

## LETTER TO THE EDITOR

# Population of the yrast superdeformed band in $^{194}\text{Pb}$

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**Abstract.** The yrast superdeformed (SD) band in  $^{194}\text{Pb}$  has been populated by means of four fusion-evaporation reactions ( $^{184}\text{W} + ^{16}\text{O}$ ,  $^{184}\text{W} + ^{17}\text{O}$ ,  $^{164}\text{Dy} + ^{34}\text{S}$ ,  $^{162}\text{Dy} + ^{36}\text{S}$ ) leading to different angular momenta and excitation energies in the various compound nuclei. The yields measured for the SD band relative to the total yield of the  $^{194}\text{Pb}$  channel do not show any dependence on excitation energies and show only a very weak increase with angular momentum. The feeding pattern of the SD band in  $^{194}\text{Pb}$  is compared to similar data for SD bands in neighbouring nuclei. All these results can be interpreted by the fission process (an important exit channel for all fusion reactions leading to Pb isotopes) which imposes a very low limit in the angular momentum of the Pb residual nuclei.

It is now well established that the superdeformed (SD) bands are populated to a higher spin than normally deformed (ND) states. Moreover, their intensities are higher (by more than an order of magnitude) than would be expected in comparison with the intensities of low-deformation states. Population mechanisms have recently been investigated for a few SD bands in each of the three mass regions,  $A = 30, 150, 190$  (see for instance [1-3]). In all cases, the SD population represents successful competition against fission: the entry distribution associated with the SD bands has been found to originate from the higher components of the total spin distribution. Thus fission sets an upper limit to the angular momentum of the residual nuclei, which can be estimated from the results of  $\gamma$ -ray spectroscopy. Since fission is an important exit channel for all fusion reactions leading to Pb isotopes (see for instance [4]), SD population studies can give a better insight into the maximum angular momentum which can be supported by Pb nuclei without fissioning.

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Table 1. Summary of experimental procedures.

Reaction	Target (Backing)	$E_{\text{lab}}$ (MeV)	Array	Numbers of detectors	Triggering condition	Number of events <sup>a</sup>
$^{184}\text{W} + ^{16}\text{O}$	$4 \times 175 + 1 \times 250 \mu\text{g cm}^{-2}$ ( $10 \mu\text{g cm}^{-2} \text{C}$ )	113	TESSA3	16 Ge	2 Ge	$9.5 \times 10^6$
		117		and	and	$7.5 \times 10^6$
$^{184}\text{W} + ^{17}\text{O}$		120		50 BGO	5 BGO	$8 \times 10^6$
$^{184}\text{W} + ^{16}\text{O}$	$2 \times 325 \mu\text{g cm}^{-2}$ ( $10 \mu\text{g cm}^{-2} \text{C}$ )	113	EUROGAM	45 Ge	5 Ge <sup>b</sup>	$860 \times 10^6$
$^{164}\text{Dy} + ^{34}\text{S}$	1 mg cm <sup>-2</sup> (14 mg cm <sup>-2</sup> Au)	157	EUROGAM			$7 \times 10^6$
		160		30 Ge	3 Ge <sup>b</sup>	$3 \times 10^6$
$^{162}\text{Dy} + ^{36}\text{S}$	1 mg cm <sup>-2</sup> (14 mg cm <sup>-2</sup> Au)	162	EUROGAM			$91 \times 10^6$

<sup>a</sup> Compton-suppressed events.

<sup>b</sup> Unsuppressed Ge.

We report here on the population intensities of the yrast SD band in  $^{194}\text{Pb}$  as a function of angular momentum and excitation energy for several projectile-target combinations. Excited states of  $^{194}\text{Pb}$  have been populated using four fusion-evaporated reactions  $^{184}\text{W}(^{16}\text{O}, 6n)$ ,  $^{184}\text{W}(^{17}\text{O}, 7n)$ ,  $^{164}\text{Dy}(^{34}\text{S}, 4n)$ , and  $^{162}\text{Dy}(^{36}\text{S}, 4n)$ . The experiments have been carried out at the Tandem accelerator of the Nuclear Structure Facility, Daresbury Laboratory, using the TESSA3 [5] and EUROGAM [6] arrays. All the experimental conditions are gathered together in table 1.

In order to extract the intensity of the SD band we have to measure the production of  $^{194}\text{Pb}$ . The existence of several isomeric states in this nucleus [7] makes the task difficult. The known normal level scheme comprises three parts: one built on the  $11^-$  isomer ( $E_{\text{exc}} = 2933$  keV,  $T_{1/2} = .124$  ns), one built on the  $12^+$  isomer ( $E_{\text{exc}} = 2628$  keV,  $T_{1/2} = 350$  ns), and one with all the transitions in prompt coincidences with the 965 keV  $2^+ \rightarrow 0^+$   $\gamma$ -ray. In thin target experiments, transitions above and below the isomers are not observed in coincidence, since the recoiling nuclei leave the focal volume of the Ge detectors. Then production of  $^{194}\text{Pb}$  is the sum of the population of the three parts. Their relative intensities have always been found to be 29%, 43%, and 28% respectively, in the present experiments. In backed-target experiments, the third part cannot be determined because the corresponding spectra, due to the coincident resolving time, include parts of the decay of the two isomeric states. In this latter case, the production of  $^{194}\text{Pb}$  has been calculated from the populations of the two long-lived isomeric states.

The population of the SD band has been deduced from the coincidence yields of the  $\gamma$ -rays between 213 and 458 keV, belonging to the plateau of the intensity curve [8]. The  $^{16}\text{O} + ^{184}\text{W}$  reaction has been studied with both arrays, allowing us to normalize the results obtained from TESSA3 with respect to those obtained with EUROGAM. The relative intensities of the SD band obtained for the seven measurements are shown in table 2.

These results can be analysed as a function of excitation energy ( $E^*$ ) and maximum angular momentum ( $l_{\text{max}}$ ) of the  $^{194}\text{Pb}$  residue, according to the following procedures. Firstly, the statistical-model code PACE [9] has been used:

- (i) to calculate the total kinetic energy of the evaporated neutrons,  $E_{\text{kin}}$ , allowing the evaluation of the excitation energy of  $^{194}\text{Pb}$ ,  $E_{\text{PACE}}^*$  given in table 2; and
- (ii) to calculate the angular momentum distribution in the compound nucleus and to

**Table 2.** Relative SD band intensities for the various bombarding energies and projectile–target combinations.

Reaction (Compound nucleus)	$E_{\text{lab}}$ (MeV)	$E_{\text{CN}}^*$ (MeV)	$l_{\text{max}}^{\text{PACE}}$ ( $\hbar$ ) <sup>a</sup>	$l^{\text{KOVAR}}$ ( $\hbar$ ) <sup>b</sup>	$E_{\text{kin}}$ (MeV) <sup>c</sup>	$E_{\text{PACE}}^*$ (MeV)	$I_{\text{SD}}$ %
$^{184}\text{W} + ^{16}\text{O}$ ( $^{200}\text{Pb}$ )	113	79.8	45	50	16.2	13.1	$1.0 \pm 0.2^{\text{d}}$ $1.0 \pm 0.1^{\text{e}}$
	117	83.4	48	52	16.8	16.1	$1.2 \pm 0.3^{\text{d}}$
$^{184}\text{W} + ^{17}\text{O}$ ( $^{201}\text{Pb}$ )	120	88.6	52	56	19.6	11.4	$1.1 \pm 0.3^{\text{d}}$
$^{164}\text{Dy} + ^{34}\text{S}$ ( $^{198}\text{Pb}$ )	157	60.0	33	44	10.0	15.8	$0.7 \pm 0.2^{\text{e}}$
	160	62.5	38	48	10.0	18.3	$0.9 \pm 0.3^{\text{e}}$
$^{162}\text{Dy} + ^{36}\text{S}$ ( $^{198}\text{Pb}$ )	162	59.5	40	50	10.0	15.3	$0.8 \pm 0.2^{\text{e}}$

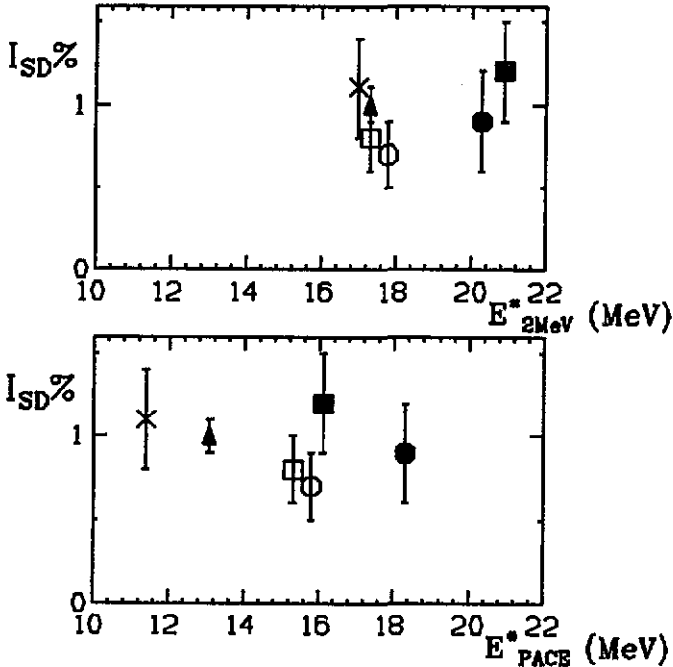
<sup>a</sup> Value of  $l$  corresponding to the maximum in the distribution of partial wave cross sections  $\sigma = f(l)$ , extracted from PACE code [9].

<sup>b</sup> Maximum value of  $l$  calculated from the barrier parameters fitted by Kovar *et al* [10].

<sup>c</sup> The neutron kinetic energy,  $E_{\text{kin}}$ , is extracted from PACE code [9].

<sup>d</sup> TESSA3 experiment (the raw results have been multiplied by 0.8, see text).

<sup>e</sup> EUROGAM experiment.



**Figure 1.** Relative population intensities of the  $^{194}\text{Pb}$  yrast SD band as a function of excitation energy of  $^{194}\text{Pb}$  (see text and table 2).

extract the maximum angular momentum ( $l_{\text{max}}^{\text{PACE}}$ ) defined as the value of  $l$  corresponding to the maximum in the distribution of the partial wave cross section,  $\sigma = f(l)$ .

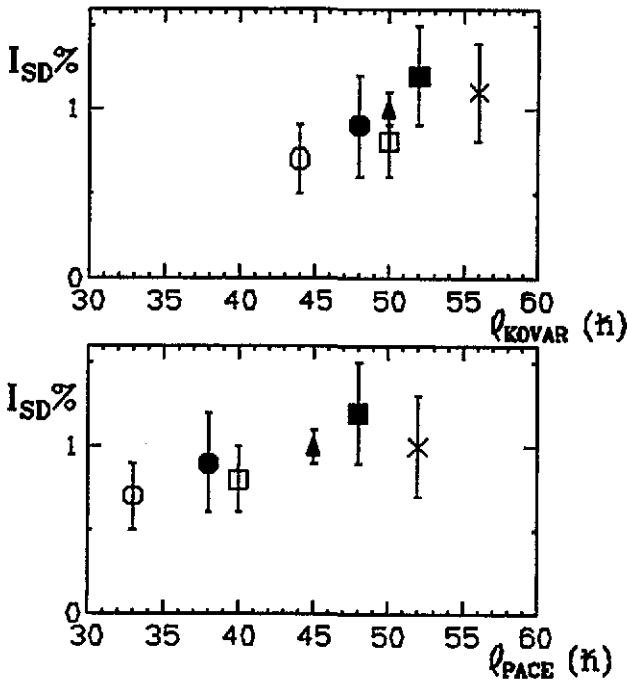


Figure 2. Relative population intensities of the  $^{194}\text{Pb}$  yrast SD band as a function of maximum angular momentum (see text and table 2).

Secondly, the angular momentum for fusion can also be calculated from the classical mechanics formula. The values  $l^{\text{KOVAR}}$  (table 2) have been obtained with the barrier parameters ( $R_B$ ,  $V_B$ ) fitted by Kovar *et al* [10]. The values  $l_{\text{max}}^{\text{PACE}}$  or  $l^{\text{KOVAR}}$  can be used to account for the input angular momentum because the diffuseness of the cut-off of the high-spin distribution is not expected to be very different in reactions induced by oxygen and sulphur beams.

The yields obtained in this work do not show any dependence on the excitation energy of  $^{194}\text{Pb}$ , as calculated from the PACE code (figure 1). Nevertheless the order of appearance of the points according to the excitation energies  $E^*$  strongly depends on the kinetic energy removed by the neutrons. It is worth noting that the total kinetic energy carried out by evaporated neutrons is not well known. It has been derived in some cases by energy balance (see for instance [11, 12]) and the average value is lower for a high number of emitted neutrons, in contrast to the calculated one.

On the other hand, in the lower angular momentum region, the relative population intensities (see figure 2) weakly increase and, within the error bars, appear to saturate for the higher  $l$  region. This overall trend is the same for both choices of the maximum angular momentum value,  $l_{\text{max}}^{\text{PACE}}$  or  $l^{\text{KOVAR}}$ . This can be viewed as the limiting effect of fission in the population of the SD states.

Population effects have recently been observed in the  $A = 150$  mass region [2]: SD population is enhanced when more symmetric reactions are used to produce the nucleus of interest. Our results cannot be analysed along such lines, as they always deal with very asymmetric reactions and the different compound nuclei are produced with various excitation energy and spin values.

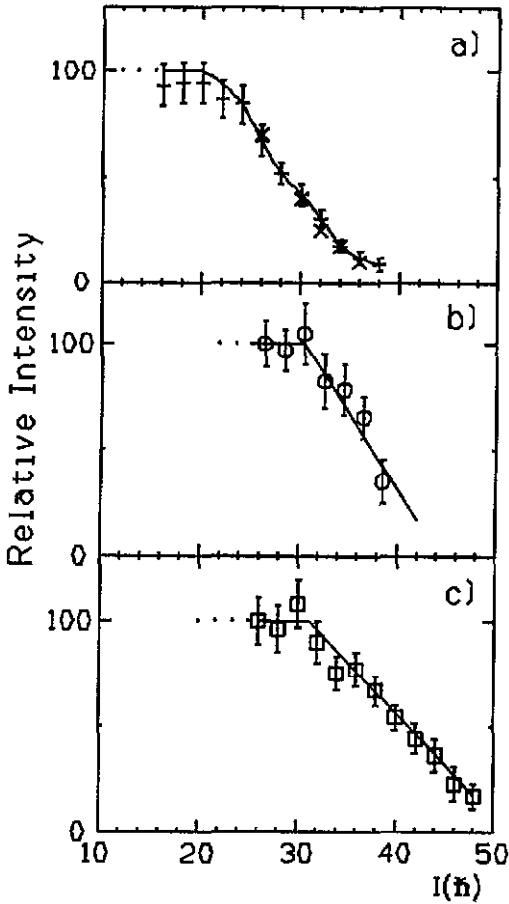


Figure 3. Relative intensity of the  $\gamma$ -ray in the SD bands as a function of the spin  $I$  of the decaying state: (a) in  $^{194}\text{Pb}$  [8], populated via the  $^{184}\text{W} + ^{16}\text{O}(+)$  and  $^{162}\text{Dy} + ^{36}\text{S}$  reactions ( $\times$ ) (the values are normalized to 100 for the 256 keV  $12^+ \rightarrow 10^+$  transition); (b) in  $^{195}\text{Tl}$  [15], populated via the  $^{186}\text{W} + ^{15}\text{N}$  at 105 MeV (the plateau has been normalized to 100); (c) in  $^{192}\text{Hg}$  [13], populated via the  $^{160}\text{Gd} + ^{36}\text{S}$  reaction at 159 MeV (the plateau has been normalized to 100).

Figure 3(a) shows the feeding pattern of the  $^{194}\text{Pb}$  yrast SD band in two reactions,  $^{184}\text{W} + ^{16}\text{O}$  and  $^{162}\text{Dy} + ^{36}\text{S}$ . The obtained results are very similar. For comparison, the feeding pattern of the SD band in  $^{192}\text{Hg}$ , populated by the reaction  $^{160}\text{Gd} + ^{36}\text{S}$  at  $E_{\text{lab}} = 159$  MeV [13], is shown in figure 3(c). This proves that states with spin as high as  $48\hbar$  can be populated with a  $^{36}\text{S}$  induced reaction at a bombarding energy just above the Coulomb barrier. The  $\gamma$ -ray intensity along the SD band increases gradually with decreasing spin value, in an interval from  $I_1$  to  $I_2$ . The population of the SD band occurs between spin  $\sim 38$  and  $\sim 22\hbar$  in  $^{194}\text{Pb}$  and between spin  $\sim 48$  and  $\sim 32\hbar$  in  $^{192}\text{Hg}$ . The lower limit ( $I_2$ ) is correlated to the spin value where the ND yrast line crosses the SD yrast line (see for instance the results of SD population simulations [14]). The difference between the  $I_2$  values for the two isotones has already been discussed [8]. A large difference of about  $10\hbar$  is observed between the maximum spin values,  $I_1$ . It should be pointed out that the  $I_1$  spin limit in  $^{195}\text{Tl}$  ( $Z = 81$ ) is  $\sim 42\hbar$  [15], exactly between the limits obtained for mercury ( $Z = 80$ ) and lead ( $Z = 82$ ) isotopes (see figure 3(b)). This feature is again consistent with the scenario where the fission selectively depletes the high- $l$  partial waves, imposing decreasing  $I_1$  limits according to the  $Z$  value of the superdeformed nucleus. A spin limited can be calculated in the framework of the rotating liquid drop model (RLDM) [16]: the maximum amount of angular momentum that a compound nucleus could support and still survive the risk of fission in the de-excitation process is obtained when the barrier against fission  $B_f$ ,

which decreases with increasing angular momentum, reaches the neutron binding energy. Such theoretical fission limits have been calculated for the three series of nuclei reached at various steps of de-excitation ( $^{198-195}\text{Pb}$ ,  $^{201-196}\text{Tl}$ ,  $^{196-193}\text{Hg}$ ) with  $B_f \approx 8$  MeV. The values,  $36 \pm 2\hbar$ ,  $44 \pm 3\hbar$ ,  $46 \pm 2\hbar$  respectively, seem to be in agreement with our observations. However, precise analyses of cross sections of fission and evaporation residues measured at several bombarding energies have shown that the fission barriers given by RLDM have to be reduced by a factor  $k_f$  [17]. For instance, results obtained for the  $^{200}\text{Pb}$  compound nucleus populated in reactions induced by  $^{19}\text{F}$  and  $^{30}\text{Si}$  are well fitted with a scaling factor independent of spin value,  $k_f \approx 0.8$  [4].

From our results, we can estimate the limit of the angular momentum of Pb residual nuclei to be  $\sim 40\hbar$ . The SD states are only populated from a well-defined  $l$  range, whatever the value of the maximum angular momentum theoretically brought to compound nuclei. This can be accounted for by the limit to angular momentum of lead nuclei imposed by the fission. The maximum spin values can now be measured using the new generation  $\gamma$ -arrays such as EUROGAM or GAMMASPHERE; this represents a first step in the use of such  $\gamma$ -ray technique to obtain new information on the fission process.

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