Statistical decay of the $E1$ giant resonance

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Available experimental data on neutron decay spectra from the $E1$ giant resonances in ^{208}Pb and ^{209}Bi are compared with the predicted spectra for statistical decay. The calculations are performed using the Hauser-Feshbach formalism with the experimental levels of the residual nuclei. The particle-vibrator model is used to assign spins and parities to experimental levels when those are unknown and also to predict the levels where there is not enough experimental information.

I. INTRODUCTION

In previous work[1,2] it has been shown that neutron spectra from a statistical decay of giant resonances (GR) cannot be represented by the widely used expression

$$N(E_n)\alpha E_n \exp(-E_n/T) , \tag{1}$$

where E_n is the neutron energy and T the nuclear temperature, because the approximations necessary to obtain this expression are too unrealistic. A Hauser-Feshbach calculation using experimental levels of the residual nucleus is the correct approach. It has also been shown that the use of a level density is inadequate to reproduce the observed nuclear level density, with its variety of spins and parities, and that when the experimental levels are not completely known from experiment, or spins and parities are not assigned, it is more reliable to use a nuclear model which reproduces well the known levels. A discussion was carried out in Ref. 2 about the influence of different parametrizations of the optical potential needed to evaluate the transmission coefficients. It was shown that different parametrizations, based on fitting of experimental data, yield nearly undistinguishable results and that the global optical potential of Rappaport *et al.*[3] is adequate.

It has been shown[2] that the decay of the $E0$ giant resonance in ^{208}Pb is dominantly statistical because the observed neutron decay spectrum is in excellent agreement with the spectrum predicted. This result was already predicted by de Haro *et al.*[4,5] performing continuum random-phase approximation (RPA) calculations both in a 1p-1h and 2p-2h basis. The 1p-1h gave a width of 100 keV for the $E0$ GR corresponding to a direct decay branch of less than 5%, which is in agreement with the present analysis, since such small decay branch cannot be excluded. The inclusion of 2p-2h configurations in the calculations leads to a width of about 2.6 MeV, in good agreement with the experimental value[6] of 2.6 ± 0.3 MeV. In the case of the isovector $E1$ dipole giant resonance, the 1p-1h continuum RPA calculation of de Haro *et al.*[5] gives a width of 1.2 MeV. Since the experimental[7] width for the $E1$ giant resonance in ^{208}Pb is 4 MeV, direct decay should be important. In this paper we analyze the available experimental data for the $E1$ giant resonance in ^{208}Pb (Refs. 8 and 9) and ^{209}Bi.[10]

II. STATISTICAL DECAY

The Hauser-Feshbach formalism[11,12] assumes that the nucleus is excited at an energy E_x by some process. The 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. When the only relevant channel is the emission of one neutron, the partial cross sections are

$$\sigma_i(E_x,U_i)=\frac{\sigma_f(E_x)\sum_{sl}T^i_{sl}(E_{n_i})}{\sum_{ks'l'}T_{s'l'}(E_{n_k})} , \tag{2}$$

where $\sigma_f(E_x)$ is the formation cross section that excites the nucleus to the energy E_x; $T_{sl}(E_{n_i})$ is the transmission coefficient for the ith decay, emitting a neutron of energy E_{n_i} and leaving the residual nucleus at the excitation energy U_i; $E_{n_i}=E_x-E_t-U_i$; E_t is the threshold energy for neutron emission, s and l are spin and angular momentum of the ejected particle and k labels the accessible levels of the residual nucleus.

A. ^{208}Pb

A high resolution spectra for the decay of the $E1$ giant resonance is shown in Fig. 1 of Ref. 8. The measurement was performed with tagged photons of energy 10.6 MeV. The result is presented in the form of a time of flight spectrum, but it is easy to convert it into a neutron energy spectrum, because the times corresponding to the energies of neutrons decaying to ground and first two excited states are given.

At the excitation energy of 10.6 MeV in ^{208}Pb we have also the isoscalar $E2$ giant resonance. However, real photons excite very weakly this mode. At 10.6 MeV photon energy the photonuclear cross section in this nucleus is $\sim$225 mb,[8] while the $E2$ peak cross section, assuming it has a width of 3 MeV and exhausts one energy weighted sum rule, would have 7 mb. Thus we can assume that the decay spectra refers purely to the decay of the $E1$ giant resonance.

For $E_x=10.6$ MeV in ^{208}Pb, the maximum excitation energy allowed in ^{207}Pb is 3.2 MeV. Up to this excitation energy all levels have been measured and their spins and parities assigned.[13] Thus it is straightforward to calculate the expected statistical decay using Eq. (2). The transmission coefficients were evaluated using the global optical potential of Rappaport *et al.*[3]

Figure 1 shows the experimental data from Ref. 8 (data points) along with the result of our calculation, performed assuming a resolution of $\Gamma = 350$ keV for neutron detection, representing each neutron line by a Gaussian with 350 keV full width at half maximum (FWHM). The agreement between measured and calculated spectrum is excellent, leading to the conclusion that the decay is dominantly statistical.

For ^{208}Pb there is also an older measurement performed using photons of energy $E_\gamma = 13.27$ MeV.[9] For this excitation energy the maximum allowed energy in ^{207}Pb is 5.87 MeV. The experimental levels are given in Ref. 13, but there are many levels without spins and/or parities assigned. In order to assign spins and parities to these levels we have used the particle-vibrator model as described in detail in Ref. 2.

Figure 2 shows the data points from Ref. 9 and the result of our calculations. The calculated spectrum is normalized to the integrated number of experimental counts. The measured spectrum seems to have a problem with the energy scale because the peaks do not coincide with the position of low lying states in ^{207}Pb. In Fig. 3 the same calculated spectrum of Fig. 2 is shown, but it is shifted by 0.3 MeV. Now the peaks of the experimental spectrum are in better agreement with the position of the calculated peaks corresponding to low lying states. Since the neutron energies of the experimental spectrum are obtained by time of flight, it is not correct to make a linear displacement of the energy scale, because the relationship between measured time of flight and neutron energy is not linear. This displacement was carried out just to illustrate the problem. This casts doubts about the accuracy of the experimental result. Assuming that the efficiency for neutron detection is correct and that there is only a problem with the energy scale, we would conclude that there is indication of nonstatistical decay, at this excitation energy, for the $E1$ giant resonance. It could be that at lower excitation energy, such as in the data of Fig. 1, the decay is dominantly statistical and as the excitation energy increases, some direct decay occurs. Nevertheless, it should be remarked that for the $E0$ giant resonance in this nucleus, the decay is dominantly statistical at this higher excitation energy (~ 13.5 MeV). It

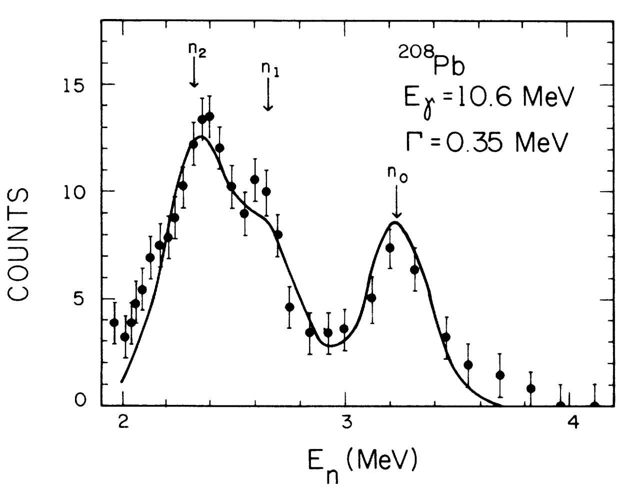

FIG. 1. Experimental neutron decay spectrum for ^{208}Pb (Ref. 8). The curve is the calculated spectrum for statistical decay.

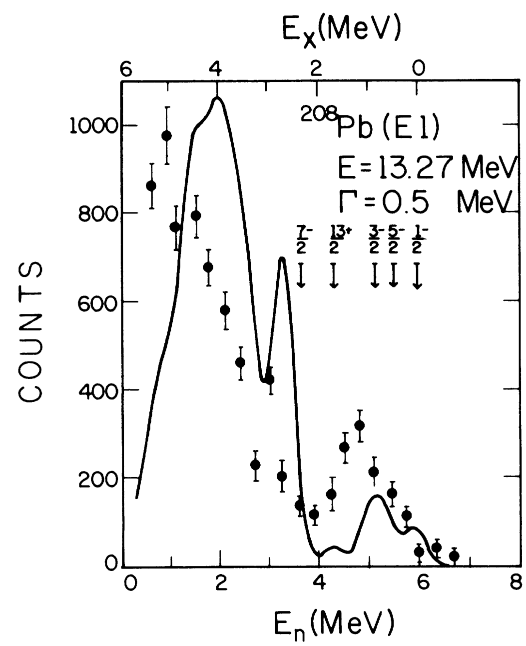

FIG. 2. Experimental neutron decay spectrum for ^{208}Pb (Ref. 9). The curve is the calculated spectrum for statistical decay.

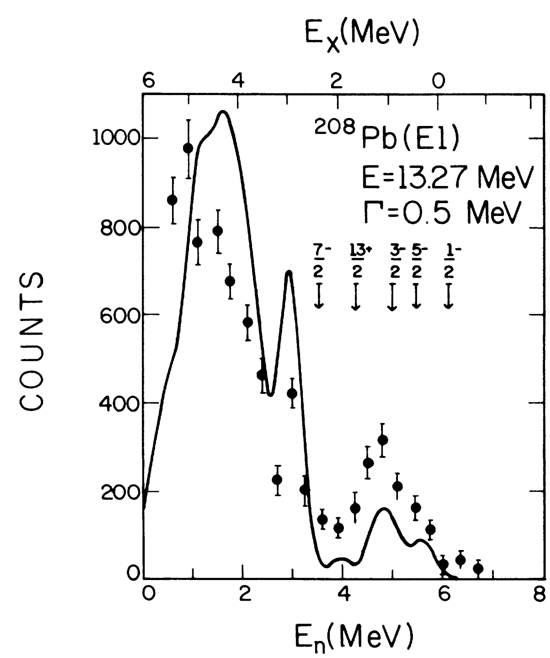

FIG. 3. The same calculated spectrum shown in Fig. 2 with the calculated points shifted in energy by 0.3 MeV (see text).

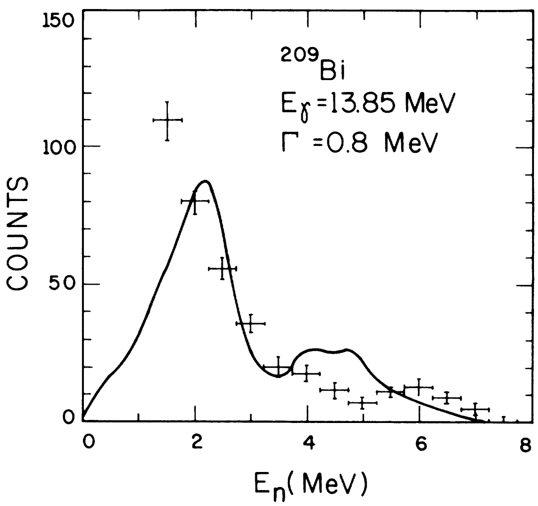

FIG. 4. Experimental neutron decay spectrum for ^{209}Bi (Ref. 10). The curve is the calculated spectrum for statistical decay.

would be interesting to have experimental data for decay of the $E1$ giant resonance in ^{208}Pb with the accuracy of that shown in Fig. 1, but at higher excitation energies.

B. ^{209}Bi

For this nucleus the experimental data from Ref. 10 are plotted in Fig. 4, which shows the neutron decay spectrum obtained with photons of incident energy 13.85 MeV. Since the ground state of ^{209}Bi is $\frac{9}{2}^-$, the $E1$ state can have angular momentum and parity, $J^{\pi}_{E1}=\frac{7}{2}^+, \frac{9}{2}^+$, and $\frac{11}{2}^+$. The threshold for neutron emission in this nucleus is $E_t=7.43$ MeV, thus ^{208}Bi can be left at excitation energies in the range 0–6.42 MeV. Up to 4 MeV excitation energy in ^{208}Bi there are 118 levels,[14–16] from which 56 have unknown spins and parities. Above 4 MeV there are few levels measured and we have to use a model to predict them, as well to assign spins and parities to the 56 levels below 4 MeV. We have used the particle-vibrator model with single particle (hole) shown in Fig. 5. The vibrator states (R,E_R) from ^{208}Pb were coupled to particle and hole states $(\mathbf{J}_p,E_p)$ and $(\mathbf{j}_n,E_n)$, respectively, to generate states $(\mathbf{I}_i,E_i)$ in ^{208}Bi:

$$\mathbf{I}_i=\mathbf{j}_p+\mathbf{j}_n+\mathbf{R}$$

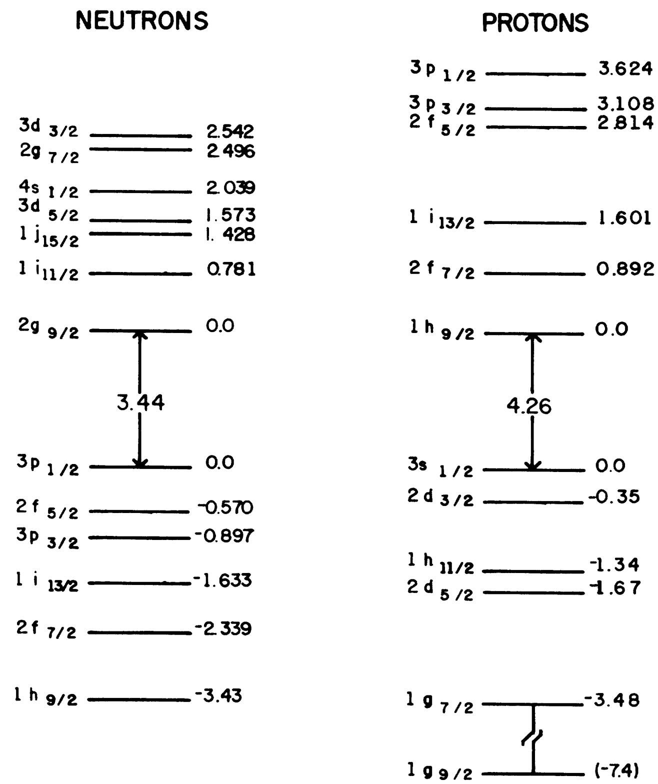

FIG. 5. Experimental single particle spacings in MeV in the lead region (Ref. 16) used for the particle-vibrator model.

with

$$E_i=E_p+E_n+E_R\leq 6.4 \text{ MeV} .$$

For $E_i<4$ MeV we have coupled the states j_p and j_n shown in Fig. 5 to the vibrator state ($\mathbf{R}=0^+$, $E_R=0.0$ MeV) and obtained good agreement with experimental energy levels. Table I compares the distribution of measured energy levels to those obtained in our calculation. For $E_i>4$ MeV we have coupled the states shown in Fig. 5 to vibrator states ($\mathbf{R}=0^+$, $E_R=0.0$ MeV) and ($\mathbf{R}=3^-$, $E_R=2.614$ MeV). The resulting level distribution is shown in Table II. In this case we cannot compare the results of our calculation with experimental data, because there are very few levels measured. However, the agree-

TABLE I. Experimental and calculated levels for ^{209}Bi. The experimental data are from Refs. 14 and 15. The predicted levels (T in the table) are the result of a particle-vibrator calculation.

Energy range (MeV)	Number of levels		Number of levels With Spin <4			Number of levels with Spin >4			Number of experimental levels without spin assignment	Distribution of levels with positive and/or negative parity			
										Positive		Negative	
	Expt.	T	Expt.	T	T-Expt.	Expt.	T	T-Expt.	spin assignment	Expt.	T	Expt.	T
0.0–1.0	11	14	3	4	1	8	10	2	0	11	14	0	0
1.0–2.0	30	22	7	7	0	15	15	0	8	9	10	13	12
2.0–3.0	30	28	7	6	−1	9	22	13	14	12	10	4	18
3.0–4.0	47	58	7	27	20	6	31	25	34	9	50	4	8
Total	118	122	24	44	20	38	78	40	56	41	84	21	38

TABLE II. Numbers of states obtained for ^{209}Bi from a particle-vibrator calculation by coupling the particle hole states to the states 0^+ and 3^- of the ^{208}Pb core.

Energy range (MeV)	Number of states $\text{p-h}\times 0^+$	$\text{p-h}\times 3^-$
4.0–5.0	26	213
5.0–6.0	24	231
Total	50	444

ment obtained for $E_i \leq 4$ MeV yields some confidence for the energy above.

Using the known experimental levels plus the levels predicted by our particle-vibrator calculation, we have calculated statistical decay spectra for the three possible values of J^{π}_{E1}. As shown in Fig. 6 the differences in the spectra corresponding to $J^{\pi}_{E1}=\frac{7}{2}^+$, $\frac{9}{2}^+$, and $\frac{11}{2}^+$ are smaller than the uncertainties of the data points (see Fig. 4). Thus in order to compare the results of our calculation with the experimental spectrum we will assume $J^{\pi}_{E1}=\frac{7}{2}^+$.

Figure 4 shows the predicted statistical decay spectrum for an energy resolution of 800 keV and the experimental results of Ref. 10. The calculated spectrum was normalized to the experiment by imposing the same number of integrated counts from $E_n = 1.75$ MeV to the end of the spectrum. The agreement between the calculated and measured spectrum is poor, thus it is not possible to drive conclusions about the statistical nature of the decay and/or the existence of direct components. It is surprising that the calculation predicts a broad peak around $E_n = 4.5$ MeV, which is not observed in the experimental data. Since this peak corresponds to excitation energies around 2 MeV in the residual nucleus, where the energy levels are well known from experiment,[14,15] the discrepancy cannot be attributed to an eventual inadequacy of our particle-vibrator calculation to predict the energy levels, spins, and parities. The discrepancy between the experimental point at $E_n = 1.75$ MeV and the calculation is not important, since the neutron detection efficiency drops fast at this energy,[10] and it is possible that the uncertainty of this point is much larger than the statistical error.

Undoubtedly the reliability of our calculation is smaller for ^{209}Bi, as compared to ^{208}Pb, due to the lack of detailed measurements of energy levels ^{208}Bi above 4 MeV, even though we find no explanation for discrepancy between measured and calculated spectrum around $E_n = 4$ MeV. Eventually this discrepancy could be caused by an uncertainty in the efficiency of neutron detection as a function of neutron energy.

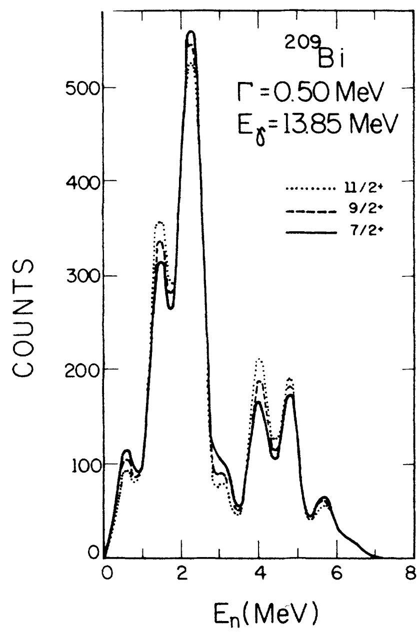

FIG. 6. Calculated statistical decay neutron spectra for ^{209}Bi assuming $J^{\pi}_{E1}=\frac{7}{2}^+$, $\frac{9}{2}^+$, and $\frac{11}{2}^+$.

III. CONCLUSIONS

We have compared existing experimental data on the decay of giant $E1$ resonance with calculated spectra for statistical decay. Using more recent data for ^{208}Pb at an excitation energy of 10.6 MeV we show that the decay of the $E1$ giant resonance is dominantly statistical. There is an excellent agreement between measured and calculated spectra.

However, for ^{208}Pb at a higher excitation energy (13.27 MeV) and also for ^{209}Bi, the agreement between measured and calculated spectra is poor. There are evidences of uncertainties in the experimental data, which were taken nearly 20 years ago, which prevent a definite conclusion. These data could be indicating that the decay is statistical at lower excitation energies, and as the energy increases direct decay occurs. However, the $E0$ giant resonance decay is dominantly statistical at an excitation energy of ~ 13.5 MeV. More experimental data, with the accuracy of that shown in Fig. 1, are needed to exploit the possibility of the onset of direct decay of the $E1$ giant resonance at excitation energies around 13.5 MeV.

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