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Statistical decay of giant monopole resonance in ^{208}Pb

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The neutron spectrum from the decay of the monopole giant resonance in ^{208}Pb is calculated using the known energy levels of ^{207}Pb. The particle vibrator model is used to assign spins and parities to the measured ^{207}Pb levels, where these were not available from experiments. The result of the Hauser-Feshbach calculation is in excellent agreement with the experimental spectrum, showing that the observed fast neutrons can be completely explained assuming a statistical decay.

I. INTRODUCTION

The decay properties of giant resonances (GR's) are of special interest for the understanding of structure and dynamics of these collective modes of nuclear excitation. Since giant resonances have mostly excitation energies above particle emission thresholds, they usually decay by particle emission. The total decay width consists of an "escape width," which represents the "direct" decay owing to the coupling of the 1p-1h doorway state to the continuum and a "spreading width" which reflects the coupling to more complicated np-nh states. For a dominant spreading width all available states of the residual nucleus are populated following statistical rules, while for a dominating escape width the decay leads predominantly to the low lying 1h states of the residual nucleus. Besides these two extreme decay modes, which are generally used to classify the decay, intermediate preequilibrium modes are also possible.

The experimental classification of decay branches as direct, preequilibrium, and statistical is often ambiguous, because there is no experimental procedure for labeling a given nuclear decay as being due to a particular reaction mechanism. Rather, we must resort to comparisons between the average decay properties observed and the predictions of specific reaction models. Typically we must resort to arguments wherein deviations from the predictions of a Hauser-Feshbach calculation[1,2] are regarded as evidence for nonstatistical contributions to the measured cross sections. The presence of nonstatistical decay is of crucial importance because the study of nonstatistical decay channels will provide insights into the microscopic character of the giant resonances.

For the giant dipole resonance, according to Cardman,[3] the most direct evidence for nonstatistical decay comes from measurements of neutron energy spectra at Illinois.[4–6] These are usually compared with the results of a statistical calculation assuming that the level density of the residual nucleus can be represented by

$$\rho=\rho_0\exp(E_x/T)\ , \qquad (1)$$

where E_x is the excitation energy of the residual nucleus and T is the nuclear temperature, taken to be constant. The excess neutrons are attributed to a direct process. For heavy nuclei this analysis led to the conclusion that 10–15% of the $E1$ GR decays are nonstatistical.[6] This technique has been employed recently by Eyrich *et al.*[7] to interpret their measured neutron spectra emitted from the $E0$ giant resonance in ^{208}Pb.

Figure 1 shows the neutron decay spectrum of the reaction ^{208}Pb$(\alpha,\alpha',\mathrm{n})^{207}$Pb between 13 and 14 MeV excitation energy in ^{208}Pb. The dotted line is the prediction of the statistical model assuming a level density for ^{207}Pb given by Eq. (1) with $T=0.7$ MeV.[7] The excess neutrons are interpreted as resulting from a direct decay. Eyrich *et al.*[7] conclude that besides a dominant statistical component there is $\approx 15\%$ direct contribution.

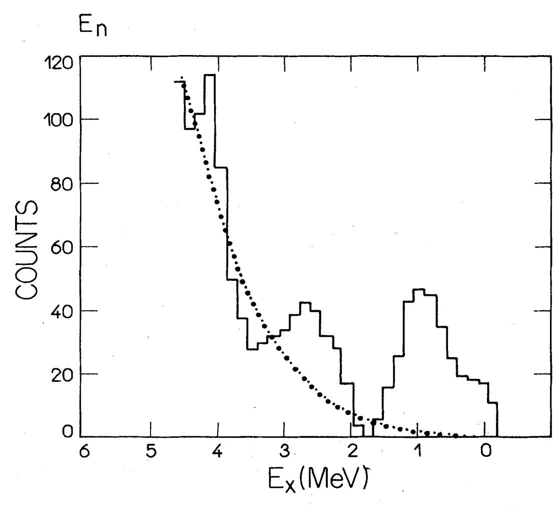

FIG. 1. Solid line: measured neutron spectrum from the decay of the $E0$ giant resonance in ^{208}Pb (Ref. 7). Dotted line: predicted neutron spectrum performing a statistical calculation using a level density function to represent the levels of ^{207}Pb. E_x is the excitation energy in ^{207}Pb.

TABLE I. Level density of ^{207}Pb.

Energy interval (MeV)	Number of levels Eq. (1)	Expt. (Ref. 8)
0—1	0.1	3
1—2	0.4	1
2—3	2	5
3—4	8	24
4—5	32	32
5—6	130	13

However, in all the studies of neutron decay spectra mentioned above, the excitation energy of the residual nucleus is not high enough for the level density to be well represented by Eq. (1). We can take the neutron spectra from the decay of the $E0$ giant resonance in ^{208}Pb as an example. Since the excitation energy is between 13 and 14 MeV, in the discussion that follows we will assume $E_x = 13.5$ MeV for simplicity. Thus the maximum excitation energy in ^{207}Pb is 6.1 MeV, because the neutron separation energy is 7.4 MeV. The levels of ^{207}Pb are known up to this excitation energy.[8] Table I shows the number of levels of ^{207}Pb compared with the number of levels predicted by Eq. (1). We have normalized Eq. (1) to agree with the number of known levels in the interval 3—4 MeV. Any other normalization leads to the same type of disagreement. The level density of (1) is unable to predict the number of levels in this range of excitation energies. It is not surprising that a level density which does not describe the actual level density will not predict the measured neutron spectrum.

We have tried to describe the ^{207}Pb level density with far more sophisticated functions, like the one given in Ref. 9, without success. In order to attribute any deviations from the predictions of the statistical model to direct contributions, the spectra have to be calculated using the actual levels of ^{207}Pb.

II. CALCULATION OF NEUTRON SPECTRA

This calculation assumes that the nucleus is excited to the $E0$ giant resonance by some process. The absorbed energy E_x is then thermalized and subsequently dissipated through particle emission. The partial cross sections, σ_i, for the various decay channels are governed by penetrabilities, i.e.,[1,2]

$$\sigma_i(E_x)=\sigma_f(E_x)\frac{\sum\limits_{sl} T^i_{ls}(E_x-Q_i)}{\sum\limits_{k}\sum\limits_{s'l'} T^k_{l's'}(E_x-Q_k)} , \qquad (2)$$

where $\sigma_f(E_x)$ is the formation cross section that excites the nucleus to the energy E_x; $T^i_{ls}(E)$ is the transmission coefficient for the ith decay channel, at an energy E above its threshold; $E=E_x-Q_i$, Q_i is the reaction threshold for the ith channel; s and l are the spin and angular momentum of the ejected particle; and k is the number of open channels.

The evaluation of the denominator of Eq. (2) requires knowledge of the energies, spins, and parities of the excited states of all nuclei to which the compound nucleus can decay. If only the low lying states are known, a level density function must be employed for higher excitation energies. Of course, the accuracy of the results will depend on how well the level density is represented.

For our particular case the decay by one neutron emission is the only relevant channel, because at 13.5 MeV excitation energy in ^{208}Pb charged particle emission is strongly inhibited by the Coulomb barrier. To evaluate Eq. (2) we need to know the levels of ^{207}Pb up to 6.1 MeV excitation energy. As shown previously (see Table I), a level density function is unable to describe the actual level density in this range.

Fortunately, ^{207}Pb has been studied extensively and there are 78 levels up to this excitation energy (see Ref. 8). However, the spins and parities are well established for

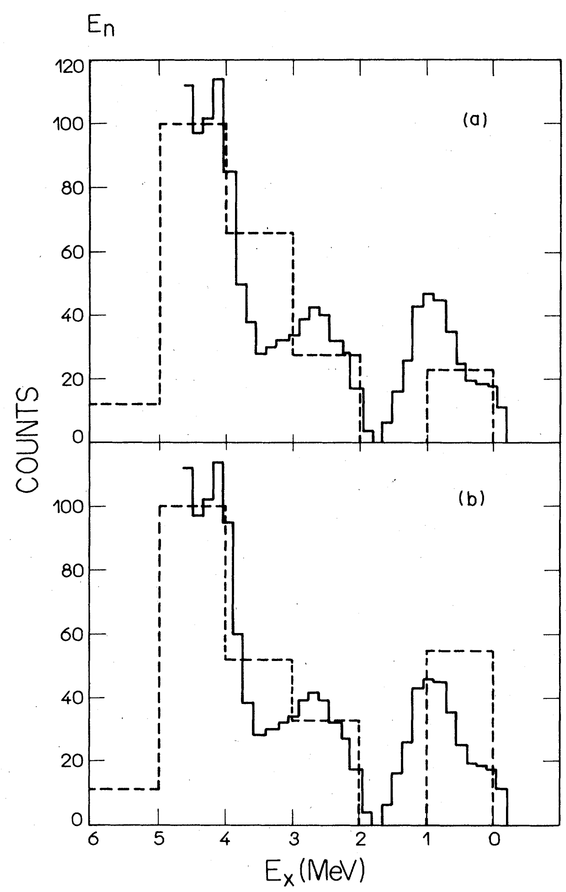

FIG. 2. The solid line is the measured neutron spectrum from the decay of the $E0$ giant resonance in ^{207}Pb (Ref. 7). The dashed line is the predicted neutron spectrum using the known levels of ^{207}Pb. The 29 levels with unknown spins and parities are assumed to be $(\frac{1}{2})^+$ in (a) and $(\frac{9}{2})^+$ in (b) (see the text). The different neutron groups are summed in 1 MeV intervals. E_x is the excitation energy in ^{207}Pb.

TABLE II. Allowed l values.

Spins	$\frac{1}{2}$	$\frac{3}{2}$	$\frac{5}{2}$	$\frac{7}{2}$	$\frac{9}{2}$	$\frac{11}{2}$	$\frac{13}{2}$	$\frac{15}{2}$	$\frac{17}{2}$	$\frac{19}{2}$
Positive parity	0	2	2	4	4	6	6	8	8	10
Negative parity	1	1	3	3	5	5	7	7	9	9

only 13 of these levels. For 36 of the levels the most probable spin and parity is indicated and we are left with 29 levels with unknown spins and parities. For these 29 levels we had to make spin and parity assignments which are discussed in the following.

The transmission coefficients that appear in Eq. (2) were evaluated using a standard optical model program with parameters taken from Rapaport *et al.*[10] Table II gives the allowed l values for all possible spin states in ^{207}Pb that can be reached from the decay of the 0^+ state in ^{208}Pb.

The evaluation of the transmission coefficients shows that the highest values of T_{ls} are obtained for $S=(\frac{1}{2})^+$. Thus we attributed the value $(\frac{1}{2})^+$ to the 29 levels with unknown spins and parities. This is an unreasonable assumption, but it gives a lower limit for the intensity of the high energy neutrons. Since most of the unknown spins are at higher excitation energies, with this assumption we are favoring the decay into these states in detriment of decay into the first few excited states of ^{207}Pb. Using this assumption we obtain the neutron spectrum shown in Fig. 2(a) by the dashed line. We have added all neutrons in 1 MeV intervals and normalized the spectrum obtained to agree with the measured spectrum in the 4—5 MeV range of excitation energy in ^{207}Pb. The number of predicted high energy neutrons is about half of the experimental result.

A more realistic assumption can be made to assign spins and parities to these 20 levels. ^{207}Pb is, perhaps, one of the best systems for the application of the particle vibrator model, because of the purity of the double shell closure and the knowledge of many and well separated levels in ^{208}Pb. The adequacy of this model was corroborated by the extensive study of ^{207}Pb levels, and by (p,p′) inelastic scattering in ^{208}Pb, carried out by Wagner *et al.*,[11] covering the same range of excitation energies used here. Several states were identified as coming from the coupling of single hole states with low lying states in ^{208}Pb.

We calculated the distribution of states in ^{207}Pb using the particle vibrator model with the single hole states 3^-, 5^-, 2^+, 4^+, and 8^+ of ^{208}Pb. Based on the results of Wagner *et al.*,[11] we considered the coupling of the positive parity states of ^{208}Pb only with $3p_{1/2}$. Using this space we obtain 84 distinguishable states while the number of observed states is 78. The distributions of spins and parities of these 84 states is shown in Fig. 3 along with the distribution of spins and parities of the 49 levels which were deduced from experiment.[8] The latter in-

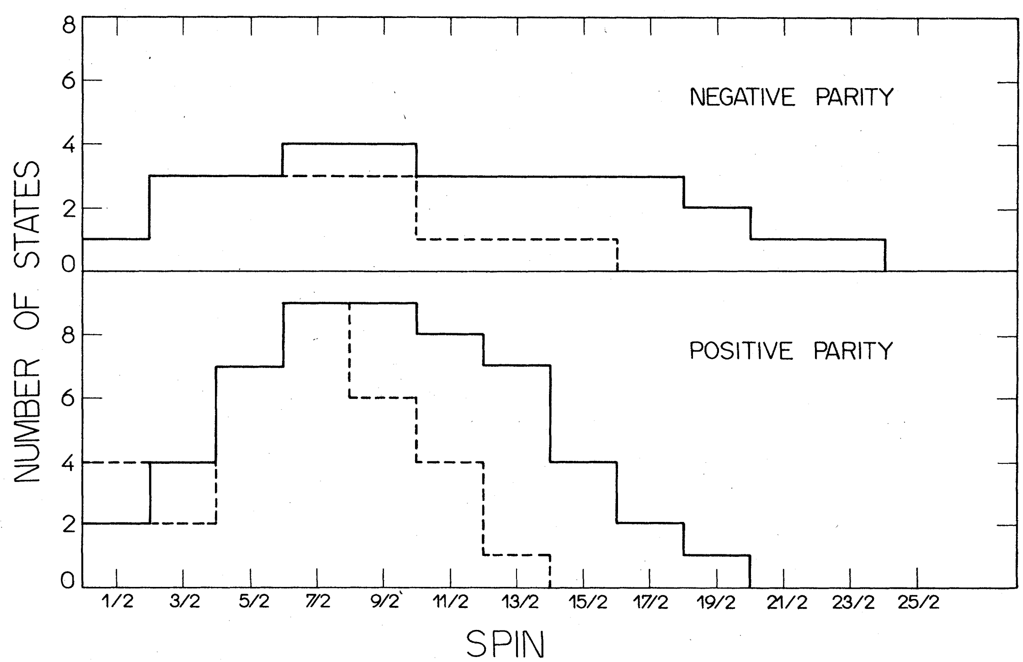

FIG. 3. Distribution of spins and parities for the levels of ^{207}Pb. The dashed curve is obtained from experimental results (Ref. 8) and the solid curve is the distribution predicted by the particle vibrator model. The areas under the dashed and solid curves are different because from the 78 levels observed in ^{207}Pb, 29 have unknown spins and parities.

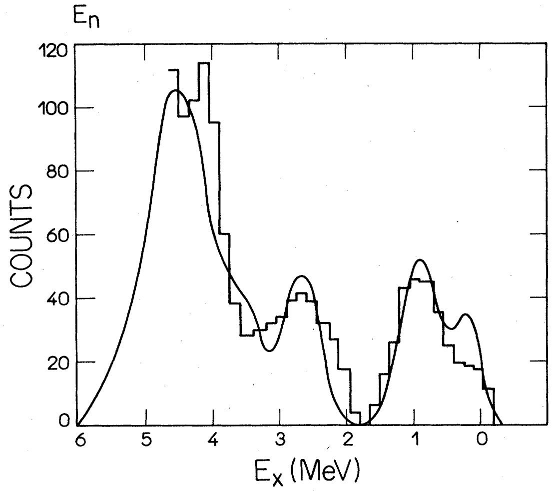

FIG. 4. The histogram is the measured neutron decay spectrum from the $E0$ giant resonance in ^{208}Pb (Ref. 7). The curve is the predicted spectrum using a Hauser-Feshbach calculation under the same assumptions as Fig. 2(b), but taking into account the resolution of the experiment (500 keV). Each of the 78 neutron groups is represented by a Gaussian with FWHM=500 keV.

cludes also the spins and parities that are indicated in Ref. 8. As Fig. 3 shows, the experimental and calculated distributions of spins and parities follow the same pattern. It is interesting to note that the distribution of even and odd parity is not identical and all level density functions assume an equal number of odd and even parity states; thus they will be inadequate for this range of excitation energies in ^{207}Pb.

Based on the calculated distribution of spins and parities we assigned spins and parities $(\frac{9}{2})^+$ to the 29 levels with unknown spins and parities, obtaining the spectrum shown in Fig. 2(b) by the dashed line. From Fig. 3, S should be $(\frac{9}{2})^+$ or higher. Figure 3 also shows that the assumption made previously of the 29 levels with $S=\frac{1}{2}$ can be excluded.

Under this more realistic assumption the relative intensity of high energy neutrons is in agreement with the experimental results as shown in Fig. 2(b). There is a difference between the detailed shape of the calculated and measured spectra. This difference is caused by the finite resolution of the experimental spectrum not taken into account in the calculated spectrum.

In Fig. 4 we show the predicted spectrum of neutrons under the same assumption of Fig. 2(b), but taking into account that the experimental resolution of the measured spectra is 500 keV.[7] It is assumed that the number of predicted neutrons feeding each of these levels is represented by a Gaussian having 500 keV FWHM. The curve shown in Fig. 4 is the sum of 78 Gaussians, one for each neutron group, having an area equal to the corresponding neutron intensity. The agreement between the measured and calculated spectrum is excellent.

III. CONCLUSIONS

We have shown that if a Hauser-Feshbach calculation is performed using the known levels of ^{207}Pb, instead of a level density function, the measured neutron spectrum, resulting from the decay of the $E0$ giant resonance, can be completely explained. Neutron decay from the $E0$ giant resonance is statistical.

If the excitation energy in the residual nucleus is only a few MeV above the ground state it is not possible to represent its levels well by a level density function. This is the case for the studies performed previously[3–6] about neutron decay spectra from the $E1$ giant resonance. Therefore the conclusions about how much is direct or statistical are questionable.

In the case of neutron decay spectra from the giant resonances it is not possible to obtain high enough excitation energies in order to represent the levels of the residual nucleus by a level density function and ignore the low lying states. When the excitation energy is $\gtrsim 8$ MeV above the threshold for 1n emission, the 2n channel will usually be open. The neutron spectrum will be dominated by 2n decays, which because of the energy available will populate low lying states in the residual nuclei. When the excitation energy is $\gtrsim 8$ MeV above the threshold for 2n decay, the 3n decay channel will be open and these decays will again populate the low lying states in the residual nuclei.

Since the dominant neutron decay mode (1n,2n,. . .) will always involve excitation energies $\lesssim 8$ MeV in the residual nuclei, it is probably better to use a nuclear model to predict the number of levels, spins, and parities, when these are not available from experiments.

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