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First observation of excited states in ^{118}Ba: Possible evidence for octupole correlations in neutron-deficient barium isotopes

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Excited states have been observed for the first time in the very neutron-deficient ^{118}Ba nuclide. The ground-state band and a side band have been observed up to spins 20 and 17 $\hbar$, respectively. The bands have been assigned to ^{118}Ba using gamma-recoil and gamma-x ray coincidences. Excitation-energy systematics suggest that the ground state of ^{118}Ba is less deformed than that of ^{120}Ba. The side band decays into the ground-state band via three transitions, which are presumed to have $E1$ character. The occurrence of $E1$ transitions and negative-parity states in the very neutron-deficient barium ($Z=56$) isotopes is discussed with respect to the possible onset of octupole correlations. [S0556-2813(98)50703-0]

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The evolution of quadrupole deformation and the predicted development of octupole collectivity are two of the motivations to study the $Z=56$ barium isotopes as the neutron number N approaches the proton drip-line. Throughout the $A\simeq 120-130$ barium isotope chain, experimental data suggest that the ground-state deformation increases as N decreases. Calculations [1] predict that the deformation will be largest for $A=118$, but at present no barium nuclei with $A<120$ have been studied by in-beam spectroscopy, and the lower limit on the trend of increasing deformation has not been experimentally established. With $N\simeq Z=56$, octupole deformation is predicted to develop. The nucleon number 56 has been cited as one of the octupole driving particle numbers [2], due to the close proximity of the Fermi level to orbitals from both the $h_{11/2}$ and $d_{5/2}$ subshells, which are characterized by differences in angular momentum $\Delta\ell=\Delta j=3$. The neutron-rich $Z=56$ barium isotopes with $N\simeq 90$ have already been shown to possess octupole deformation [3]. In those nuclei, the neutron Fermi level lies close to $i_{13/2}$ and $f_{7/2}$ ($\Delta\ell=\Delta j=3$) orbitals, so that both the protons and neutrons can contribute to the octupole deformation. For the very neutron-deficient barium isotopes, the neutron octupole correlations will increase as N decreases towards 56. The barium isotopes offer the unique possibility of studying octupole correlations in two different regions of the nuclear chart. This paper reports on the first observation of excited states in ^{118}Ba, which is the most neutron-deficient barium isotope to which excited states are assigned. The ground-state band and a side band are observed to spins 20 and 17 $\hbar$, respectively. The side band decays into the ground-state band via three transitions which presumably have $E1$ character. This structure is suggestive of octupole correlations.

The main reason why the barium isotopes with $A<120$ have remained unstudied by in-beam gamma-ray spectroscopy is that they lie in a region which is experimentally very difficult to access. The best method to populate high-spin states in these nuclei is to use heavy-ion fusion-evaporation reactions. However, the most neutron-deficient compound nuclei that can be produced with Z just above 56 are $^{121}_{57}$La, $^{122}_{58}$Ce, $^{127}_{59}$Pr, and $^{128}_{60}$Nd. Clearly, the only reactions with a reasonable chance of populating ^{118}Ba will involve $p2n$ or $2p2n$ evaporation from the $^{121}_{57}$La or $^{122}_{58}$Ce compound nuclei, respectively. In this region, charged-particle evaporation dominates, making the total evaporation-residue cross section highly fragmented. Spectroscopy of the residues following neutron evaporation is only possible when channel-selection techniques and sensitive gamma-ray detectors are used. In this work, the ^{58}Ni(^{64}Zn,$2p2n$) reaction was used to populate excited states in ^{118}Ba, for which the predicted cross section is of the order of a few mb. High-spin spectroscopy was performed with the GAMMASPHERE array, and Z and A assignments were made in a separate experiment using the Argonne Fragment Mass Analyser (FMA) [4] where recoil-gamma ray and x ray-gamma ray coincidences were observed.

Initially, high-spin states were populated using the ^{58}Ni(^{64}Zn,$2p2n$)^{118}Ba reaction, and deexcitation gamma rays were detected using the GAMMASPHERE array [5]. The ^{64}Zn beam at 265 MeV was provided by the 88-inch cyclotron at the Lawrence Berkeley National Laboratory. The beam was incident on a target consisting of two stacked 500-μg/cm^2, self-supporting, 99%-pure ^{58}Ni foils. At the time of the experiment, the GAMMASPHERE array had 56, 75%-efficient escape-suppressed germanium detectors in place, which were arranged in rings of constant polar angle, θ, and which provided a near-isotropic solid-angle coverage. With the condition that 3 or more suppressed germanium detectors fired before an event was recorded, a total of 9×10^8 gamma-ray coincidence events were written to magnetic tape. In the offline analysis, each n-fold event ($n\geqslant 3$) was unfolded into ${}^nC_3$ threefold gamma-ray coincidences,

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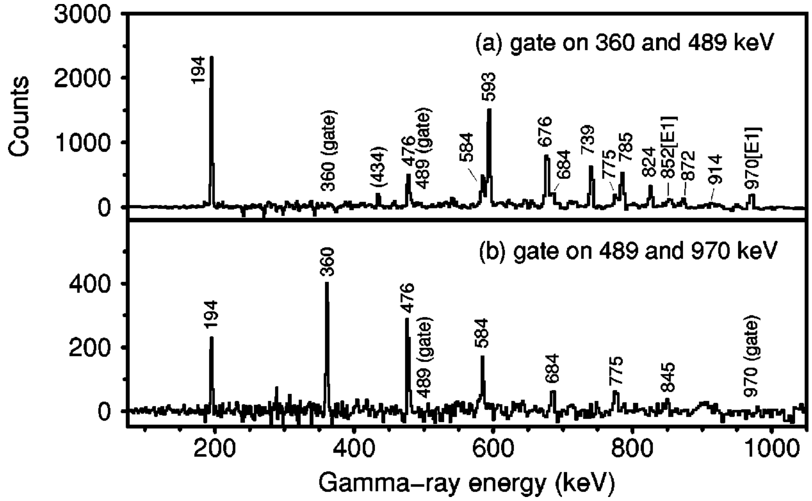

FIG. 1. Representative spectra from the GAMMASPHERE data. The spectra are projected from the cube by specifying two gating transitions: spectrum (a) is gated on the 360- and 489-keV transitions and shows both the ground-state and negative-parity bands and the linking $E1$ transitions; spectrum (b) is gated on the 489- and 970-keV transitions and primarily shows transitions in the negative-parity band. The peaks are labeled with the gamma-ray transition energy, given to the nearest keV and all of the labeled peaks correspond to transitions in ^{118}Ba. The 434-keV transition is a contaminant from a neighboring nucleus.

yielding a total of approximately 6×10^9 unfolded triples $(E_{\gamma1}E_{\gamma2}E_{\gamma3})$, which were subsequently used to increment a three-dimensional histogram, or *cube*. Spectroscopic information was extracted from the cube using the interactive analysis code LEVIT8R [6] which projects one-dimensional spectra incremented by $E_{\gamma3}$, after $E_{\gamma1}$ and $E_{\gamma2}$ have been specified. By gating on known transitions, approximately 15 nuclei were identified in the data. The most intensely populated nuclei were ^{118}Xe ($4p$ evaporation), ^{119}Cs ($3p$), and ^{116}Xe ($\alpha2p$), which were produced with approximately 33%, 30%, and 19% of the total evaporation-residue cross section, respectively. In addition, over 20 gamma-ray cascades were observed which were not in coincidence with any known gamma rays. One of these cascades, which was populated with less than 0.5% of the total cross section (approximately 2 mb), was tentatively assigned to ^{118}Ba on the basis of excitation-energy systematics and statistical-code calculations [7]. Figure 1 shows two representative spectra from the GAMMASPHERE data, gated on suspected ^{118}Ba gamma rays.

Using energy- and intensity-balance arguments, together with coincidence relationships derived from the cube, the level structure shown in Fig. 2 was deduced. A type of angular-distribution measurement helped in assigning the spin values to the levels. Two gamma-gamma correlation matrices were constructed with gamma-ray energy from any germanium detector on one axis, and the gamma-ray energy measured in the detectors at a particular value of θ on the other axis. By gating on the ''any germanium'' axis and projecting the spectrum of gamma rays measured at a particular θ, the intensity I^θ was measured. Using this method, the intensity of gamma rays in the 6 detectors at 90°, (I^{90}), and the intensities in the 34 detectors at 31°, 37°, or 50°, (I^{fwd}), were determined. After normalization, assuming that the energy dependence of the detection efficiencies of the GAMMASPHERE detectors were all equal, the ratio I^{fwd}/I^{90} was found to be near 0.7 for a stretched-dipole and near 1.3 for a stretched-quadrupole transition. These values were calibrated using known transitions in ^{119}Cs [8] and ^{118}Xe [9]. With this technique, the spin assignments up to 14 $\hbar$ in Fig. 2 were determined. Of the three transitions connecting the side band and the ground-state band, it was possible to confirm that the 970-keV transition has an angular-intensity ratio consistent with it having stretched dipole character; however, the 852- and 1104-keV transitions were not of sufficient intensity to extract the ratios.

In order to define the nuclei from which gamma rays originated, a second experiment was performed in which gamma rays were detected in coincidence with recoiling reaction products and with x rays. A self-supporting, 500-μg/cm^2 ^{64}Zn foil was bombarded with a ^{58}Ni beam from the Argonne Tandem Linac Accelerator System (ATLAS). Two beam energies of 230 and 240 MeV were used. Gamma and x rays were detected at the reaction site in an array of 10, 25%-efficient escape-suppressed germanium detectors; the thresholds on 2 of the detectors were reduced to about 25 keV in order to detect $\sim$35-keV K x rays, from the reaction products with $Z\simeq56$. Recoiling evaporation residues were separated according to their mass-to-charge state ratio (M/q) by the FMA and were detected in a parallel-grid avalanche counter (PGAC) at the focal plane. With the requirement that two or more germanium detectors fired, or that a gamma ray was detected in coincidence with a recoil at the focal plane, approximately 9×10^7 events were recorded. The transmission efficiency of the FMA was determined to be approximately 15%.

The spectrum recorded by the PGAC at the focal plane is shown in Fig. 3(a). With a mass resolution of 1 in $\sim$470, $M=118$ recoils corresponding to charge states $q=24$, 25, and 26 were detected at the focal plane. Approximately half of the detected evaporation residues had $M=118$, but by far the majority of these corresponded to the ^{118}Xe [9] and ^{118}Cs [10] nuclei. The data were sorted into various gamma-gamma correlation matrices including an ungated (no recoil requirement) matrix and matrices gated by mass from $M=115$ to $M=120$. Gating on the strongest transitions in ^{117}Cs [11] and ^{119}Cs [8] in the $M=118$-gated matrix indicated that contamination from adjacent masses was negligible. The method used to assign excited states to ^{118}Ba is essentially the same as that described in Ref. [10]. The spectrum in Fig. 3(b) is the total projection of the $M=118$-gated matrix. Some of the transitions suspected to belong to ^{118}Ba can be seen, but are generally buried beneath a background of stronger transitions. Figure 3(c) shows gamma rays in coincidence with a $M=118$ recoil, and either a 360- or a 489-keV gamma ray. The spectrum reveals the same coinci-

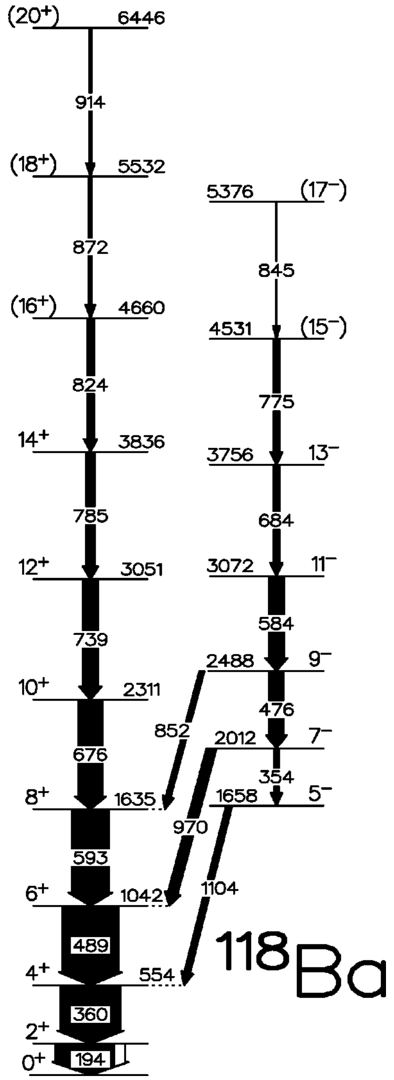

FIG. 2. The level structure of ^{118}Ba deduced in this work. The width of the arrows is proportional to the gamma-ray intensity. The errors of the intensities range from 5% to 20%, and the errors on the energies range from 0.1 keV to 0.5 keV, with the larger errors associated with the weak or degenerate transitions. The fraction of decay which proceeds by internal conversion is given as the unfilled portion of the intensity arrow (this is only significant for the 194-keV $2^+ \to 0^+$ transition). Where there is more than one path to the ground state, the level energies were fit using the RADWARE code LEVIT8R.

dent transitions as would be expected from the level scheme of Fig. 2, and confirms that the bands belong to a nucleus with mass 118. Figure 3(e) is a gate on the 360-keV transition in the ungated matrix. Clearly the spectrum is not contaminated apart from small peaks that can be attributed to ^{120}Ba (via coincidences with the 358-keV $4^+ \to 2^+$ transition in ^{120}Ba [12]) and ^{117}Cs (possibly via the 357-keV transition in ^{117}Cs [12]). The K-x ray region of the spectrum is shown on an expanded scale in Fig. 3(d), in comparison with gates on uncontaminated transitions in ^{119}Cs [8] and ^{118}Xe [9]. Despite the low statistics in the ^{118}Ba-gated spectrum, there are clearly more counts in the channels where the barium K x rays are expected, verifying the assignment to ^{118}Ba. It should be pointed out that this method of isotopic assignment is only possible because the 194-keV $2^+ \to 0^+$ transition has a relatively large internal-conversion coefficient of 0.195, which generates sufficient x-ray intensity that the K-x ray peak can be observed.

Given the level scheme of Fig. 2, information about the structure of ^{118}Ba can be inferred. An estimate of the ground-state quadrupole deformation β_2 can be made from the energy of the $2^+ \to 0^+$ transition. The deformations of the even-even barium isotopes, extracted in this way using the relationship derived by Raman [13], are shown in Fig. 4 as a function of neutron number, together with the predictions of both total-Routhian surface (TRS) calculations [14,15], and the microscopic-macroscopic calculations of Möller, Nix, Myers, and Swiatecki [1]. Both calculations predict that the deformation will be a maximum for ^{118}Ba. The experimental data, however, suggest that ^{118}Ba is already less deformed than ^{120}Ba. These data therefore establish a lower limit on the trend of increasing deformation in the neutron-deficient barium isotopes.

The ground-state band in ^{118}Ba has been observed to 20 $\hbar$. Cranked shell model calculations [14] have been performed which predict the alignment of a pair of $h_{11/2}$ neutrons $[\nu(h_{11/2})^2]$ at a rotational frequency ~ 0.41 MeV/$\hbar$, followed almost immediately by the alignment of a pair of $h_{11/2}$ protons $[\pi(h_{11/2})^2]$ at ~ 0.42 MeV/$\hbar$. The ground-state band of ^{118}Ba shows a large gain in aligned angular momentum between frequencies 0.3 and 0.5 MeV/$\hbar$. In this work, it is proposed that the alignment observed in ^{118}Ba is due solely to $h_{11/2}$ protons. The reason for this interpretation is twofold. First, the frequency of the alignment, the gain in aligned angular momentum, and interaction strength at the alignment in ^{118}Ba are very nearly identical to the $\pi(h_{11/2})^2$ alignment observed in the $\nu h_{11/2}$ band of ^{119}Ba [11], where the $\nu(h_{11/2})^2$ alignment is blocked. The deformations predicted by TRS calculations are very similar for the ground-state band of ^{118}Ba and the $\nu(h_{11/2})$ band of ^{119}Ba, suggesting that a comparison of alignments is valid. Second, recent data for ^{120}Ba [11] reveal distinct $\pi(h_{11/2})^2$ and $\nu(h_{11/2})^2$ bands above the respective alignments in the ground-state band. The alignment observed in ^{118}Ba is analogous to the alignment of $h_{11/2}$ protons in ^{120}Ba.

A side band has been observed to 17 $\hbar$ in ^{118}Ba. The band feeds into the ground-state band via three transitions. The data for ^{118}Ba suggest that the 970-keV transition, linking the side band to the ground-state band, has stretched-dipole character. Furthermore, excitation-energy systematics would suggest that the side band in ^{118}Ba has negative parity; a negative-parity side band has been observed in all of the even-even barium isotopes with $A < 132$. This negative-parity band in ^{118}Ba does not show the $\pi(h_{11/2})^2$ alignment at ~ 0.4 MeV; the absence of this alignment suggests that the band is probably based on a configuration involving an $h_{11/2}$ proton, such as $\pi(h_{11/2}) \otimes \pi(d_{5/2}/g_{7/2})$. Despite this argument, the lowest negative-parity states in ^{118}Ba cannot easily be explained in terms of a rotational band built on a two-quasiparticle excitation. For example, the excitation energy of the 5^- state is less than twice the pairing gap, essentially ruling out a pure two-quasiparticle excitation. Furthermore, although the states above about 11 $\hbar$ appear to form a rotational sequence, the lower members of the band do not fit a rotational description. (This has also been observed in the neighboring heavier barium isotopes [22].) In addition, the

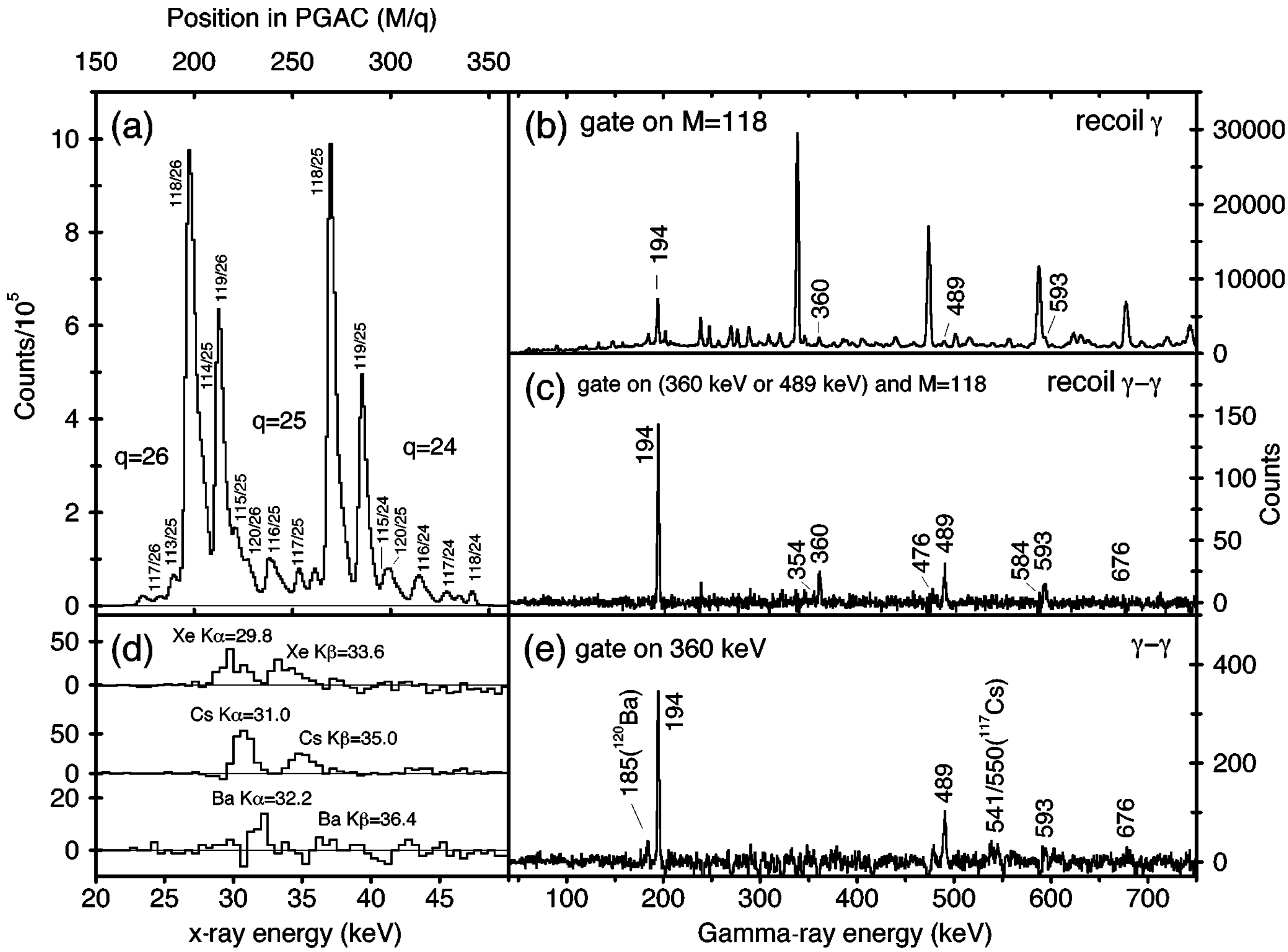

FIG. 3. Results from the ATLAS/FMA experiment. Panel (a) shows the spectrum of recoils recorded by the PGAC at the focal plane. The peaks are labeled with M/q. Panel (b) shows the total projection of a $\gamma\gamma$ matrix gated on $M=118$-recoils. The largest peaks belong to ^{118}Xe and ^{118}Cs. The 194-keV ^{118}Ba transition is buried underneath several more-intense 193/194-keV ^{118}Cs transitions. Panel (c) shows a sum of spectra projected from the $M=118$-gated matrix, gated on the 360- and 489-keV transitions. Panel (d) shows the K-x ray region of spectra projected from an ungated matrix. The lowermost spectrum is that gated on the 360-keV transition. K x rays in coincidence with gates on uncontaminated transitions in ^{118}Xe (upper) and ^{119}Cs (middle) are also given on panel (d). The higher-energy part of the 360-keV gated spectrum is shown in panel (e) and shows almost nothing but ^{118}Ba transitions. Peaks in panels (b), (c), and (e) are labeled with energies to the nearest keV and belong to ^{118}Ba unless otherwise indicated.

Nilsson orbitals which are most likely to be involved in the configuration are the [550]$1/2^-$ and [422]$3/2^+$, giving $K=2$ for the band. If the negative-parity band has $K=2$ it is difficult to explain the relatively intense $E1$ transitions to the $K=0$ ground-state band (although $K=1$ is also possible). For these reasons it is proposed that the lowermost negative-parity states arise due to the mixing of a $\pi(h_{11/2})\otimes\pi(d_{5/2}/g_{7/2})$ two-quasiparticle configuration and a collective octupole band involving both proton and neutron $d_{5/2}$ and $h_{11/2}$ ($\Delta\ell=\Delta j=3$) orbitals.

Specific calculations have predicted that octupole correlations will become important around $^{112}_{56}$Ba$_{56}$ [23,24]. The calculations predict that the ground-state octupole deformation will decrease rapidly as N increases above 56, but the possibility that rotation will enhance the octupole correlations at about 6 or 8 $\hbar$ in the heavier ($N\simeq 60$) barium isotopes is not ruled out. The strength of octupole correlations is difficult to quantify experimentally and it is often inferred from the relative excitation energies of the positive- and negative-parity states, or from the strength of $E1$ transitions (although it should be remembered that the $E1$ strength is subject to shell corrections [25]). Some evidence for octupole correlations in this region has already been presented; large $B(E1)$ values have been reported in the nuclei ^{114}Xe [26], ^{117}Xe [27], and ^{110}Te [28]. In this work, $B(E1)$ values for ^{118}Ba have been estimated from the $B(E1)/B(E2)$ ratios. Assuming a quadrupole moment of 496 $e$fm^2 [from TRS calculations for the $\pi(h_{11/2})\otimes\pi(d_{5/2})$ configuration], $B(E1)$ values of approximately 6×10^{-5} e^2fm^2 have been extracted for the $7^-\rightarrow6^+$ and $9^-\rightarrow8^+$ transitions, which are comparable in magnitude to the values reported in ^{114}Xe and ^{117}Xe. Furthermore, for the even-even barium isotopes, the excitation of the negative-parity states decreases steadily with N, from $A=132$ to $A=118$. The nucleus ^{118}Ba is interesting in this respect because the positive-parity states are displaced upwards in excitation energy with respect to ^{120}Ba, yet the negative-parity states are lower. This suggests that in the lighter barium isotopes the positive- and negative-parity

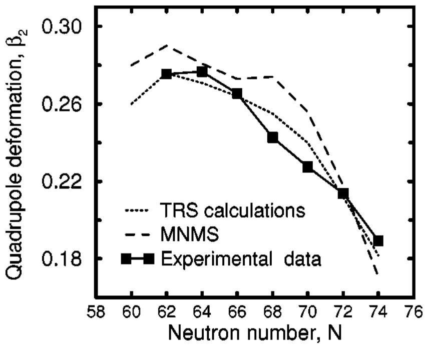

FIG. 4. Quadrupole deformation parameters, β_2, of the even-even barium isotopes, plotted as a function of neutron number. The experimental values, deduced using Raman's relation [13], are compared to the TRS calculations, and the predictions of Möller, Nix, Myers, and Swiatecki [1]. The experimental data are taken from Refs. [12,16–21], apart from ^{118}Ba from this work.

states may form an interleaving sequence with the I^- states lying lower in energy than the adjacent $(I+1)^+$ states at low spin. The observation of such a band would present a valuable insight into octupole collectivity in this region, but in-beam spectroscopy of barium isotopes with $A<118$ with stable beams and targets will prove to be very difficult. These nuclei are, however, excellent candidates to be studied once suitable radioactive-ion beams have been developed.

In summary, excited states have been observed and identified for the first time in the very neutron-deficient nuclide ^{118}Ba. Spectroscopy was made possible using the high resolving power of the GAMMASPHERE array. Channel identification was performed using the FMA, by detecting recoil-gamma ray and x ray-gamma ray coincidences. The ground-state deformation of ^{118}Ba appears to be smaller than that of ^{120}Ba, thus establishing a lower limit on the trend of increasing deformation with decreasing neutron number in the $A\simeq120$–130 barium isotopic chain. The observation of a low-lying negative-parity band, decaying by relatively strong $E1$ transitions, cannot easily be explained as a two-quasiparticle rotational structure at the lowest spins and is proposed as possible evidence for octupole correlations.

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