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**Nuclear Science Division**

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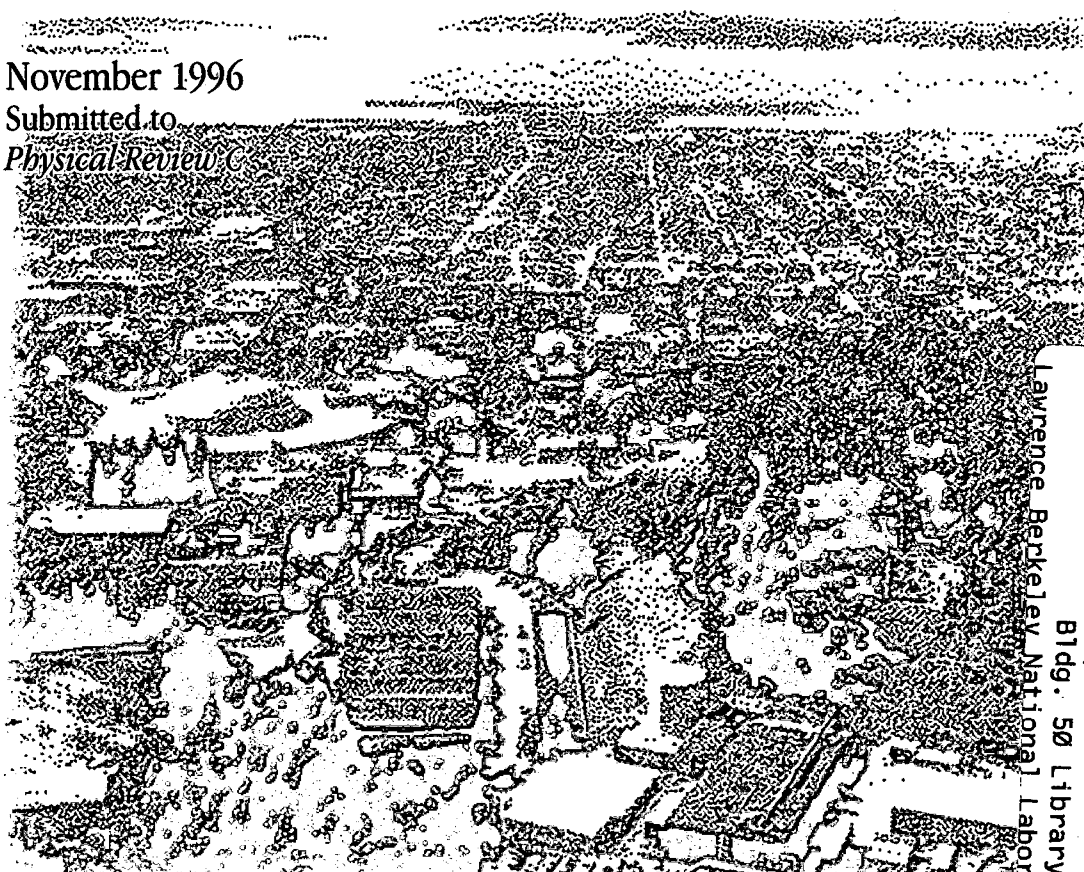

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November 1996


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# The decay out of the superdeformed band in $^{194}$Pb: Electromagnetic Properties

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## Abstract

Lifetimes of the $14^+$, $12^+$, $10^+$ states and, for the first time, the $8^+$ state in the yrast superdeformed (SD) band of $^{194}$Pb were measured at Gammasphere with the recoil-distance Doppler-shift method. Constant transition quadrupole moments with an average of 18.8 (11) e b were found at the bottom of the SD band. The decay out of the SD band can be viewed as governed by a small admixture of normal deformed (ND) states to the SD wavefunction which is assessed for the $8^+$ and $10^+$ SD states based on a simple mixing model. The electromagnetic properties of the ND states involved in the decay out are extracted for the first time by investigating the decay strength of the discrete linking transitions. Despite the large intensity of observed linking transitions, the new data show that the decay out of the SD band is statistical in nature.

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The sudden disappearance of the intensity at the bottom of superdeformed (SD) bands has been a puzzling and intensively investigated problem. Only recently, major breakthroughs have been accomplished with the first observations of discrete linking transitions between the SD bands in $^{194}$Hg [1] and $^{194}$Pb [2–4] and the respective normal deformed (ND) levels. These observations have for the first time enabled the determination of the excitation energy, spins and, in the case of $^{194}$Pb, parity [4] of superdeformed states in the 190-mass region. During recent years other information about the decay out of SD bands in this mass region has been gathered, including studies of the continuum $\gamma$ rays in the decay [5,6] and measurements of lifetimes of those SD states that show considerable branching to ND states [7–11].

The yrast SD band of $^{194}$Pb extends to spin 6 $\hbar$, the lowest spin of any SD state outside the actinide region. For this SD band 21% of the band intensity has been linked to near-yrast states by twelve transitions with energies between 1.8 and 3.1 MeV [4]. This is a significantly larger fraction than in $^{194}$Hg, where so far only about 5% of the SD intensity decays by high-energy discrete transitions. Another difference between these two SD bands is the fact that in $^{194}$Pb transitions to positive- and negative-parity states have been observed, while in $^{194}$Hg only transitions to the negative-parity states were found. The large number of linking transitions together with the relatively low excitation energy at spin 6 $\hbar$ of 2.743 MeV above yrast gives rise to the question of whether the decay of this SD band is statistical in nature. One may also wonder whether the large intensity of discrete linking transitions reflects a larger amount of mixing between the SD and ND states at the point of the decay out, indicating a disappearance of the SD potential minimum. These questions can be addressed by investigating the electromagnetic properties of these transitions by means of lifetime measurements for the lowest SD states.

We report an experiment in which the lifetimes of the $14^+$, $12^+$, $10^+$ states and, for the first time, the $8^+$ state in the yrast SD band of $^{194}$Pb were measured. Since the lifetimes of these states are in the range of several picoseconds, we applied the recoil-distance Doppler-shift method. The deduced transition quadrupole moments of the intra-band transitions were found to be constant within the experimental uncertainties, which supports the earlier findings [7–12] that the structure of the SD states is not drastically changed even when large fractions of the intensity do not remain in the SD band. We used the measured lifetimes to extract the electromagnetic properties of the observed linking transitions and to address the questions raised above.

Superdeformed states in $^{194}$Pb were populated in the reaction $^{164}$Dy($^{34}$S,4n) using a 166-MeV beam from the 88-Inch Cyclotron of the Lawrence Berkeley National Laboratory. The 0.5 mg/cm$^2$ $^{164}$Dy target was supported by a 1.5 mg/cm$^2$ tantalum layer, which was facing the beam. The recoiling $^{194}$Pb nuclei were stopped in a 12 mg/cm$^2$ thick gold foil. The target and stopper foils were mounted in the Cologne coincidence plunger. The target-to-stopper distance was controlled using the capacitance between the two foils. During a calibration before the experiment the capacitance was related to a mechanical distance measurement using a magnetic transducer. During the experiment the capacitance was continuously measured and changes in the distance due to thermal expansions of the mechanical components were corrected by a feedback system that uses piezoelectric crystals for the corrections of the target position. Due to this feedback, the positions of the foils were stabilized to better than 1% of a given distance. The emitted $\gamma$ rays were detected by Gammasphere [13], which at the time of the experiment consisted of 95 high efficiency ($\approx$75%) Compton suppressed Ge detectors. Three-fold and higher coincidence events were written to magnetic tape at 12 target-to-stopper distances. At each of the 8 smaller distances (2.57(3), 9.56(2), 18.72(3), 32.29(4), 52.50(7), 80.5(1), 127.2(3) and 185.6(4) $\mu$m from electrical contact) data were accumulated for an average of about 12 hours while only 2 hours were used for the 4 larger distances (299(2), 473(3), 700(5) and 1200(9) $\mu$m). About $2\times10^8$ and $4\times10^7$ events were recorded at each of the eight smaller and four larger distances, respectively. The average velocity of the recoiling nuclei was found to be 1.65 % of the velocity of light.

The Gammasphere array consists of a total of 17 rings, where all detectors of one ring have the same angle with respect to the beam axis. Only 12 of these rings provide enough Doppler-shift to be analyzed in this recoil-distance experiment (at angles of 17.3°, 31.7°, 37.4°, 50.1°, 58.3°, 69.8°, 110.2°, 121.7°, 129.9°, 142.6°, 148.3° and 162.7°). At each distance a background subtracted spectrum (for each of these 12 rings) was created for the SD band in $^{194}$Pb by double gating on the shifted components of higher lying SD transitions. Additionally, at least 5 unsuppressed Ge detectors were required in the event. The spectra of these 12 rings were summed up after they were modified so that the Doppler-shifted peaks lie at a position that corresponds to a detector angle of 17.3°, while the position of the unshifted peak remained unchanged. Figs. 1 and 2 show these summed spectra for the four lowest established SD transitions of the yrast SD band in $^{194}$Pb at four selected distances. The spectra obtained at different distances were normalized to the same number of beam induced events. The spectra shown for 299 $\mu$m are the sum of the statistics from the four longer distances, since all SD transitions are fully shifted at 299 $\mu$m. The areas of the unshifted and shifted peaks were determined at each distance. Fig. 3 shows the normalized intensities of the shifted peaks of the four lowest SD transitions as a function of the target-to-stopper distance. The lifetimes of the $8^+$, $10^+$, $12^+$ and $14^+$ SD states were determined by means of the differential decay curve method (DDMC) [14,15], which has been previously applied in other recoil-distance experiments on SD bands [8,10,11,16]. In this method, when gating on higher feeding transitions, the lifetime of a level is determined from the observed intensities of its feeding and depopulating transitions only. The feeding history of the level of interest does not enter the analysis and therefore uncertainties following from assumptions about lifetimes of higher lying states are eliminated. Side-feeding times and intensities play no role since the pathway of the cascade is defined by the gates above the level of interest. The other advantage is that only relative target-to-stopper distances enter the analysis and no knowledge of the absolute distance is required.

The lifetimes obtained in the present work for the $8^+$, $10^+$, $12^+$ and $14^+$ SD states are summarized in Table I together with the reduced transition probabilities B(E2) and transition quadrupole moments $Q_t$ for the intra-band transitions. For comparison the table also shows the results previously obtained for three of these SD states [10]. The new results are more accurate than the previous ones and agree within the experimental uncertainties.

They are, however, slightly lower on average ($\overline{Q}_t^{RDM} = 18.8 \pm 1.1$ e b) than those from a previous DSAM experiment [17] ($\overline{Q}_t^{DSAM} = 20.2 \pm 1.7$ e b).

The lifetime of the $8^+$ state is essential to understand the decay mechanism and its influence on the structure of the states involved in the decay out of the SD band. The extracted $Q_t$-values clearly show that even though 10(7)% and 34(6)% of the SD intensity leave the SD band at spin 10 $\hbar$ and 8 $\hbar$ [4], respectively, no reduction of $Q_t$ is observed for the intra-band transitions within the experimental uncertainties. This indicates that the decay out of the SD band in $^{194}$Pb takes place without a significant change in the structure of the SD level, offering support for the assumption of the existence of the superdeformed potential minimum down to a SD $0^+$ state (see for example Krieger *et al.* [18]).

Using the known branching ratios between the intra-band decay and the decay out of the SD band at spin 8 $\hbar$ and 10 $\hbar$, one can easily determine the transition probability for the decay out at a given spin by:

$$\lambda_{out} = \frac{(1 - N_{in})}{\tau}. \tag{1}$$

Here $N_{in}$ is the relative intensity of the intra-band transition with respect to the population of the SD level of interest and $\tau$ its mean lifetime. In Table II values for $N_{in}$, obtained from the branching ratios given in Ref. [4], and the deduced values for $\lambda_{out}$ are presented for the $8^+$ and $10^+$ SD states.

Spins and parity of the SD states were determined by Hauschild *et al.* [4] on the basis of the asymmetry ratios for the discrete linking transitions. Those, together with the lifetimes of the $8^+$ and $10^+$ SD states and their branching ratios [4] determine the reduced transition probabilities for the discrete linking transitions. The $10^+$ SD state decays by a 1888-keV transition, which is assumed to be an E1 transition (i.e. the final state is newly placed in the level scheme and tentatively assigned spin and parity $11^-$ [4]). With this multipolarity and the intensity of 1.0(4)% of the SD band this transition has a B(E1) value of $5(2)\times10^{-8}$ W.U. For the firmly established 1.3(6)% 2628 keV and 1.7(5)% 2806 keV E1-transitions depopulating the $8^+$ SD level [4], one obtains B(E1) values of $1.1(6)\times10^{-8}$ W.U.

and 1.3(9)$\times10^{-8}$ W.U., respectively. One can easily understand these highly retarded B(E1) values as the result of a very small admixture of a normal deformed (ND) component into the SD wavefunction. This mixing scenario [10,12,19–22] will be discussed below.

In order to estimate the amount of these admixtures to the $8^+$ and $10^+$ SD states we applied the approach outlined in Ref. [12]. The E1 transition probability $\lambda_n^{E1}$ for these ND states was estimated by statistical model calculations taking into account the tail of the GDR. The level density in this approach is calculated using the Fermi-gas model. These calculations are normalized to the $\gamma$-strength typical for this mass region at the neutron separation energy. The uncertainties of these statistical model calculations are estimated to be about one order of magnitude. The fact that linking transitions with other multipolarities besides E1 were observed in $^{194}$Pb certainly raises the question whether it is sufficient to only consider E1 transitions. However, one can view the calculated values for $\lambda_n^{E1}$ (Table II) as a lower limit for the total decay probability of the ND states, since additional decay paths would only increase this transition probability.

The total squared mixing amplitude $a_n^2$ of ND components to the SD wavefunction are then determined by

$$a_n^2 = \frac{\lambda_{out}}{\lambda_n^{E1}}. \tag{2}$$

Values for $a_n^2$ for the $8^+$ and $10^+$ SD states are presented in Table II. The very small $a_n^2$-values obtained show that even at the second step of the decay the SD configuration is hardly disturbed.

It is also possible to extract estimates for the admixture of the $6^+$ SD state by using an upper limit for the intensity of the intra-band transition at 124 keV of 5% [23]. If we assume that the wave function of this state is mainly unperturbed and the transition quadrupole moment of the 124-keV intra-band transition is still 18.8 e b, it is possible to extract the partial decay probability for the decay out of this state and the squared mixing amplitude $a_n^2$. The resulting values are also given in Table II. It is noteworthy that there is an increase of the admixture by one order of magnitude in this step of the decay. Similar increases of the admixture were also observed in the cases of $^{192}$Hg [12] and $^{194}$Hg [11]. The reason for this sudden increase is not yet fully understood but is most likely due to a significant change in the barrier between the SD and ND potential minima. However, the case of $^{194}$Pb stands out of these three examples because of the fact that three SD states show significant decay out of the band, while in the mercury isotopes the decay is more rapid and only two SD states are involved. Whether this less rapid decay of the SD band in $^{194}$Pb is due to its lower excitation energy and the larger level spacing of the ND states remains an open question.

Having discussed the properties of the SD states involved in the decay-out, we now turn to the properties of the discrete linking transitions that connect the SD states and the near-yrast ND states. The strength of these transitions can give us an insight into the properties of the ND states that mix into the SD states. With the estimated squared mixing amplitudes and postulating that transition matrix elements between pure ND and pure SD wavefunctions are negligible, it is possible to extract the reduced E1 transition probabilities B(E1) for the pure ND to ND transitions for those states that mix into the $8^+$ and $10^+$ SD states. These B(E1) values are simply obtained by dividing the B(E1) values given earlier on for these transitions by the estimated squared mixing amplitudes. We have obtained values of $1.7(6)\times10^{-5}$ W.U., $2(2)\times10^{-6}$ W.U., and $3(4)\times10^{-6}$ W.U. for the 1888-, 2628- and 2806-keV transitions, respectively. These B(E1) values are consistent with what is observed for E1 transitions in the decay of neutron resonances and for transitions between bound states [24]. The fact that the deduced B(E1) values are not enhanced points to a statistical nature of the decay of the ND states involved in the decay out of the yrast SD band in $^{194}$Pb.

There are several transitions depopulating the $6^+$, $8^+$, and $10^+$ SD states which have a M1/E2-mixed multipolarity. The asymmetries measured for these transitions [4] were not sufficient to establish mixing ratios. However, one can give upper limits for their B(M1) and B(E2) values by simply assuming the transitions to be of purely one multipolarity. After correcting for the mixing amplitudes one obtains upper limits of the order of some $10^{-2}$ W.U. for the B(E2) values and some $10^{-4}$ W.U. for the B(M1) values. These limits are both on the low side of the range observed for transitions between bound states [24]. The fact that the set of observed linking transitions in $^{194}$Pb does not include any stretched E2 transitions leads to limits for these stretched B(E2) values that are similar to those stated above. Therefore the absence of stretched E2 transitions cannot be considered abnormal.

We point out that none of the reduced transition probabilities for any of the considered multipolarities shows an enhancement with respect to values typical for a statistical decay. The limits set are even found to be on the lower side of what one might have expected. As we have pointed out before, there is an uncertainty of about one order of magnitude in the statistical model calculations. However, even reduced transition probabilities that are 10 times larger than the values given above do not show any significant enhancement. Therefore, despite the large intensity of observed links, there is no evidence that structural matrix elements play an important role in the decay out of the SD band in $^{194}$Pb.

The mixing amplitudes $a_n^2$ can be used to set upper limits on the interaction strength $v = |\langle ND|\hat{V}|SD\rangle|$ between the SD and ND states, which are separated by a potential barrier. The ND states in the vicinity are complex states and one can assume that each of these ND states has a similar interaction matrix element with the SD state. The maximal interaction is then obtained for the case where only the two nearest neighboring ND states contribute to the admixture. This approach has been described in detail in Ref. [12]. The maximum interaction strength $v_{max}$ can then be calculated from the mixing amplitude $a_n^2$ and the average level spacing $D_n$ by

$$v_{max}^2 = \frac{1}{8} D_n^2 \cdot a_n^2. \tag{3}$$

The level spacings $D_n$ were determined by the Fermi-gas calculations and are given in Table II. Resulting values for $v_{max}$ are also presented in Table II.

Summarizing, we have measured lifetimes of the $8^+$, $10^+$, $12^+$, and $14^+$ states in the yrast SD band of $^{194}$Pb using the recoil-distance Doppler-shift method. The results have twice the accuracy as those from a previous measurement of the $10^+$, $12^+$, and $14^+$ states [10]. No reduction of the extracted transition quadrupole moments for the intra-band transitions was observed within the experimental uncertainties. Following the approach of a simple mixing picture between SD and ND states [12,19,20] for the mechanism of the decay out, we have estimated the squared mixing amplitudes $a_n^2$ for the admixture of ND states to the SD band members. The obtained values for $a_n^2$ are very small and support the findings in other nuclei of this mass region [7–12].

From the present lifetimes it was possible to extract reduced transition probabilities for some of the transitions linking this SD band to the near-yrast level scheme. By correcting for the amount of admixture between SD and ND states we were able to extract the electromagnetic properties of the pure ND states. The reduced transition probabilities for the E1 transitions were found to be of the order of $10^{-6}$-$10^{-5}$ W.U. Upper limits of the B(E2) values for stretched and unstretched E2 transitions were found to be on the order of $3\times10^{-2}$ W.U., which is very small. The upper limits for B(M1) values of the M1/E2 admixed transitions are of the order of $5\times10^{-4}$ W.U. These transition probabilities are all consistent with a statistical decay, even when the possibility of an increase by one order of magnitude is considered. They show no enhancement that would point to the presence of structural effects. We therefore conclude that the decay out of the yrast SD band in $^{194}$Pb is statistical in nature and has no significant effect on the structure of the SD states involved.

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## TABLES

TABLE I. Mean lifetimes $\tau$ of SD states in the yrast SD band in $^{194}$Pb. Reduced transition probabilities B(E2) and transition quadrupole moments $Q_t$ are given for the intra-band transitions. Corrections for branching ratios and conversion coefficients have been applied. For comparison the transition quadrupole moments $Q_t$ from Ref. [10] are given.

| | | present work | | | Ref. [10] |
|---|---|---|---|---|---|
| $I^\pi$ | $E_\gamma$ [keV] | $\tau$ [ps] | B(E2) $10^3$ W.U. | $Q_t$ [eb] | $Q_t$ [eb] |
| $14^+$ | 298 | 2.6±0.7 | $1.8^{+0.8}_{-0.4}$ | $18.5^{+3.2}_{-2.0}$ | $19.6^{+5.7}_{-3.9}$ |
| $12^+$ | 256 | 5.5±1.0 | $1.7^{+0.3}_{-0.3}$ | $18.2^{+1.9}_{-1.5}$ | $23.6^{+7.3}_{-5.0}$ |
| $10^+$ | 214 | 8.3±1.7 | $2.2^{+0.6}_{-0.4}$ | $20.7^{+2.5}_{-1.8}$ | $19.7^{+7.5}_{-2.0}$ |
| $8^+$ | 170 | 20.0±6.9 | $1.5^{+0.7}_{-0.4}$ | $17.3^{+4.0}_{-2.4}$ | – |

TABLE II. Relative intensities of the intra-band decay $N_{in}$ and partial decay probabilities for the decay out $\lambda_{out}$ for the $8^+$ and $10^+$ yrast SD states in $^{194}$Pb. Also presented are the calculated statistical E1-transition probabilities for ND states at the excitation energy of the SD states $\lambda_n^{E1}$, the average level spacing of these ND states $D_n$, the estimated squared mixing amplitude of these ND states into the $8^+$ and $10^+$ SD states $a_n^2$, and the maximum interaction strength between SD and ND states $v_{max}$. For the $6^+$ SD state estimates for $\lambda_{out}$, $a_n^2$ and $v_{max}$ are given on the basis of a 5% limit for the intensity of the 124-keV intra-band transition [23] and an assumed transition quadrupole moment of 18.8 e b. The unusual spin behavior of $\lambda_n^{E1}$ and $D_n$ is due to the irregular behavior of the ND yrast line in this spin region.

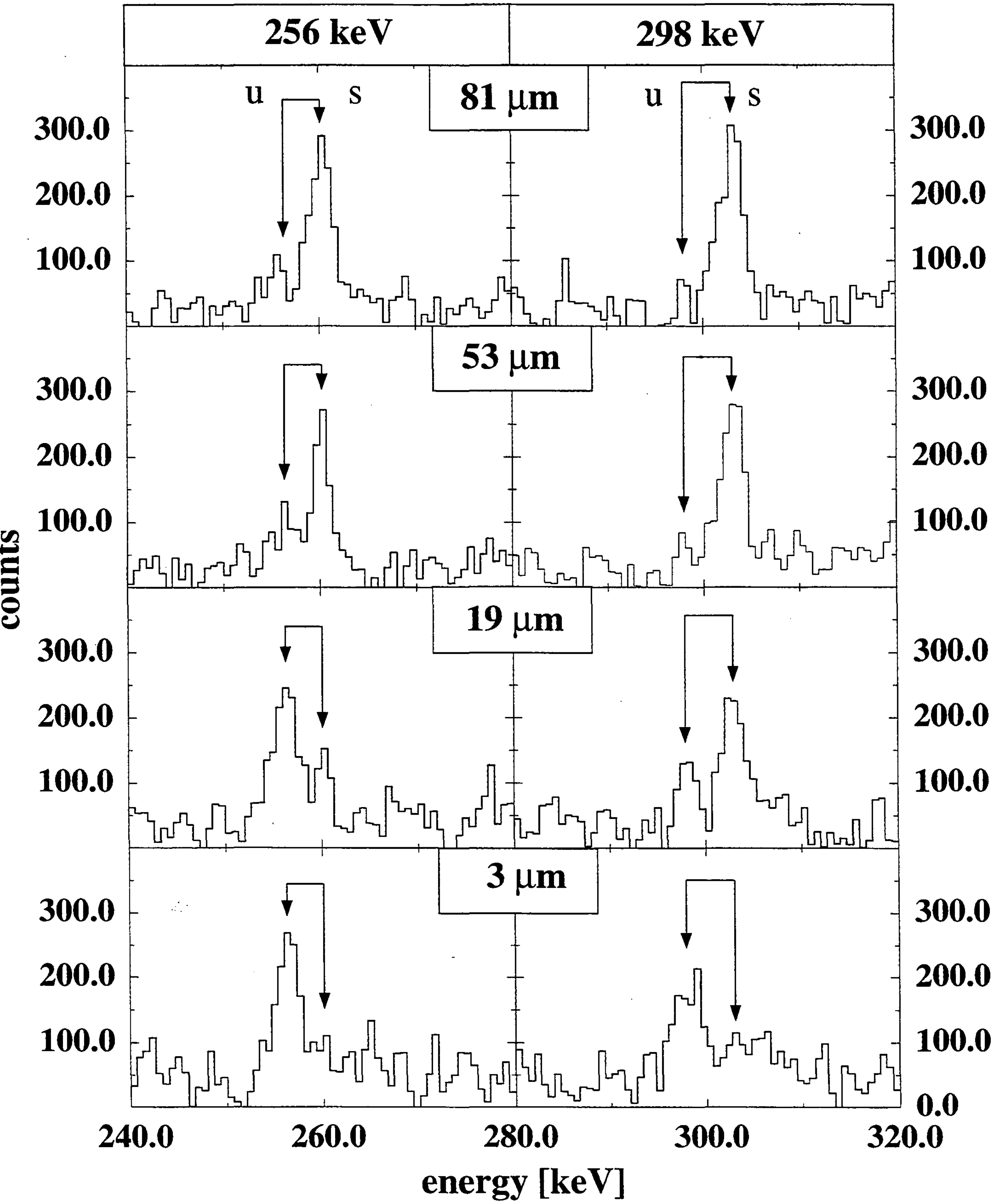
| $I^\pi$ | $E_\gamma$ [keV] | $N_{in}$ | $\lambda_{out}$ [$ps^{-1}$] | $\lambda_n^{E1}$ [$ps^{-1}$] | $D_n$ [keV] | $a_n^2$ [%] | $v_{max}$ [eV] |
|---|---|---|---|---|---|---|---|
| $10^+$ | 214 | 0.90 (6) | $0.012^{+0.006}_{-0.004}$ | 3.9 | 1.9 | 0.3(2) | 37 |
| $8^+$ | 170 | 0.62 (12) | $0.019^{+0.007}_{-0.006}$ | 3.9 | 1.9 | 0.5(1) | 48 |
| $6^+$ | (124) | <0.09 | 0.182 | 5.0 | 0.8 | 3.6 | 54 |

# FIGURES

FIG. 1. Double gated spectra for the 256-keV and 298-keV SD transitions in $^{194}$Pb at 4 different target-to-stopper distances (approximate distances from electrical contact are given in the insets). The spectra include the statistics of all detectors with considerable Doppler-shift (see text for details of the spectra manipulation). The unshifted (u) and Doppler-shifted (s) components of the transitions are marked.

FIG. 2. As Fig. 1 for the 170-keV and 214-keV SD transitions, however, for a different set of distances. The spectra shown for the target-to-stopper distance of 299 $\mu$m are the sum of the statistics from the four longer distances at 299, 473, 700, and 1200 $\mu$m.

FIG. 3. Intensities of the Doppler-shifted component of the 170-, 214-, 256-, and 298-keV SD transitions as a function of the target-to-stopper distance. The intensities are normalized to the same number of events per distance and to the intensity at the largest distance.


256 keV
298 keV
81 µm
53 µm
19 µm
3 µm
u
s
u
s
counts
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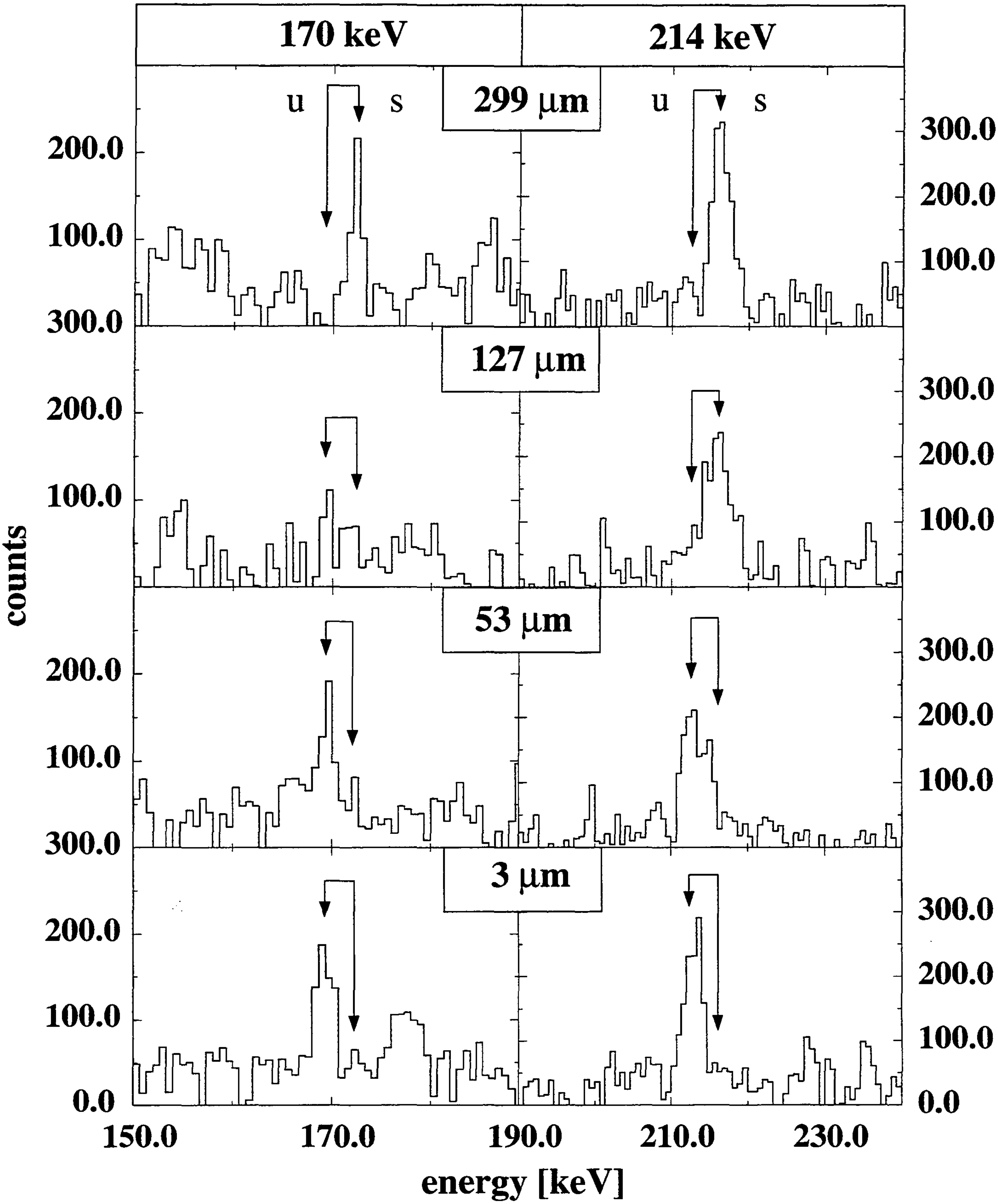
260.0
280.0
300.0
320.0
energy [keV]



170 keV
214 keV
299 μm
u
s
127 μm
53 μm
3 μm
counts
energy [keV]
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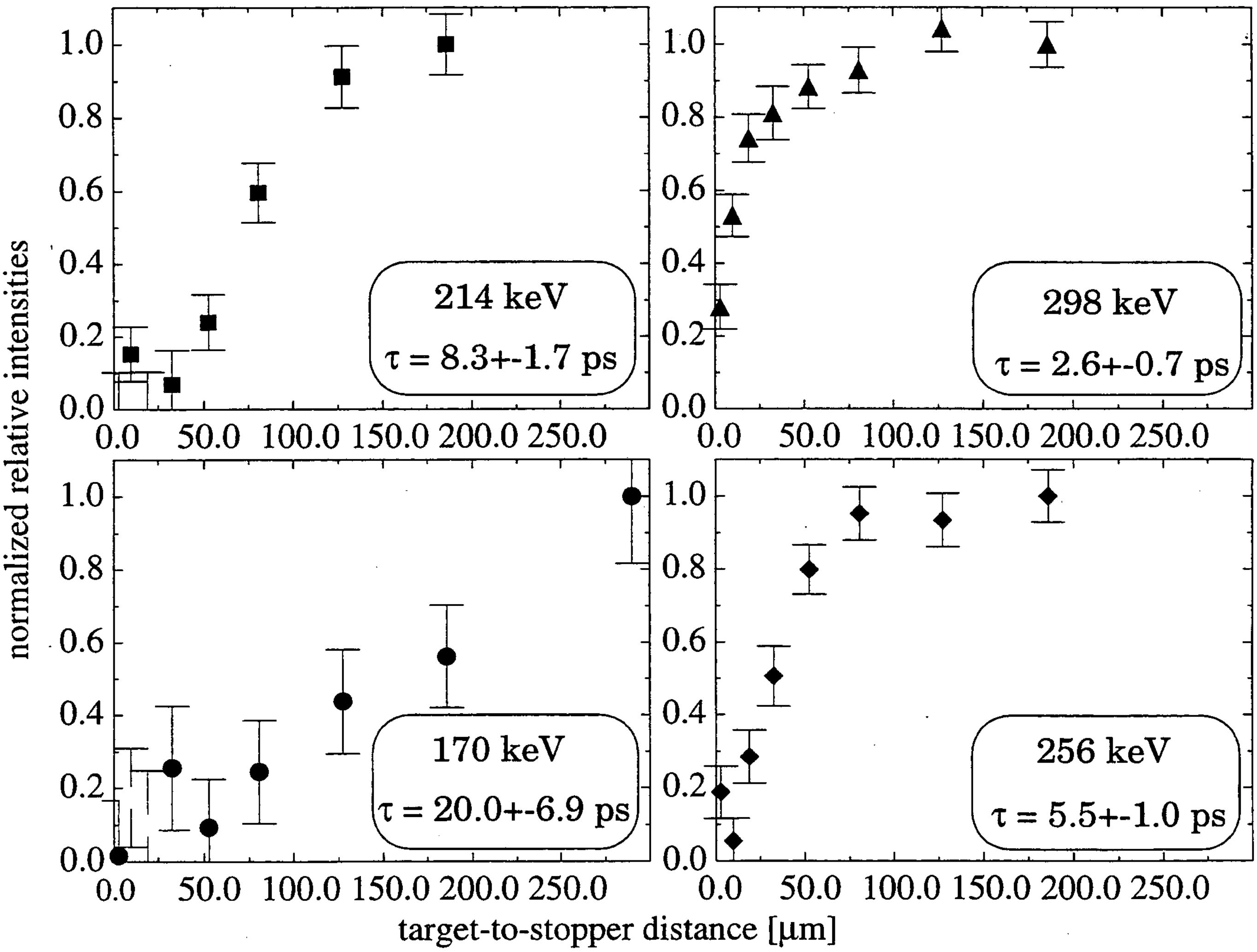

214 keV
τ = 8.3+-1.7 ps
298 keV
τ = 2.6+-0.7 ps
170 keV
τ = 20.0+-6.9 ps
256 keV
τ = 5.5+-1.0 ps
normalized relative intensities
target-to-stopper distance [µm]
0.0
0.2
0.4
0.6
0.8
1.0
0.0
50.0
100.0
150.0
200.0
250.0

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