# Lifetimes in the yrast and an octupole-vibrational superdeformed band in $^{196}$Pb

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Lifetimes have been measured for states in the yrast (band 1) and an excited superdeformed band (band 2) in $^{196}$Pb. The excited band is thought to be built on an octupole vibration, rather than a quasiparticle excitation. Centroid shifts and line shapes of transitions in $\gamma$-ray coincidence spectra measured with the EUROBALL spectrometer have been analyzed. The transition quadrupole moments deduced from these data for the yrast and the excited superdeformed band are identical within the experimental uncertainties. This result shows that the excited band is not built on different deformation-driving orbitals compared to band 1. It is compatible with the previous suggestion of an octupole-vibrational excitation for the signature partner bands 2 and 3.

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## I. INTRODUCTION

In recent years, a large number of superdeformed (SD) rotational bands has been observed in nuclei in the mass ≈190 region [1]. In order to make reliable assignments of nucleonic configurations to these bands, it is essential that spectroscopic information beyond transition energies becomes available. The large $\gamma$-ray spectrometer arrays EUROBALL [2] and GAMMASPHERE [3] have allowed great progress to be made in this respect, e.g., it has been possible to establish the linking transitions to normal-deformed (ND) states in $^{194}$Hg [4,5] and $^{194}$Pb [6,7], thus determining spins and transition energies. Furthermore, transitions between SD bands in several nuclei were observed [8–12]. Such measurements provide invaluable information on the orbitals forming the nucleonic configurations of the SD states. Recent work has also indicated that several of the excited bands in even-even nuclei are based on octupole vibrations, rather than quasiparticle excitations [5,12–15]. Here, we present results on lifetime measurements of SD states in $^{196}$Pb which support this interpretation.

In $^{196}$Pb four SD bands are known [16,17]. One of the excited bands (SD band 3) decays into the yrast SD band via several very enhanced electric dipole transitions [13] with $B(E1)$ values of $\approx 10^{-4}$ W.u. Together with theoretical calculations [14,18], these results strongly suggest that band 3 and its signature partner band 2 are built on an octupole vibration in the SD potential energy minimum of $^{196}$Pb.

In this work, we report on a measurement of lifetimes of states within the yrast SD band 1 and the excited SD band 2. Lifetimes of states in the yrast band have been measured previously [19], but for the excited bands no lifetime information exists. As the analysis of Doppler shifts of transitions in the two bands was performed on $\gamma$-ray spectra obtained under identical conditions, the relative quadrupole moments deduced from the lifetimes are very reliable. We find that the

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quadrupole moments for the yrast SD band 1 and for SD band 2 are identical within the experimental uncertainties. This result is compatible with the assignment of band 2 as an octupole vibration. Such an excitation should have no large effect on the deformation, as it involves many different components in the wave function. If band 2 would instead be based on an excitation involving strongly deformation-driving quasiparticle orbitals, like the $N=6\, i_{13/2}$ or $N=7\, j_{15/2}$ intruder orbitals, a deviation in the deformation from the yrast SD band would be expected.

In the following section the experimental methods and results are described. In the last section the results are discussed, followed by a brief summary.

## II. EXPERIMENTAL METHODS AND RESULTS

High-spin states in $^{196}$Pb were populated in the reaction $^{170}$Er($^{30}$Si,4$n$) at a beam energy of 144 MeV, the $^{30}$Si beam being provided by the VIVITRON Tandem accelerator at the Institute de Recherches Subatomiques, Strasbourg. The target consisted of an enriched $^{170}$Er foil of 1.65 mg/cm$^2$ thickness on a 6.64-mg/cm$^2$-thick Au backing. Gamma-ray coincidences were measured with the EUROBALL-IV spectrometer [2]. It comprises 30 Compton-suppressed conventional Ge detectors and 26 clover and 15 cluster composite Ge detectors. At the time of the experiment 230 individual Ge detector crystals were operational. An inner ball of 210 BGO scintillators was used as a multiplicity filter. Coincidence events were recorded when four or more Ge detectors before Compton suppression and five or more BGO detectors of the inner ball gave coincident signals. After the presorting of the data, in which gain matching, pile-up suppression, and add back for the composite detectors was carried out and a window was set on the prompt time peak, a total of $1.1\times10^9$ events with coincidence fold $\geqslant$3 remained. These data were stored in a BLUE database [20] which was used for the further analysis.

For the Doppler-shift analysis the Ge crystals of the EUROBALL spectrometer can be grouped into eight rings at the following average angles with respect to the beam direction: 15.5°, 34.6°, 52.3°, 76.6°, 103.3°, 129.7°, 137.1°, and 156.2°. Spectra were created for each of these angles for both bands from the BLUE database. Combinations of three energy gates on transitions of the respective bands were required. As an example, Fig. 1 shows two such spectra from forward and backward detectors for the yrast SD band 1. Spectra from the near-90° detectors were used to locate possible contaminations at the position of the shifted peaks in the spectra from the forward and backward detectors.

Two Doppler-shift attenuation methods (DSAM's), the analysis of centroid shifts and of line shapes, were used to determine lifetimes in the SD bands. It is well known that lifetime measurements by Doppler-shift methods suffer from the problem of unknown side-feeding lifetimes. In high-statistics coincidence measurements this problem can be solved by setting gates on transitions above the states for which the lifetimes are to be determined, thus eliminating the side feeding into these states. For band 2 only spectra with gates below the transitions of interest had sufficient statistical accuracy, but here we could use the side-feeding model tested for the yrast SD band. For that band the intensity was sufficient to analyze spectra with both, gates above and below the transitions of interest.

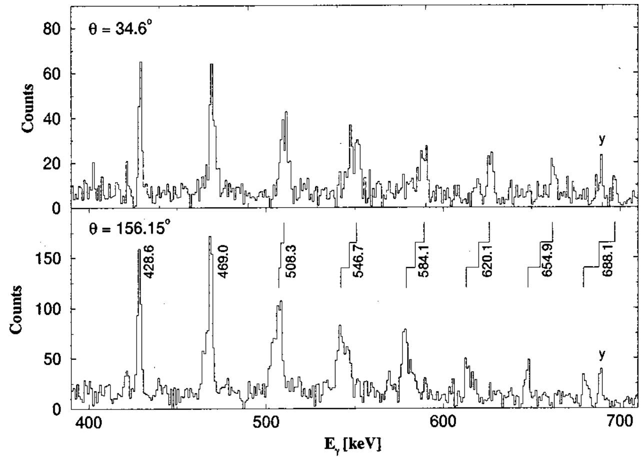


FIG. 1. Triple-gated background-subtracted spectra of the yrast SD band 1 from the ring of forward detectors at 34.6° (upper panel) and the ring of backward detectors at 156.2° (lower panel). The peaks are marked with their unshifted $\gamma$-ray energy. A transition from the ND level scheme is marked $y$.

The centroid-shift analysis was carried out in the following manner. From the centroids of the $\gamma$-ray lines in the spectra of both bands measured at the different angles with respect to the beam direction, the fractional Doppler shifts $F(\tau)=(\langle E_\gamma(\Theta)\rangle - E_0)/E_0\beta_{\max}\cos\Theta$ are determined. Here,

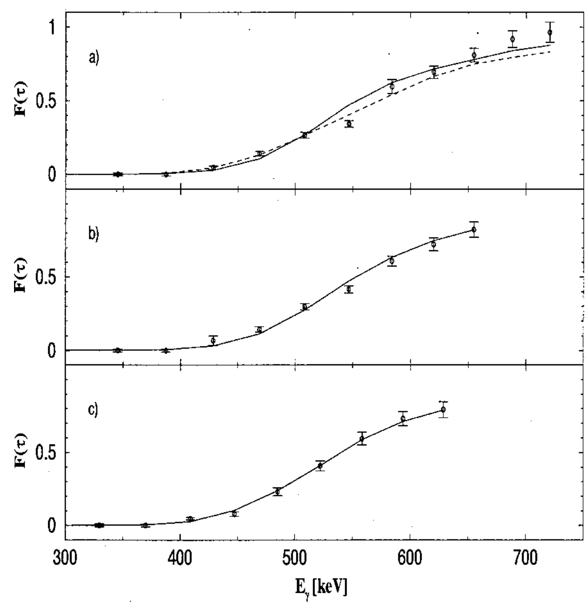


FIG. 2. Fractional Doppler shifts $F(\tau)$ for the yrast SD band [panels (a) and (b)] and SD band 2 [panel (c)] in $^{196}$Pb. For the yrast SD band spectra created with gates below [panel (a)] and above [panel (b)] the transitions of interest were analyzed. The curves represent calculated shifts assuming constant quadrupole moments for each band (see text for details). The dashed curve corresponds to a fit with slightly different quadrupole moments.

TABLE I. Results of the centroid-shift analysis for the yrast SD band 1 and the excited SD band 2 in $^{196}$Pb.

| Band | Gating | $Q_t$ [b] | $Q_{sf}$ [b] |
|---|---|---|---|
| Yrast SD 1 | below | $17.8^{+1.3}_{-1.6}$ | $16.0^{+1.1}_{-1.4}$ |
| | above | $18.9^{+0.7}_{-0.9}$ | |
| Excited SD 2 | below | $19.8^{+0.7}_{-0.9}$ | $17.8^{+0.7}_{-0.7}$ |

$E_0$ is the energy of the unshifted line, and $\beta_{max}=v_{max}/c=1.53\%$ was calculated from the reaction parameters for the center of the target. $F(\tau)$ is determined by a linear fit to the experimental values of $\langle E_\gamma(\Theta)\rangle$ plotted as a function of $\cos\Theta$. These $F(\tau)$ values are displayed as a function of $\gamma$-ray energy in Fig. 2.

$F(\tau)$ curves were calculated using a program developed by Moore *et al.* [21]. In the program a rotational cascade with a constant transition quadrupole moment $Q_t$ is assumed. Where spectra with coincidence gates below the transition of interest were used, the side feeding was modeled by a cascade of five transitions with a constant quadrupole moment $Q_{sf}$ and with a constant dynamic moment of inertia of $\mathfrak{J}^{(2)}=110\hbar^2/\text{MeV}$. This corresponds to the average moments of inertia of the known SD bands in the range of rotational frequencies where the lifetimes are determined. The side-feeding intensities are obtained from the measured $\gamma$-ray intensities within the bands. The electronic stopping powers were calculated using the tables of Ziegler *et al.* [22] and the nuclear component was treated according to the theory of Lindhard *et al.* [23]. The calculated $F(\tau)$ curves were fitted to the data with the quadrupole moments $Q_t$ and $Q_{sf}$ as free parameters. The results are summarized in Table I. The quoted errors include the statistical uncertainties and the covariance between the fit parameters. The systematic uncertainties associated with the stopping powers are not included.

In addition to the fractional shifts, line shapes of a number of transitions in both bands were analyzed. For the yrast SD band the line shapes of the nine transitions between 387 and 688 keV could be analyzed and for the SD band 2 the shapes of the five transitions between 447 and 594 keV [16,17] could be fitted. For the yrast SD band we used coincidence spectra with gates below and above the transitions of interest, for SD band 2 only spectra gated below the transitions of interest had sufficient statistics.

To fit calculated line shapes to the measured spectra a program described by Gascon *et al.* [24] was used. In a first step of the calculation, a Monte Carlo simulation of 6000 histories of nuclei recoiling through the target and stopper foils is performed. Starting with the initial recoil velocity, $v_{max}/c=1.53\%$, this results in statistical velocity distributions at about 850 different times with time intervals of 1 fs. In the second step, the details of the detector geometry are taken into account and a line shape for each decay time is calculated, using the velocity distributions obtained in the first step and the stopping powers. The side-feeding and stopping powers were treated in a similar way as in the $F(\tau)$ analysis described above. Finally, the theoretical line shapes are fitted to the experimental ones with the quadrupole moments as free parameters. Figure 3 shows examples of the experimental line shapes of transitions in SD band 2 together with results of the fits. These examples demonstrate the low statistics in the individual spectra, particularly for band 2. However, final values for the quadrupole moments are averages of the ones determined from many such spectra.

In the fitting procedure, starting values for the quadrupole moments were taken from the results of the $F(\tau)$ analysis, and each line shape was first fitted individually in the spectra from the forward, near-90° and backward detectors. The line shapes of three consecutive transitions in each band were then fitted simultaneously. In this way, several values for the in-band transition quadrupole moments $Q_t$ and the side-feeding quadrupole moments $Q_{sf}$ were obtained for each state which agreed within the limits of error. The adopted values, which are averages of these quadrupole moments, are summarized in Table II and compared graphically in Fig. 4. The uncertainties of the values given in the table were obtained by taking the statistical and systematic errors into account, the latter being estimated by varying fitting parameters, starting values and assumptions on the side feeding. The uncertainties introduced by the stopping powers are not included.

Inspection of Table II shows that the side-feeding quadru-

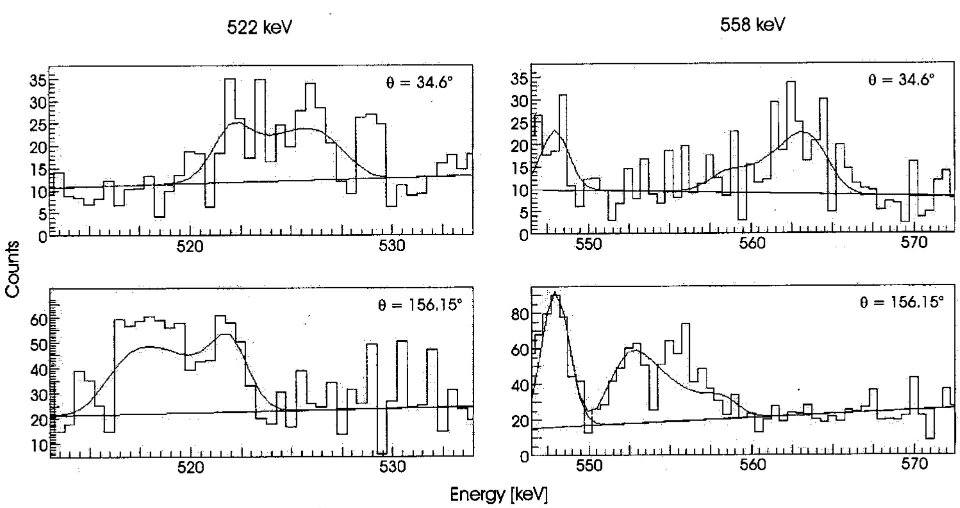


FIG. 3. Line shapes of the 522- and 558-keV transitions of SD band 2 in $^{196}$Pb measured at forward (upper panels) and backward (lower panels) detectors. The fitted line shapes are given by the curves. In the spectra of the 558-keV transition a contamination was taken into account when fitting the line shapes.

TABLE II. Results of the Doppler-shift line shape analysis of transitions in the yrast (band 1) and excited SD band (band 2) in $^{196}$Pb.

| Band | Transition [keV] | $Q_t$ [b] | $B(E2)$ [W.u.] | $\tau$ [ps] | $Q_{sf}$ [b] |
|---|---|---|---|---|---|
| Yrast SD 1 | 387 | 20.0±1.7 | 2090±350 | 0.66±0.11 | 13.3±2.0 |
| Gating below | 429 | 21.9±1.8 | 2520±410 | 0.33±0.06 | 18.1±1.7 |
| | 469 | 21.2±1.7 | 2370±380 | 0.22±0.04 | 17.2±1.5 |
| | 508 | 21.9±1.5 | 2540±350 | 0.14±0.02 | 17.7±1.4 |
| | 547 | 20.2±1.8 | 2170±390 | 0.11±0.02 | 14.6±1.7 |
| | 584 | 20.4±1.6 | 2210±350 | 0.080±0.013 | 18.8±1.6 |
| | 620 | 18.2±1.6 | 1770±310 | 0.075±0.013 | 16.6±1.6 |
| | 655 | 22.5±1.8 | 2710±430 | 0.037±0.006 | 19.5±1.7 |
| | 688 | 17.8±2.0 | 1700±380 | 0.046±0.010 | 14.2±1.9 |
| Yrast SD 1 | 387 | 18.6±1.6 | 1800±310 | 0.77±0.13 | |
| Gating above | 429 | 20.1±1.8 | 2120±380 | 0.39±0.07 | |
| | 469 | 19.2±1.8 | 1940±360 | 0.27±0.05 | |
| | 508 | 20.2±1.8 | 2160±390 | 0.17±0.03 | |
| | 547 | 19.2±1.6 | 1960±330 | 0.13±0.02 | |
| | 584 | 21.0±1.8 | 2350±400 | 0.076±0.013 | |
| | 620 | 15.7±2.5 | 1320±420 | 0.100±0.032 | |
| | 655 | 21.2±1.8 | 2400±400 | 0.042±0.007 | |
| Excited SD 2 | 447 | 16.7±2.0 | 1470±350 | 0.46±0.11 | 16.7±1.9 |
| Gating below | 485 | 19.8±2.2 | 2070±460 | 0.22±0.05 | 18.4±1.6 |
| | 522 | 19.3±1.9 | 1980±390 | 0.16±0.03 | 17.1±1.4 |
| | 558 | 20.6±1.7 | 2260±370 | 0.098±0.016 | 18.0±1.5 |
| | 594 | 19.6±2.1 | 2050±440 | 0.080±0.017 | 19.3±1.8 |

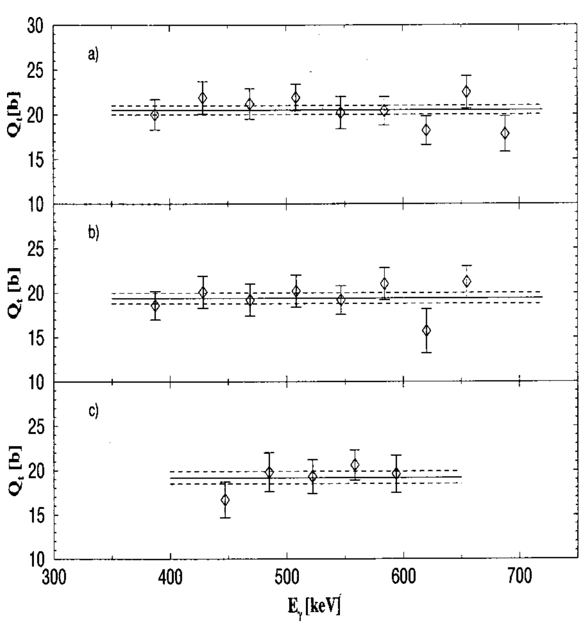


FIG. 4. Transition quadrupole moments as a function of transition energy for the yrast [panels (a) and (b)] and excited SD band [panel (c)] derived from the line shape analysis. For the yrast SD band spectra created with both, gating below [panel (a)] and above [panel (b)] the transitions of interest were analyzed. The average values of 20.5(5), 19.4(6), and 19.2(7) b are indicated by the solid and dashed lines in panels (a), (b), and (c), respectively.

pole moments $Q_{sf}$ are generally similar or somewhat smaller than the transition quadrupole moments $Q_t$. Furthermore, for SD band 1 the transition quadrupole moments obtained from spectra gated above and below the transitions of interest agree within the limits of error. This consistency gives confidence in the treatment of the side feeding.

## III. DISCUSSION

Combining all the experimental results, the weighted average values for the transition quadrupole moments of the yrast SD band 1 and the excited SD band 2 are $Q_t = 19.7(3)$ b and $Q_t = 19.5(5)$ b, respectively. Within the experimental uncertainties the quadrupole moments and thus the deformations in the two bands are identical. Our value for the yrast SD band is in agreement with previous results [19] with an average of $Q_t = 19.5(4)$ b.

In SD $^{196}$Pb the excited bands 2 and 3 have been interpreted as signature partner bands based on an octupole vibration [13]. This interpretation is supported by the unusually large transition rates ($\approx 10^{-4}$ W.u.) of the $E1$ interband transitions between band 3 and the yrast SD band. Furthermore, band 3 is excited by approximately 845 keV relative to the yrast band, if extrapolated to spin $I = 0$, which is less than would be expected if it were to correspond to a quasiparticle excitation.

The properties of the excited SD bands of even-even nuclei in the $A = 190$ region have been well reproduced in random-phase approximation (RPA) calculations [15,18] and in calculations using the generator-coordinate method [14]. These calculations suggest that most, if not all, of the excited bands are based on collective octupole vibrations. The presently available experimental information [5,12,13] seems to support this conjecture. For $^{196}$Pb the lowest excitation is predicted to be the $K=2$ octupole state and bands 2 and 3 should be the $\alpha=0$ and 1 signature partners, respectively, built on that excitation. The calculations also show that only the $\alpha=1$ band 3 will exhibit a strong decay to the yrast SD band, as is observed in experiment [13]. Such decay becomes possible through mixing with lower-$K$ components in the wave function, which is much larger for the $\alpha=1$ band 3 than for the $\alpha=0$ band 2 [15,18].

For an octupole vibration it may be assumed that the deformation and hence the quadrupole moment is similar to that of the yrast band. An octupole vibration may be described by superpositions of a large number of two-quasiparticle states, each of which comprises only a small fraction of the total amplitude of the wave function. As pointed out by Nakatsukasa *et al.* [18], for the lowest $\alpha=1$ octupole state in $^{196}$Pb the largest component of the total wave function, which is a two-quasineutron excitation occupying $N=5$ and $N=6$ orbitals, has an amplitude at $\omega_{\rm rot}=0$ which is less than 10% of the total amplitude. The largest component associated with intruder orbitals from the $N=7$ shell has an amplitude of $|\psi|^2=0.04$ at $\omega_{\rm rot}=0$. This amplitude still decreases towards higher rotational frequencies. Thus the blocking of $N=7$ intruder orbitals is extremely weak in the octupole vibrational excitation, which results in a similar deformation of SD bands 2 and 3 and the yrast SD band. Indeed, our average experimental quadrupole moments are the same for the yrast and excited SD band. On the other hand, if the excited band would correspond to a quasiparticle excitation, rather than an octupole vibration, the deformation of bands 1 and 2 could be rather different. In particular, if the content of high-$j$ $N=6$ and $N=7$ intruder orbitals involved in the configuration of band 2 was significantly different, their strong deformation-driving effects could lead to a sizable difference in the quadrupole moments. For instance, a systematic study of the quadrupole moments of the yrast SD bands in Pb isotopes [19] revealed a difference of $\approx$3 b in $Q_t$ for band 1 of $^{193}$Pb in which one less $\nu j_{15/2}$ quasineutron is populated.

Using the lifetimes derived in the present work and the interband ($E1$) to in-band ($E2$) branching ratios, the absolute $E1$ transition rate can be calculated. In our previous work [13], a quadrupole moment of 19.5(5) b was assumed for the excited SD band 3. That value is the same as the one obtained in the present work for the signature partner band 2 of 19.5(5) b. Thus the strong enhancement of the interband $E1$ transitions, $B(E1)\approx10^{-4}$ W.u., that was derived in the previous work is confirmed.

Finally, we want to comment on the behavior of the quadrupole moments within the bands. The values given in Table II and Fig. 4 show that $Q_t$ remains fairly constant over the measured range for both bands, although there seems to be a small decrease at the lowest spin in band 2. This indicates that the deformations of the bands do not change with increasing spin. On the other hand, the dynamic moments of inertia $\mathfrak{J}^{(2)}$ of the yrast and excited SD bands in $^{196}$Pb show an increase with increasing rotational frequency. Similar observations have been made for other SD bands in this mass region and it has been argued [25–27] that the observed changes in $\mathfrak{J}^{(2)}$ are not due to deformation changes, but result from a gradual alignment of quasiparticles combined with a pairing reduction. Furthermore, the moments of inertia of the excited bands in $^{196}$Pb are somewhat larger at low and medium frequency than those of the yrast band but the transition quadrupole moments for the individual states are identical within the limits of error; see Fig. 4.

## IV. SUMMARY

In summary, lifetime measurements have been performed using the DSAM for the SD bands 1 and 2 in $^{196}$Pb. For both bands fractional Doppler shifts as well as line shapes have been analyzed. For the yrast SD band 1 the results obtained from spectra gated above and below the transitions of interest could be compared. The average transition quadrupole moments, $Q_t=19.7(3)$ b and $Q_t=19.5(5)$ b for the two bands agree within the experimental error. This shows that the deformation is very similar in the two bands as can be expected if band 2 is based on an octupole-vibrational excitation. The quadrupole moments of the individual states are constant within the bands. They do not reflect the increase of the dynamical moments of inertia as a function of rotational frequency which is caused by alignment effects and not by a deformation change.

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[1] X.-L. Han and C.-L. Wu, At. Data Nucl. Data Tables **73**, 43 (1999).
[2] J. Simpson, Z. Phys. A **358**, 139 (1997).
[3] I. Y. Lee, Nucl. Phys. **A520**, 641c (1990).
[4] T. L. Khoo *et al.*, Phys. Rev. Lett. **76**, 1583 (1996).
[5] G. Hackman *et al.*, Phys. Rev. Lett. **79**, 4100 (1997).
[6] A. Lopez-Martens *et al.*, Phys. Lett. B **380**, 18 (1996).
[7] K. Hauschild *et al.*, Phys. Rev. C **55**, 2819 (1997).
[8] M. J. Joyce *et al.*, Phys. Rev. Lett. **71**, 2176 (1993).
[9] S. Bouneau *et al.*, Phys. Rev. C **53**, R9 (1996).

[10] L. Ducroux *et al.*, Phys. Rev. C **53**, 2701 (1996).
[11] N. Buforn *et al.*, Eur. Phys. J. A **9**, 29 (2000).
[12] A. Korichi *et al.*, Phys. Rev. Lett. **86**, 2746 (2001).
[13] D. Roßbach *et al.*, Phys. Lett. B **513**, 9 (2001).
[14] H. Dancer *et al.*, Nucl. Phys. **A654**, 655c (1999).
[15] T. Nakatsukasa *et al.*, Phys. Rev. C **53**, 2213 (1996).
[16] U. J. van Severen *et al.*, Z. Phys. A **353**, 15 (1995).
[17] S. Bouneau *et al.*, Z. Phys. A **358**, 179 (1997).
[18] T. Nakatsukasa *et al.*, Proceedings of the International Conference on Nuclear Structures at the Limits, Argonne, IL, ANL/PHY-97/1, 111, 1996.
[19] U. J. van Severen *et al.*, Phys. Lett. B **434**, 14 (1998).
[20] M. Cromaz *et al.*, Nucl. Instrum. Methods Phys. Res. A **462**, 519 (2001).
[21] E. F. Moore *et al.*, *Proceedings of the Workshop on Gammasphere Physics* (World Scientific, Singapore, 1996).
[22] J. F. Ziegler *et al.*, *The Stopping and Ranges of Ions in Matter* (Pergamon, London, 1985).
[23] J. Lindhard *et al.*, Mat. Fys. Medd. K. Dan. Vidensk. Selsk. **33**, 10 (1963); **33**, 14 (1963); **36**, 10 (1968).
[24] J. Gascon *et al.*, Nucl. Phys. **A513**, 344 (1990).
[25] P. Willsau *et al.*, Nucl. Phys. **A574**, 560 (1994).
[26] E. F. Moore *et al.*, Phys. Rev. C **55**, R2150 (1997).
[27] B. C. Busse *et al.*, Phys. Rev. C **57**, R1017 (1998).