Preprint
UCRL-JC-147589

Radiative Strength Functions and Level Densities

A. Schiller, J.A. Becker, L.A. Bernstein, A. Voinov, M. Guttormsen, M. Hjorth-Jensen, J. Rekstad, S. Siem, G.E. Mitchell, E. Tavukcu

This article was submitted to Eleventh International Symposium on Capture Gamma-Ray Spectroscopy, Pruhonice near Prague, Czech Republic, September 2-6, 2002

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

August 28, 2002

Approved for public release; further dissemination unlimited

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

This work was performed under the auspices of the United States Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

This report has been reproduced directly from the best available copy.

Available electronically at http://www.doc.gov/bridge

Available for a processing fee to U.S. Department of Energy
And its contractors in paper from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-mail: reports@adonis.osti.gov

Available for the sale to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-mail: orders@ntis.fedworld.gov
Online ordering: http://www.ntis.gov/ordering.htm

OR

Lawrence Livermore National Laboratory
Technical Information Department's Digital Library
http://www.llnl.gov/tid/Library.html

RADIATIVE STRENGTH FUNCTIONS AND LEVEL DENSITIES

A. SCHILLER, J.A. BECKER AND L.A. BERNSTEIN
LLNL, 7000 East Avenue, Livermore, CA 94551, USA
E-mail: Andreas.Schiller@llnl.gov

A. VOINOV
FLNP, Joint Institute of Nuclear Research, 141980 Dubna, Moscow reg., Russia

M. GUTTORMSEN, M. HJORTH-JENSEN, J. REKSTAD AND S. SIEM
Department of Physics, University of Oslo, N-0316 Oslo, Norway

G.E. MITCHELL AND E. TAVUKCU
North Carolina State University, Raleigh, NC 27695, USA

Radiative strength functions and level densities have been extracted from primary γ-ray spectra for ^{27,28}Si, ^{56,57}Fe, ^{96,97}Mo, and several rare earth nuclei. An unexpectedly strong ($\sim 1\,\mathrm{mb\,MeV}$) resonance at 3 MeV in the radiative strength function has been observed for well-deformed rare earth nuclei. The physical origin of this resonance and its connection to the scissors mode is discussed.

1. Introduction

Radiative strength functions and level densities are important quantities in low-energy nuclear structure. Since the first estimate of level densities by Bethe in 1936[1], level densities and related thermodynamical quantities like entropy and the caloric curve have been investigated in order to map out structural changes in atomic nuclei like the pairing phase transition[2,3,4,5]. On the experimental side, level densities have been studied by a variety of methods like counting of discrete levels[6,7] at low energies, the study of neutron resonance spacings[8] at the neutron binding energy B_n, evaporation spectra[9] over large energy intervals, and Erickson fluctuations[10] for light nuclei ($A \leq 60$). Modern nuclear theory treats the problem of nuclear level densities by a variety of methods like relativistic mean field theory[11], finite temperature random phase approximation[12], finite temperature Hartree

Fock Bogoliubov method[13] and shell model Monte Carlo calculations[14,15]. Those methods have the advantage that realistic nucleon-nucleon interactions are taken into account.

Radiative strength functions are a measure of the average electromagnetic response of atomic nuclei. The concept of radiative strength functions was introduced by Blatt and Weisskopf[16]. They showed that the square of the γ-transition matrix element connecting compound states is proportional to the level spacing of the initial states with equal spin and parity. This led to the model-independent definition of the radiative strength function of multipolarity XL in terms of average partial radiative widths Γ_i, level spacing D_i and transition energy E_γ according to:

$$f_{XL} = \Gamma_i/(E_\gamma^{2L+1}D_i). \tag{1}$$

The most important radiative strength functions for the statistical decay of nuclei are the electric dipole ($E1$), the magnetic dipole ($M1$) and to a lesser extend the electric quadrupole ($E2$) strength functions. Experimentally, information about radiative strength functions has been obtained by the study of photoabsorption cross sections[17,18], by various methods involving radiative neutron capture like the spectrum fitting method[19], the investigation of primary γ rays of different multipolarities[20,21,22] and the two-step cascade method[23,24], and finally by a sequential extraction method involving charged particle reactions[25]. Theoretical investigations of radiative strength functions improved when Axel realized that the energy independent Weisskopf estimate failed to describe the experimental $E1$ strength function[26]. Instead, resonance models were developed for the different strength functions, including the $E1$ giant electric dipole resonance (GEDR), the $M1$ giant magnetic dipole or spin flip resonance (GMDR)[21,27] and the weakly collective isovector $M1$ orbital resonance or scissors mode (SM)[28,29]. Special interest remains in the investigation of the tail of the GEDR. Popov showed in his fundamental work on $(n,\gamma\alpha)$ reactions, that the $E1$ strength function in spherical nuclei like ^{144}Nd tends to approach a finite value for small transition energies[30]. Based on this observation, temperature dependent models of the tail of the GEDR were developed[31,32]. The exact mechanism for a temperature dependent width of the GEDR is presently still under discussion[33,34,35,36]. Also, microscopic calculations of strength functions have been attempted in some cases[37,38].

An important application of level densities and radiative strength functions are Hauser-Feshbach calculations of reaction cross-sections[39]. The knowledge of such cross-sections is important for astrophysical applications[40], accelerator driven transmutation of radioactive nuclear waste and the production of radioisotopes[41].

Recently, the group at the Oslo Cyclotron Laboratory (OCL) substantially improved the sequential extraction method. They achieved the simultaneous extraction of radiative strength functions and level densities without making *a priori* assumptions on the functional form of either quantity[42]. This progress has spawned several articles on level densities, thermodynamical properties and radiative strength functions of different nuclei[43,44,45,46,47,48,49,50,51,52,53]. The present work recapitulates the most exciting findings of this work and gives examples of several new investigations.

2. Method

Experiments were carried out with 45-MeV ^{3}He projectiles at the OCL. Particle-γ coincidences were measured with the CACTUS multidetector array[54] using the (^{3}He,$\alpha\gamma$) and (^{3}He,^{3}He$'\gamma$) reaction on ~ 1.5 mg/cm^2, self supporting targets of high isotopic enrichment ($\sim 95\%$). The light charged particles were detected with eight particle telescopes placed at an angle of 45° relative to the beam axis. An array of 28 NaI γ-ray detectors with a total efficiency of $\sim 15\%$ of 4π surrounded the target and particle detectors.

Total γ cascade spectra can be sorted out with respect to the initial excitation energy E from measured particle-γ coincidences, since the nuclear reaction can be fully reconstructed kinematically. These spectra are unfolded using a Compton-subtraction method[55]. A subtraction procedure is then applied to extract the primary γ-ray spectra $P(E, E_\gamma)$[56] which is subsequently factorized according to the Axel-Brink hypothesis[26,57]:

$$P(E, E_\gamma) \propto T(E_\gamma)\rho(E - E_\gamma). \tag{2}$$

Here, T is the γ-ray transmission coefficient and ρ is the level density at the final state. Both quantities can now be derived simultaneously by a least χ^2 method without *a priori* assuming a specific functional form for either of them[42]. Unfortunately, the structural form of Eq. (2) is such that an infinite number of solutions to the problem yield exactly the same, minimal χ^2. All of these infinitely many solutions can be obtained[42] by transforming one randomly picked solution by:

$$\begin{aligned} \tilde{\rho}(E - E_\gamma) &= A\,\rho(E - E_\gamma)\,\exp(\alpha[E - E_\gamma]), \\ \tilde{T}(E_\gamma) &= B\,T(E_\gamma)\,\exp(\alpha E_\gamma). \end{aligned} \tag{3}$$

The parameters A, B and α have therefore to be determined by additional physics input outside our experimental method. Only with this additional information can unambiguous values for ρ and F be obtained. The parameters A and α are usually determined with the help of two anchor points of the level density which are derived from counting of discrete levels at low excitation energies and from neutron resonance spacing data at B_n[48]. The parameter B can then be determined using the average total radiative width $\langle\Gamma\rangle$ of neutron resonances[50].

3. Experimental results

The OCL group emphasized measurement and interpretation of the level densities of rare earth nuclei. A common finding for all nuclei has been step-structures in the level density curves at energies where the breaking of Cooper pairs is expected[43]. A schematic microscopic calculation supports this interpretation as due to breaking of one or several pairs[46]. One of the most recent findings was the observation of step structures in the level densities of ^{56,57}Fe isotopes[58] (see Fig. 1). These results extend our investigations into regions where microscopic calculations with realistic interactions become possible.

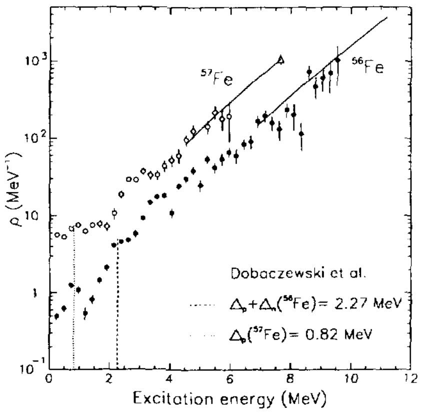

Figure 1. Step structures at 2 and 3 MeV in the level density of ^{57}Fe and ^{56}Fe, respectively, are just above the pairing gap calculated according to Ref.[59] (dotted and dashed lines respectively). This difference is to be expected since breaking a pair requires also to promote the unpaired nucleons to available single-particle levels somehow removed from the Fermi surface. The bumps and steps at 1 and 2 MeV in the level density of ^{56}Fe denote the first and second excited state. Solid lines are Fermi-gas models forced through the neutron resonance spacing data (triangle).

Thermodynamical quantities derived from level densities have mostly been discussed within the statistical canonical ensemble. It has been found that the heat capacity shows a characteristic S-shape in the region of the first pair breaking[47], interpreted as the signature of a second-order phase transition. A simple, phenomenological model has been developed by the OCL group in order to account for this observation[48,51]. A different analysis of this model in terms of the distribution of zeros in the complex temperature plane supports the finding of a second-order phase transition for rare earth nuclei[53].

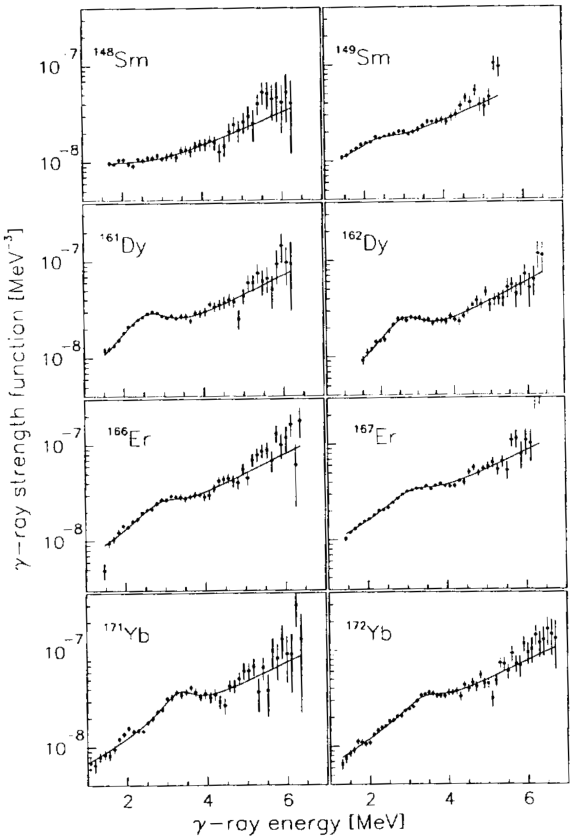

Figure 2. Radiative strength functions in different rare earth isotopes from experiments (data points) and model calculation (lines). Details on the models are given in the text. The Figure is taken from[52].

Investigation of level densities has now entered a new phase with a Gammasphere experiment on ^{157}Gd which yielded a unique dataset of (^{3}He,$\alpha\gamma\gamma$) coincidences with at least one γ ray detected in a high-resolution Ge(HP) detector. The experiment has benefited from the development of a new, segmented charged particle detector with ten times higher solid angle coverage than the previous detectors[60]. The goal of this experiment is to look for statistical γ spectra feeding discrete states with particular spin, parity and K quantum numbers and eventually to extract spin and K-dependent level densities. Analysis is in progress.

In the field of radiative strength functions it has been shown that contrary to the general belief, the tail of the GEDR in deformed rare earth nuclei can be described by the Kadmenskiĭ-Markushev-Furman (KMF) model. However, the temperature parameter in the KMF model was assumed to be a constant fit parameter independent of final state energy and therefore it is not representative for the actual nuclear temperature. In the description of our data, we also took into account a Lorentzian GMDR model. Further, conclusive evidence has been given for the existence of a Lorentzian pygmy resonance with a centroid of around ~3 MeV and a width of ~1 MeV[50,49,52] (see Fig. 2).

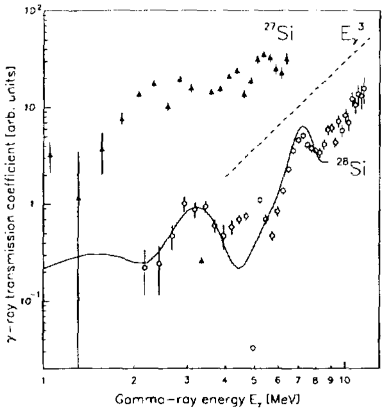

Figure 3. Experimental γ-ray transmission coefficient $T(E_\gamma)$ (data points) compared to converted lifetimes from literature (solid line)[61]. The dashed line shows the expected E_γ dependence in the single-particle model.

We have shown that experimental data on radiative strength functions are in excellent agreement with previous literature data where those two datasets overlap (see, e.g., Fig. 3 of Ref.[50] or Fig. 12 of Ref.[52]). Of special interest is here the case of ^{28}Si, where the radiative strength function can be obtained from literature data on lifetimes which can be converted to partial radiative widths[61] (see Fig. 3). Further, Monte Carlo simulations have been carried out to calculate the total γ cascade spectra after average resonance neutron capture using experimental level densities and radiative strength functions. Also these results agree very well with experimental data (see, e.g., Fig. 5 of Ref.[50] or Fig. 5 of Ref.[52]).

It is tempting to interpret the pygmy resonance in the present data as the observation of the SM in the quasicontinuum[62]. This argument is mainly based on the general agreement of resonance energy and width and the fact that no other resonances are expected in this γ-ray energy region. On the other hand, the mass-dependence of the resonance energy in the present data (see Fig. 2) and in other literature data on the pygmy resonance[63], i.e., a steady increase with mass[a], is different from the observation for the SM (constant or slightly decreasing with A)[28]. Also, the resonance strength in the present data is about twice the strength observed in photon scattering experiments[28,29]. Unfortunately, it is not possible with the present method to measure the multipolarity of the pygmy resonance directly. However, it has been suggested[64] that the combination of present data and the investigation of $(n, 2\gamma)$ spectra might yield the electromagnetic character of the pygmy resonance unambiguously. To this end, a ^{171}Yb$(n, 2\gamma)$ experiment at the Los Alamos Neutron Science Center (LANSCE) has been carried out. Already, Bečvář could demonstrate that $(n, 2\gamma)$ experiments are sensitive to the presence of the pygmy resonance[24], and he has claimed the observation of the SM on excited states[65]. Our investigation, however, will have the advantage that the level density and radiative strength function are already known experimentally and do not have to be taken from models.

4. Conclusions and Outlook

The OCL group has developed a new method to obtain level densities and radiative strength functions. This method has been shown to work in a wide range of the nuclear chart from Si and Fe to Mo and rare earth nuclei.

---

[a] Also the transition in $(n, 2\gamma)$ experiments from double-humped spectra in Gd isotopes to single-humped spectra in Dy and Yb isotopes might be tentatively explained by the presence of a pygmy resonance with a resonance energy which is increasing with mass number.

From level density curves, thermodynamical properties and the evidence of a second-order pairing phase transition could be extracted. The gap in the present data for Gd isotopes is currently being filled by a Gammasphere experiment on ^{157}Gd.

The radiative strength function is shown to agree with available data from literature and can be understood in terms of temperature-dependent models. The pygmy resonance is the subject of ongoing investigations. Hopefully, the combination of $(n, 2\gamma)$ experiments with the present data will shed light on the electromagnetic character of the pygmy resonance and whether the pygmy resonance in the present data is equivalent to the scissors mode seen in photon scattering.

Acknowledgments

Part of this work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract W-7405-ENG-48. Financial support from the Norwegian Research Council (NFR) is gratefully acknowledged. One of us (A.V.) acknowledges support from a NATO Science Fellowship under project number 150027/432.

References

1. H.A. Bethe, *Phys. Rev.* **50**, 332 (1936).
2. Mitsuo Sano and Shuichiro Yamasaki, *Prog. Theor. Phys.* **29**, 397 (1963).
3. L.G. Moretto, *Nucl. Phys.* **A185**, 145 (1972).
4. K. Tanabe and K. Sugawara-Tanabe, *Phys. Lett.* **97B**, 337 (1980).
5. Alan L. Goodman, *Nucl. Phys.* **A352**, 45 (1981).
6. A.V. Ignatyuk et al., *Phys. Rev.* **C47**, 1504 (1993).
7. P.E. Garrett et al., *Phys. Rev.* **C64**, 024316 (2001).
8. A. Gilbert and A.G.W. Cameron, *Can. J. Phys.* **43**, 1446 (1965).
9. A.L. Caraley et al., *Phys. Rev.* **C62**, 054612 (2000).
10. F.B. Bateman et al., *Phys. Rev.* **C55**, 133 (1997).
11. B.K. Agrawal et al., *Phys. Rev.* **C62**, 044307 (2000).
12. Nguyen Dinh Dang, *Z. Phys.* **A335**, 253 (1990).
13. J.L. Egido et al., *Phys. Rev. Lett.* **85**, 26 (2000).
14. H. Nakada and Y. Alhassid, *Phys. Rev. Lett.* **79**, 2939 (1997).
15. S. Liu and Y. Alhassid, *Phys. Rev. Lett.* **87**, 022501 (2001).
16. J.M. Blatt and V.F. Weisskopf, *Theoretical Nuclear Physics*, Wiley, New York, (1952).
17. G.M. Gurevich et al., *Nucl. Phys.* **A351**, 257 (1981).
18. Samuel S. Dietrich and Barry L. Berman, *At. Data Nucl. Data Tables* **38**, 199 (1988).
19. E.D. Earle et al., *Can. J. Phys.* **52**, 989 (1974).

20. J. Kopecky et al., *Phys. Rev.* **C47**, 312 (1993).
21. J. Kopecky and R.E. Chrien, *Nucl. Phys.* **A468**, 285 (1987).
22. W.V. Prestwich et al., *Z. Phys.* **A315**, 103 (1984).
23. M.A. Ali et al., *J. Phys. G* **20**, 1943 (1994).
24. F. Bečvář et al., *Phys. Rev.* **C52**, 1278 (1995).
25. G.A. Bartholomew et al., *Can. J. Phys.* **48**, 687 (1970).
26. Peter Axel, *Phys. Rev.* **126**, 671 (1962).
27. A. Richter, *Prog. Part. Nucl. Phys.* **34**, 261 (1995).
28. N. Pietralla et al., *Phys. Rev.* **C58**, 184 (1998).
29. J. Enders et al., *Phys. Rev.* **C59**, R1851 (1999).
30. Yu. P. Popov, *Sov. J. Part. Nucl.* **13**, 483 (1982).
31. S.G. Kadmenskiĭ et al., *Sov. J. Nucl. Phys.* **37**, 165 (1983).
32. V.K. Sirotkin, *Sov. J. Nucl. Phys.* **43**, 362 (1986).
33. Osman Yilmaz et al., *Phys. Lett.* **B472**, 258 (2000).
34. W.E. Ormand et al., *Phys. Rev. Lett.* **77**, 607 (1996).
35. Nguyen Dinh Dang and Akito Arima, *Phys. Rev.* **C64**, 024302 (2001).
36. Denis Lacroix et al., *Phys. Lett.* **B489**, 137 (2000).
37. V.G. Soloviev et al., *Phys. Part. Nucl.* **31**, 385 (2000)].
38. Alfredo Poves, *INPC 2001*, AIP CP610 (2002), p. 15.
39. W. Hauser and H. Feshbach, *Phys. Rev.* **87**, 366 (1952).
40. Thomas Rauscher et al., *Phys. Rev.* **C 56**, 1613 (1997).
41. IAEA-TECDOC-1024, IAEA, Vienna (1998).
42. A. Schiller et al., *Nucl. Instrum. Methods Phys. Res.* **A447**, 498 (2000).
43. E. Melby et al., *Phys. Rev. Lett.* **83**, 3150 (1999).
44. A. Schiller et al., *Phys. Rev.* **C61**, 044324 (2000).
45. M. Guttormsen et al., *Phys. Rev.* **C61**, 067302 (2000).
46. M. Guttormsen et al., *Phys. Rev.* **C62**, 024306 (2000).
47. A. Schiller et al., *Phys. Rev.* **C63**, 021306(R) (2001).
48. M. Guttormsen et al., *Phys. Rev.* **C63**, 044301 (2001).
49. E. Melby et al., *Phys. Rev.* **C63**, 044309 (2001).
50. A. Voinov et al., *Phys. Rev.* **C63**, 044313 (2001).
51. M. Guttormsen et al., *Phys. Rev.* **C64**, 034319 (2001).
52. S. Siem et al., *Phys. Rev.* **C65**, 044318 (2002).
53. A. Schiller et al., *Phys. Rev.* **C66**, 024322 (2002).
54. M. Guttormsen et al., *Phys. Scr.* **T32**, 54 (1990).
55. M. Guttormsen et al., *Nucl. Instrum. Methods Phys. Res.* **A374**, 371 (1996).
56. M. Guttormsen et al., *Nucl. Instrum. Methods Phys. Res.* **A255**, 518 (1987).
57. D.M. Brink, *Ph.D. thesis*, Oxford University, (1955).
58. E. Tavukcu et al., *FNS 2002*, AIP CP (to be published).
59. J. Dobaczewski et al., *Phys. Rev.* **C63**, 024308 (2001).
60. A. Schiller et al., Talk at the HRIBF Workshop: Transfer Reactions, ORNL June 21-22 2002.
61. M. Guttormsen et al., preprint nucl-ex/0203013.
62. A. Schiller et al., preprint nucl-ex/0011018.
63. M. Igashira et al., *Nucl. Phys.* **A457**, 301 (1986).
64. A. Voinov et al., preprint nucl-ex/0205007.
65. F. Bečvář et al., *CGS-10 1999*, AIP CP529, (2000), p. 657.