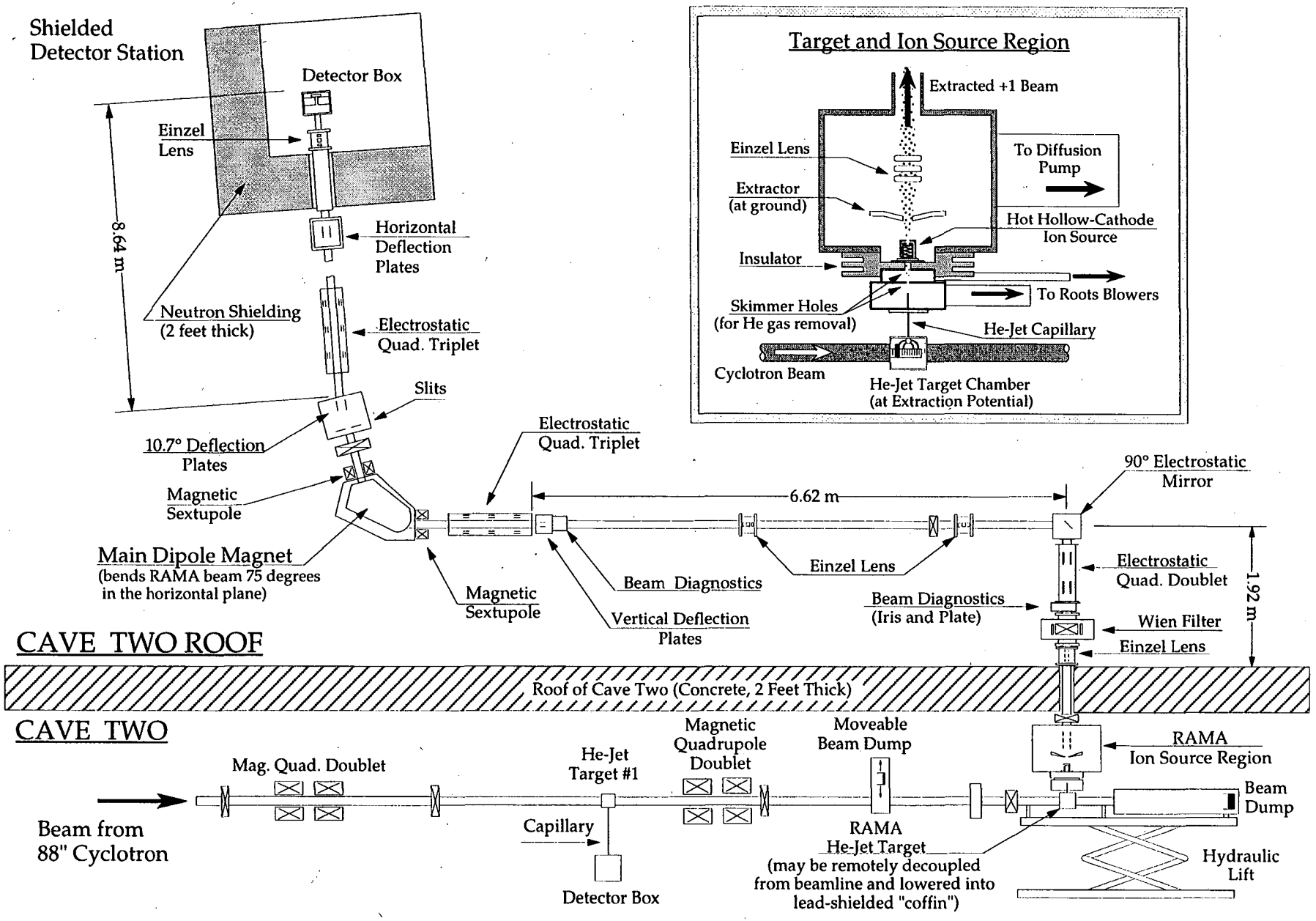

Shielded
Detector Station
Detector Box
Einzel
Lens
8.64 m
Horizontal
Deflection
Plates
Neutron Shielding
(2 feet thick)
Electrostatic
Quad. Triplet
Slits
10.7° Deflection
Plates
Magnetic
Sextupole
Main Dipole Magnet
(bends RAMA beam 75 degrees
in the horizontal plane)
Target and Ion Source Region
Extracted +1 Beam
Einzel Lens
To Diffusion
Pump
Extractor
(at ground)
Hot Hollow-Cathode
Ion Source
Insulator
To Roots Blowers
Skimmer Holes
(for He gas removal)
He-Jet Capillary
Cyclotron Beam
He-Jet Target Chamber
(at Extraction Potential)
Electrostatic
Quad. Triplet
6.62 m
90° Electrostatic
Mirror
Beam Diagnostics
Einzel Lens
Electrostatic
Quad. Doublet
1.92 m
Beam Diagnostics
(Iris and Plate)
Wien Filter
Einzel Lens
Magnetic
Sextupole
Vertical Deflection
Plates
CAVE TWO ROOF
Roof of Cave Two (Concrete, 2 Feet Thick)
CAVE TWO
Mag. Quad. Doublet
He-Jet
Target #1
Magnetic
Quadrupole
Doublet
Moveable
Beam Dump
RAMA
Ion Source Region
Beam
Dump
Beam from
88" Cyclotron
Capillary
Detector Box
RAMA
He-Jet Target
(may be remotely decoupled
from beamline and lowered into
lead-shielded "coffin")
Hydraulic
Lift

Figure 2

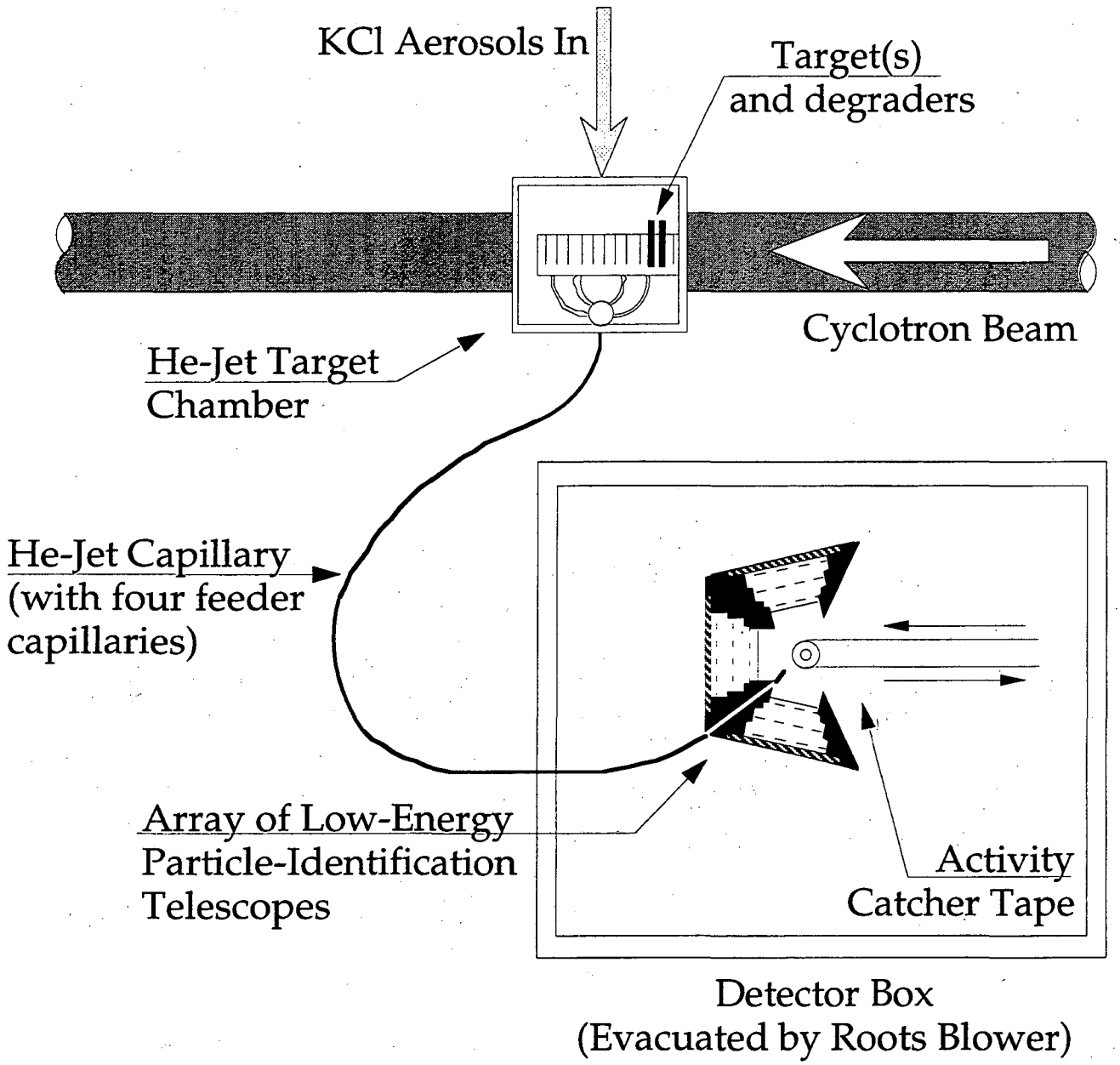

KCl Aerosols In
Target(s)
and degraders
Cyclotron Beam
He-Jet Target
Chamber
He-Jet Capillary
(with four feeder
capillaries)
Array of Low-Energy
Particle-Identification
Telescopes
Activity
Catcher Tape
Detector Box
(Evacuated by Roots Blower)

Figure 3

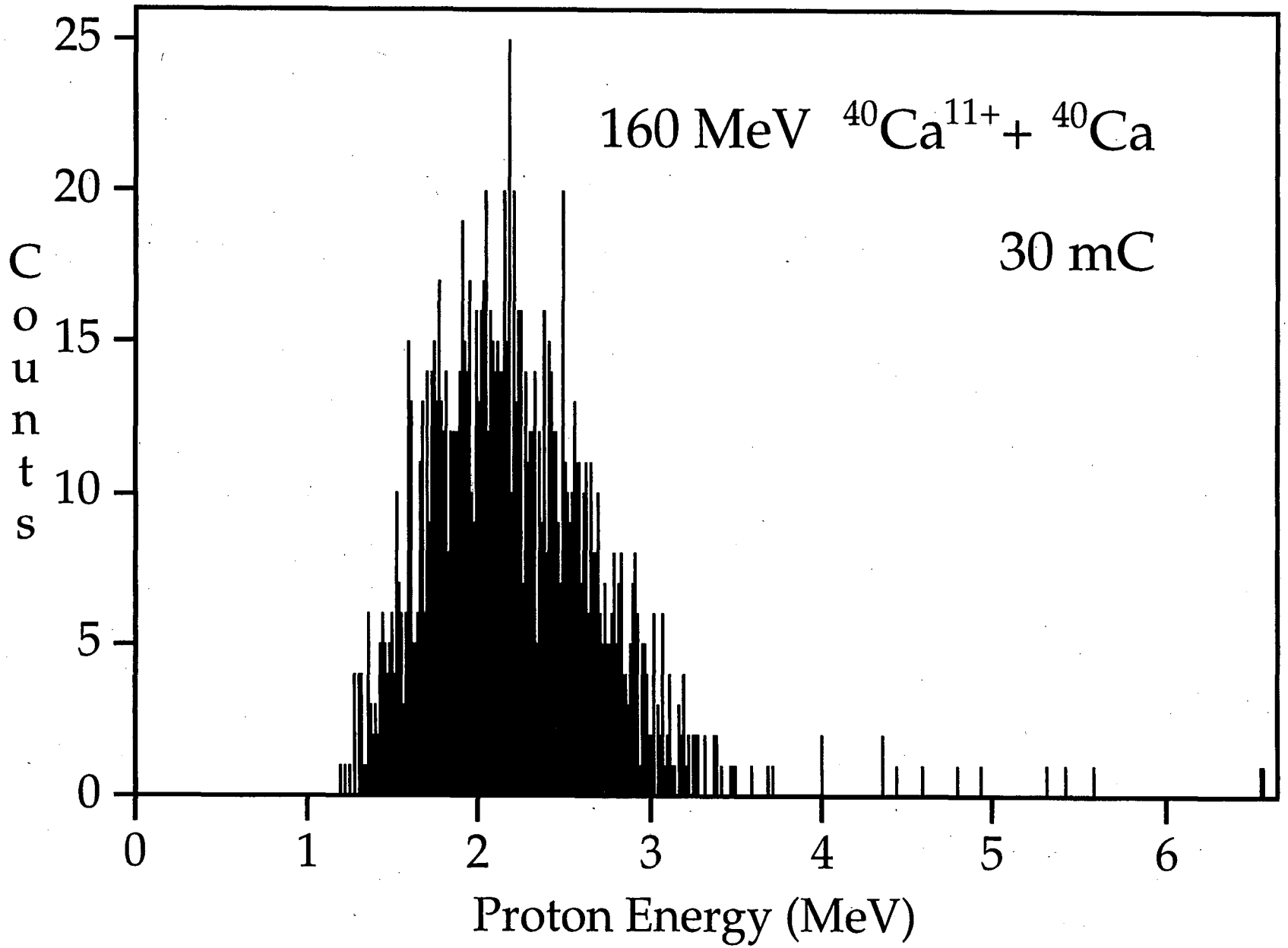

160 MeV $^{40}Ca^{11+}$ + ^{40}Ca
30 mC
Counts
Proton Energy (MeV)
0
5
10
15
20
25
0
1
2
3
4
5
6

Figure 4

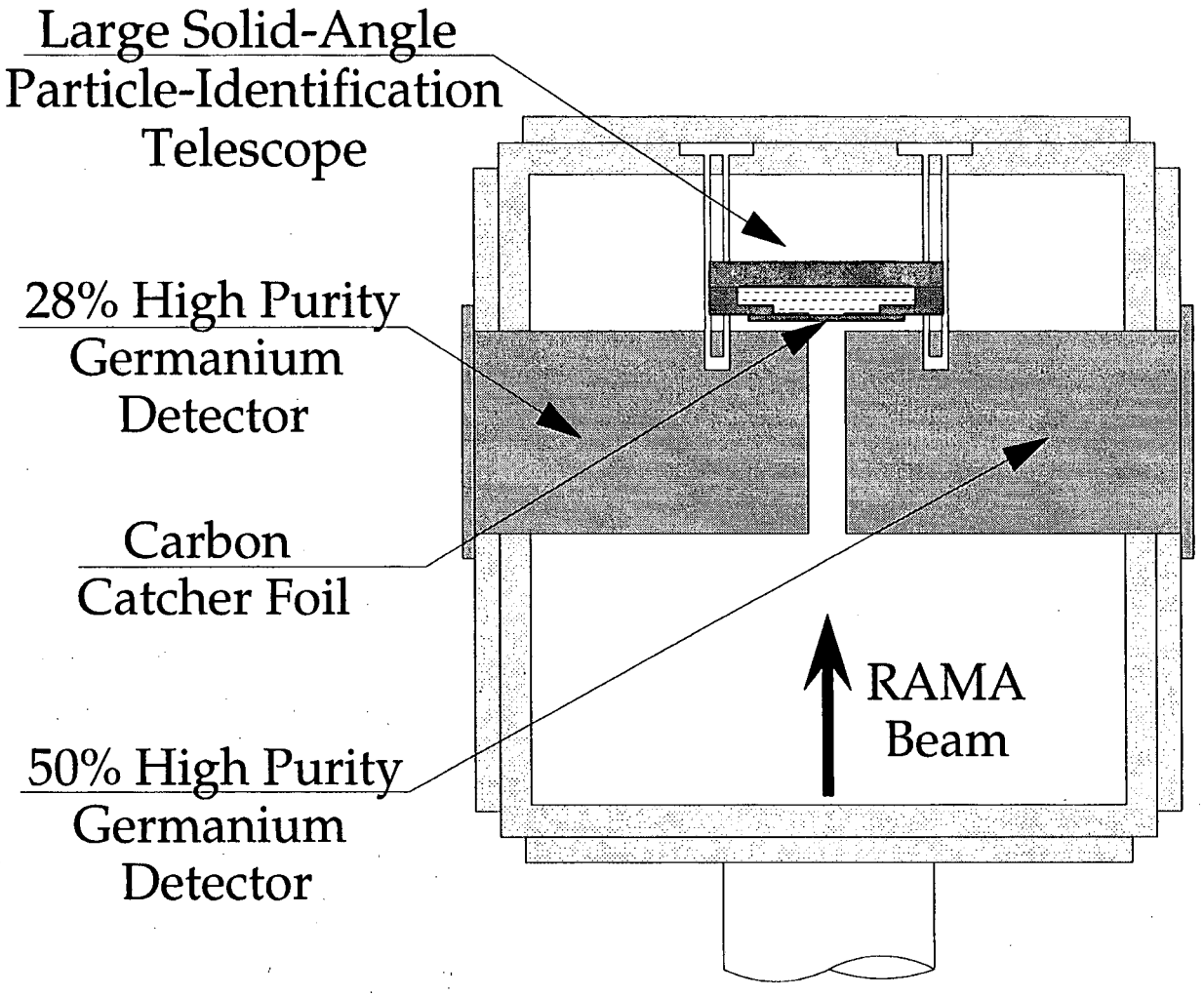

Large Solid-Angle
Particle-Identification
Telescope
28% High Purity
Germanium
Detector
Carbon
Catcher Foil
50% High Purity
Germanium
Detector
RAMA
Beam

Figure 5

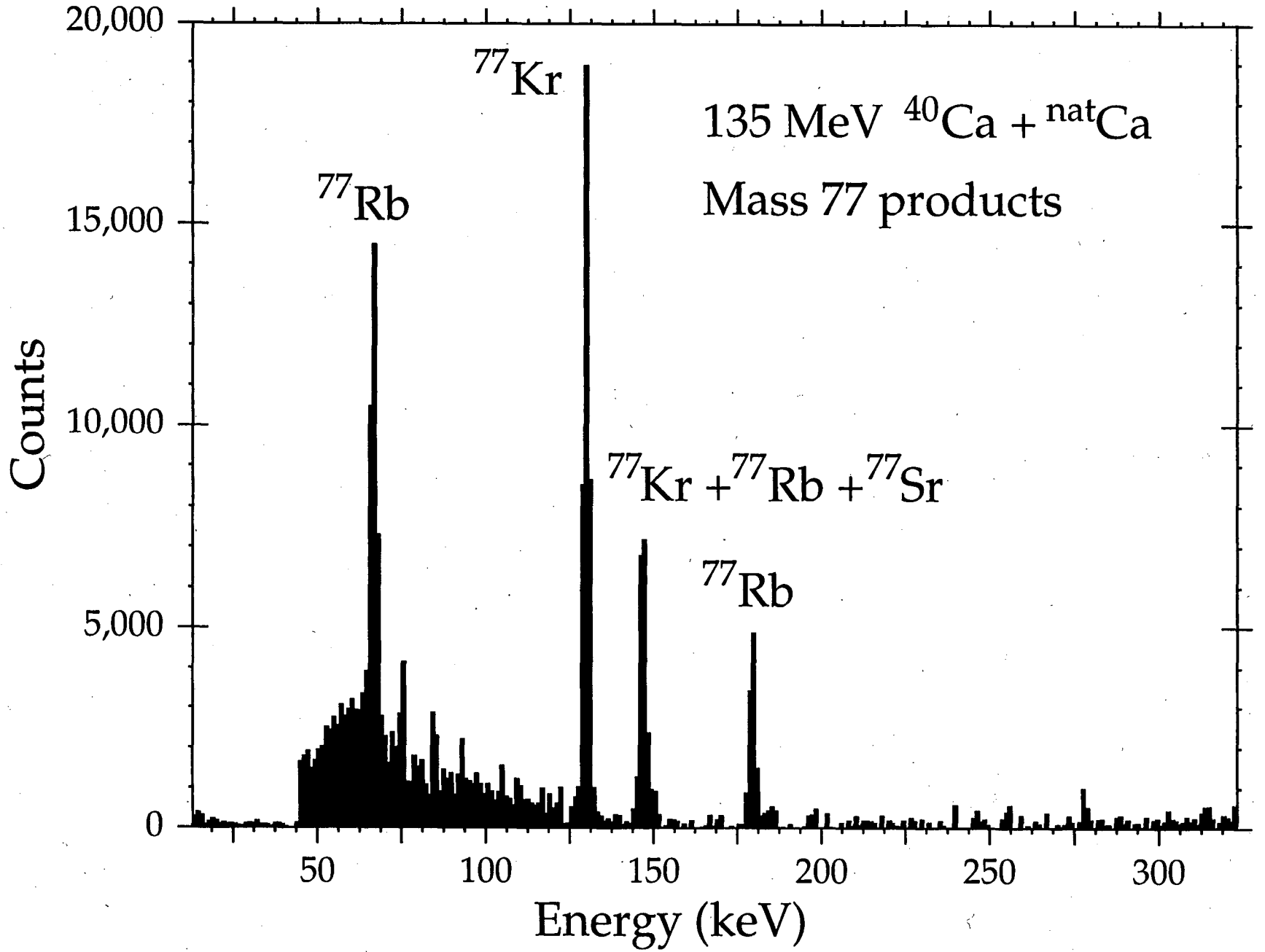
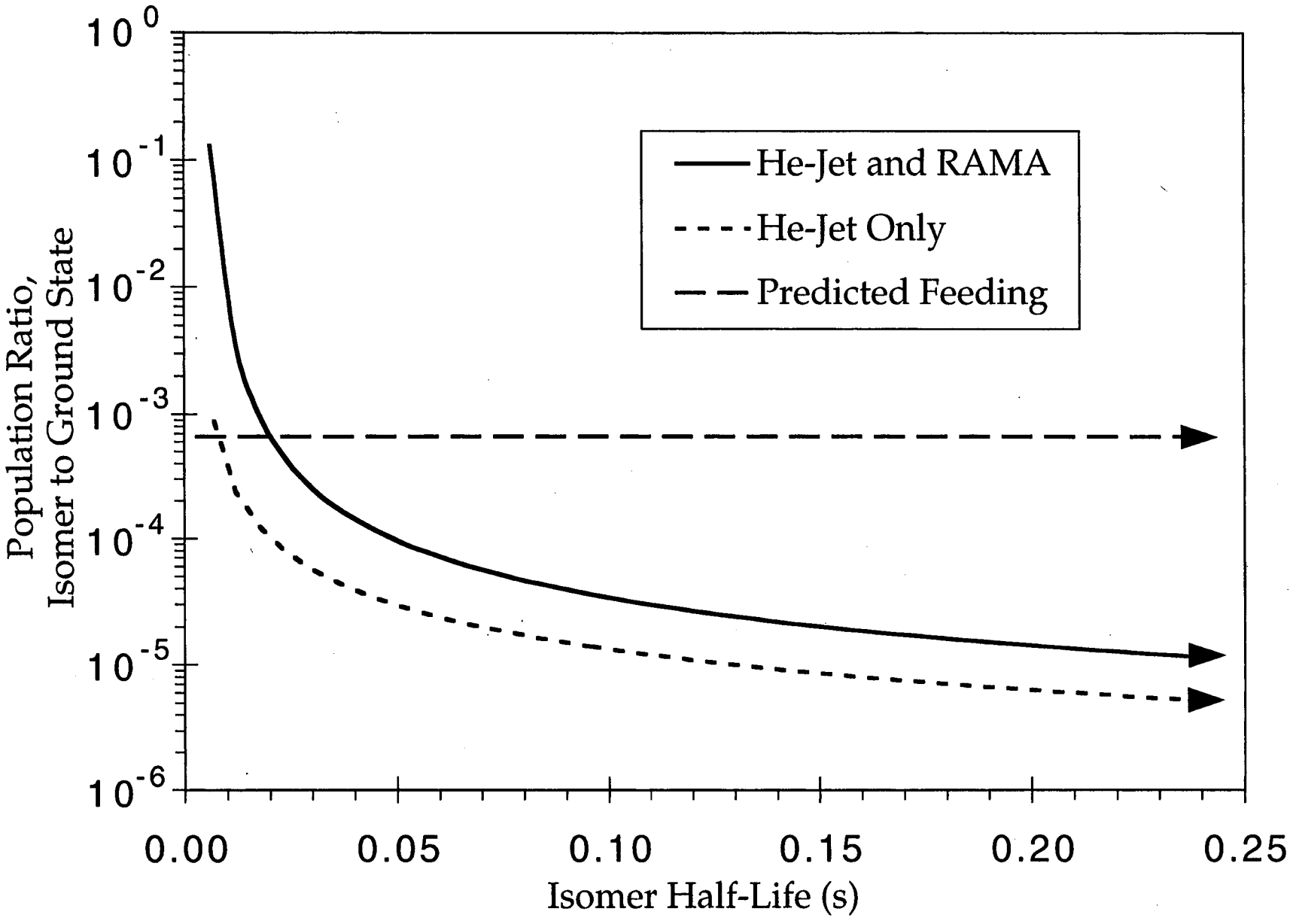

20,000
15,000
10,000
5,000
0
Counts
50
100
150
200
250
300
Energy (keV)
77Kr
77Rb
135 MeV 40Ca + natCa
Mass 77 products
77Kr +77Rb +77Sr
77Rb

Figure 6


Population Ratio,
Isomer to Ground State
10 0
10 -1
10 -2
10 -3
10 -4
10 -5
10 -6
He-Jet and RAMA
He-Jet Only
Predicted Feeding
0.00
0.05
0.10
0.15
0.20
0.25
Isomer Half-Life (s)

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