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Evidence for a (semi)direct component in the decay of the isoscalar giant monopole in ^{208}Pb

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Branching ratios to the neutron hole states resulting from the decay of the isoscalar giant monopole resonance in ^{208}Pb have been extracted from our previously published data. The results are compared to other experimental data. An upper limit for (semi)direct decay is obtained and compared to recent calculations. Considerable discrepancies are found.

One of the important questions in the decay of giant resonances is whether there is evidence for a nonstatistical (semi)direct decay component. Whereas for light nuclei such as ^{40}Ca and ^{24}Mg strong evidence for such a component has been found, the data for medium-heavy and heavy nuclei indicate that if such a (semi)direct component is present, it is small, i.e., 10–15 % (see, for instance, Ref. 1, and references therein).

Of special importance is the study of the decay of the isoscalar giant monopole resonance (GMR) in ^{208}Pb, since various groups have performed microscopic RPA-type calculations on the GMR decay properties for this nucleus (see Ref. 2, and references therein). In particular, Bracco *et al.* have recently shown[2] that different model Hamiltonians which reproduce the energy and sum-rule strength of the GMR result in quite different decay properties. They have also calculated the (semi)direct escape width to the various low-lying hole states in ^{207}Pb. Consequently, experiments on the decay of the GMR, in which the branching ratios of the decay to these hole states are measured, allow us to discriminate between microscopic descriptions of the GMR.

Experimentally the decay properties of the GMR in ^{208}Pb have been studied by three groups using different techniques to excite the GMR and to measure the hole state population in the residual nucleus ^{207}Pb. In Ref. 2 the calculations were compared with the experimental results of Bracco *et al.*[3] In this experiment the GMR was excited by inelastic scattering of ^{17}O ions. The ^{207}Pb final-state spectrum resulting from the neutron decay of the excited nucleus was determined by measuring the γ-ray spectrum after neutron decay in coincidence with the scattered ^{17}O. One of the drawbacks of this experiment is that also the continuum under the GMR is excited, at least as strongly if not more strongly than the giant resonances.[4] Since the continuum also decays to the hole states, its contribution has to be separated from that of the GMR proper. This was done by assuming that in this experimental setup the characteristics of the decay of the continuum in the excitation energy region of 15–16 MeV were the same as those in the GMR excitation energy region of 13–15 MeV.[2]

In the other two experiments[5,6] the hole state population was directly deduced from a measurement of the decay neutron spectrum. An important feature of our experiments (Ref. 6) is that the decay properties of both the GMR and the continuum under the GMR, which is also strongly excited, were obtained separately from the same measurement. This was done by measuring the neutron spectrum at backward angles in coincidence with α particles of 120 MeV inelastically scattered into the angular range $0° \leq \theta_{\alpha'} \leq 3°$ and applying the spectrum subtraction technique.[6] The validity of this method is based on the very steep angular dependence of the GMR excitation cross section in this angular range and on the assumption that the nature and excitation cross section of the continuum under the GMR does not vary significantly in the angular range under consideration. It turns out[6] that in the GMR excitation energy range of 12.5–15.5 MeV, only about 15% of the spectrum associated with GMR excitation can be due to excitation of continuum components with a multipolarity $L \neq 0$.

The purpose of the present paper is twofold. In the first place, we will compare the experimental data of Bracco *et al.*[2,3] on the branching ratios to the hole states to experimental branching ratios extracted from our data.[6] In order to obtain these ratios we had to analyze our data in somewhat more detail. Such a comparison is interesting, since these two sets of data are obtained with quite different techniques. Moreover, these ratios can then be compared to the calculated[2] ones, thus making it possible to compare in great detail calculated and experimental branching ratios.

The experimental results on the decay of the continuum and the GMR are reproduced again in Figs. 1(a) and (b) respectively. The spectra are characterized by a broad bump at the higher excitation energies in the residual nucleus ^{207}Pb, while at lower excitation energies (high neutron energies) the population of the hole states can be recognized. The broad bump is presumably due to the statistical decay process. For the lowest neutron energies, corresponding to highest excitation energies in the residual nucleus ^{207}Pb, the shape of the spectrum is modified due to the energy-dependent efficiency of the neutron detectors. The histograms are the result of a statistical-model calculation folded with the efficiency and energy resolution of the neutron detectors and the shape of the relevant (α,α') spectrum. These calculations were normalized to the data by normalizing to the total number of counts in the neutron spectrum. This corresponds to the assumption that the decay is entirely statistical.

As already discussed in Ref. 6 it can be concluded from the comparison between the calculated and experimental spectra that the decay of both the continuum and the GMR is consistent with 100% statistical decay. The discrepancies for the continuum [Fig. 1(a)] can be explained by assuming that also some $J^{\pi} \geq 4^{+}$ strength is excited in the (α,α') reaction.[6] A similar conclusion with respect to the GMR decay was obtained in Ref. 7 using the data of Refs. 5 and 6. An *upper* limit for a (semi)direct branch of the GMR to the low-lying hole states was deduced from the fact that there were still small discrepancies between the calculated, 100% statistical decay spectrum and the measured one, especially for the population of the ground state and for the group of data points around 4 MeV excitation. By lowering the statistical decay contribution to the extent that the group of data points at 4 MeV excitation energy was fitted by the calculations [see Fig. 1(c)] it was found that, in that case, the excess population to the low-lying hole states, if identified with the (semi)direct decay branch, corresponds to an *upper* limit of about 10% (semi)direct decay. It also implies that, in that case, there should be a contribution of a preequilibrium decay process in which, presumably, states resulting from the coupling of hole states to surface vibrations are populated.[6] The ground-state population in this case is still below the calculated one, but in view of the large experimental uncertainties this discrepancy is statistically not an impossibility.

The branching ratios for the decay to the various hole

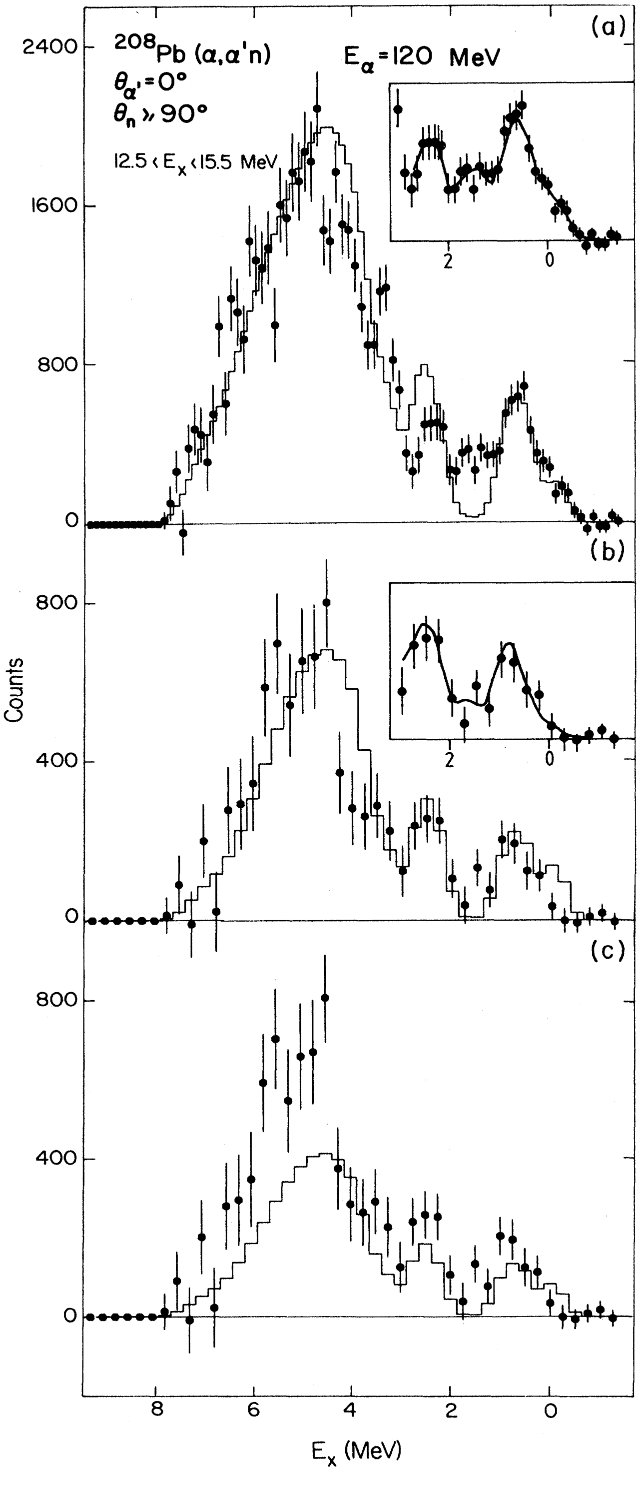

FIG. 1. Experimental (points) and calculated (histograms) final-state spectra (Ref. 6) for the excitation energy range $12.5 < E_x < 15.5$ MeV in ^{208}Pb for the continuum under the GMR (a) and for the GMR proper assuming 100% (b) and 60% (c) statistical decay. The insets in (a) and (b) show the fits to the experimental data from which the branching ratios to the low-lying final states in ^{207}Pb were determined.

states were determined using a peak-fitting program to disentangle the contributions of the different hole states. The excitation energies of the states included in the fit were kept fixed. In the fits the experimental energy resolution of 500 keV was used. The fits are displayed in the insets in Figs. 1(a) and (b). The peak contents were converted to branching ratios by reconstructing the total neutron decay spectrum from the data, taking into account the variation of the neutron detector efficiency with neutron energy.[6] The contribution of neutrons with an energy below the detection threshold was estimated from the spectrum obtained from a statistical-model calculation. This last step introduced a correction of less than 15% so that the final result is not very sensitive to the assumed extrapolated shape. The decay is assumed to be isotropic, which is of course true for the GMR. As has been experimentally verified,[6] it also holds for the continuum. As an additional check, it was ascertained that the contents of the reconstructed neutron spectra of continuum and GMR together, integrated over the total solid angle, were within 10% the same as the total contents of the singles spectrum in the corresponding excitation energy range. Since we measured the total neutron spectrum the branching ratios for the population of the hole states can be obtained directly from the coincidence spectrum, in contrast to the experiment described in Ref. 3 where only the high-energy part of the neutron spectrum was measured and thus the ratio of coincidence to singles cross section has to be determined.

The experimental results for the GMR and for the underlying continuum are given in Table I. In some cases the energy resolution is not sufficient to separate clearly the contributions to neighboring levels. This is especially true for the $\frac{7}{2}^-$ hole state at 2.34 MeV and the $\frac{5}{2}^+$-$\frac{7}{2}^+$ doublet at 2.6 MeV, for which only the summed contribution could be reliably extracted. Also given in Table I are the branching ratios to the hole states for GMR decay, assuming that 100% and 60% of the total number of counts in the neutron spectrum are due to statistical decay, respectively.

Since no branching ratios are given in Refs. 2, we compare here the escape widths $\Gamma_i^\uparrow$ of the GMR to the individual final states. For our data the $\Gamma_i^\uparrow$ values for the GMR were extracted from the corresponding branching ratios $B(i)$ by writing $B(i) \cong (\Gamma_i^\uparrow + \Gamma_i^\downarrow)/\Gamma$ with $\Gamma = 2500$ keV. This approximation is allowed as long as the direct component is small, as is the case here. $\Gamma_i^\downarrow/\Gamma$ was taken as the calculated branching ratio for "60%" statistical decay which, as we have argued, is a lower limit: thus, the extracted values for $\Gamma_i^\uparrow$ are *upper* limits.

Various comments can be made. First of all we find that our values for the direct decay widths are in some cases smaller than the values quoted in Ref. 2. This is especially true for the $f_{5/2}$ state. It probably also holds for the $f_{7/2}$ state at 2.34 MeV since the summed contribution of this state and the $(\frac{5}{2}^+, \frac{7}{2}^+)$ doublet at 2.6 MeV gives as an *upper* limit a branching ratio about equal to the value quoted in Ref. 2 for the $f_{7/2}$ state alone. Also, the value of (75±35) keV for the $i_{13/2}$ state, which is not affected by the assumed contribution of statistical decay, seems to be smaller than the one obtained in Ref. 2. This might be an indication that in Refs. 2 and 3 the supposedly pure GMR data are contaminated with high multipolarity contributions. It is well known that in the excitation energy range of 13–15 MeV in ^{208}Pb a considerable amount of $L \geq 4$ strength is present,[1] probably more than in the range 15–16 MeV which was used in Ref. 2 and 3 for the continuum subtraction.

Comparing our results with the calculated widths for direct decay,[2] there is qualitative agreement in the sense that the total calculated direct decay width, $\Gamma^D = \Sigma_i \Gamma_i^\uparrow$, is not inconsistent with our upper limit. Quantitatively there is agreement in the sense that the predicted direct decay width of the $p_{1/2}$ ground state is very small, in agreement with our data. However, there are also some differences, the most notable being the direct decay widths associated with the $i_{13/2}$ and $f_{5/2}$ hole states. For the $i_{13/2}$ state the calculated value is much smaller than the experimental one, while for the $f_{5/2}$ and probably also the $f_{7/2}$ hole states the calculated values are larger. Note that if we would have taken the calculated statistical decay values listed under "100%" the discrepancy for the $i_{13/2}$ level would remain the same but the discrepancy

TABLE I. Experimental and calculated (in the statistical model) branching ratios for the decay of the GMR and the underlying continuum in ^{208}Pb.

		Experimental values (%)[a]		Calculated values GMR(%)[b]		$\Gamma_i^\uparrow$ (keV)		
							Ref. 2	
Final state	E_x (MeV)	GMR	Continuum	100%	60%	This work[c]	Expt.	Theor.
$p_{1/2}$	0	0.75±1.1	1.6±0.4	4.1	2.4	75±35	140±35	5
$i_{13/2}$	1.63	2.9±1.3	3.4±0.5	<0.1	<0.1			6
$f_{5/2}$	0.57	2.6±1.7	3.2±0.7	4.9	3.0	<35	70±15	92
$p_{3/2}$	0.89	5.3±1.8	5.1±0.7	3.9	2.4	75±40	50±10	8
$f_{7/2}$	2.34	11.4±1.3	7.2±1.7	4.4	2.7	<140±30[d]	165±40	174
$\frac{5}{2}^+ + \frac{7}{2}^+$	2.6			5.2	3.1			

[a] Values calculated from the spectra shown in Fig. 1.

[b] Values deduced from a calculated statistical decay spectrum: 100% and "60%" mean that the calculated spectra are normalized to the total number of counts in the experimental spectrum and to 60% of the total number, respectively.

[c] Values calculated assuming "60%" statistical decay. Thus, they are upper limits except for the value of the $i_{13/2}$ state for which the statistical contribution is, anyhow, negligible.

[d] This value of (140±30) corresponds to the sum of the $f_{7/2}$ and $(\frac{5}{2}^+ + \frac{7}{2}^+)$ states.

for the $f_{5/2,7/2}$ states would become even larger. It should also be remarked that in our experiment the discrepancy noted above for the $i_{13/2}$ state cannot be due to contamination of the GMR spectrum with high multipolarity components: as Table I shows, the experimental values for the branching ratios to this state in continuum and GMR decay are approximately the same, and since the continuum contributes at most 15% to the "GMR" spectrum[6] its possible effect on the experimentally observed $i_{13/2}$ branching ratio of the GMR can only be small.

In conclusion we have extracted from our old data[6] on the neutron decay of the GMR in ^{208}Pb branching ratios to the various low-lying hole states in the residual nucleus ^{207}Pb. The (semi)direct decay widths associated with these branching ratios are in some cases significantly different from the experimental values quoted in Ref. 2. Also, comparing our results for the *upper* limits of the (semi)direct decay widths with the calculated ones of Ref. 2, we find for some specific hole states significant differences. This is especially true for the high-spin $i_{13/2}$ hole state. It indicates the need for a further refinement of the calculations. In this connection it is interesting to note that recently we have also found that in the GMR decay of ^{90}Zr the only clear semidirect decay branch is to the $J^{\pi}=\frac{9}{2}^{+}$ high-spin ground state.[8]

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[1] A. van der Woude, Prog. Part. Nucl. Phys. **18**, 217 (1987).

[2] A. Bracco, J. R. Beene, N. Van Giai, P. F. Bortignon, F. Zardi, and R. A. Broglia, Phys. Rev. Lett. **60**, 2603 (1988).

[3] A. Bracco, Nucl. Phys. **A482**, 421c (1988).

[4] P. E. Bertrand *et al.*, Phys. Rev. C **35**, 111 (1987).

[5] W. Eyrich *et al.*, Phys. Rev. C **29**, 418 (1984).

[6] S. Brandenburg *et al.*, Nucl. Phys. **A466**, 29 (1987).

[7] H. Dias, N. Teruya, and E. Wolynec, Phys. Rev. C **33**, 1955 (1986).

[8] W. T. A. Borghols, thesis, University of Groningen, 1988; W. T. A. Borghols *et al.* (unpublished).