PROCEEDINGS OF SCIENCE

Gamma Strength Functions in Closed Shell Lead Nuclei

N.U.H. Syed[a*], **M. Guttormsen**[a], **A.C. Larsen**[a], **S. Siem**[a], **F. Ingebretsen**[a], **J. Rekstad**[a], **T. Lönnroth**[b], **A. Schiller**[c], **A. Voinov**[d]

[a] *Department of Physics, University of Oslo, P.O.Box 1048 Blindern, N-0316 Oslo, Norway*
[b] *Åbo Akademi University, FIN-20500 Åbo, Finland*
[c] *National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA*
[d] *Department of Physics and Astronomy, Ohio University Athens, OH, USA*

The γ-ray strength function is one of the keys for understanding nuclear reaction rates and finds its application in e.g. astrophysics. The γ-ray strength functions for $^{205-208}$Pb isotopes are extracted using the Oslo method. The experimental findings of (^{3}He,$\alpha\gamma$) and (^{3}He,^{3}He'γ) reactions are compared with another experimental finding of (γ,n) reactions in the Pb isotopes. The preliminary results indicate the presence of intermediate resonances in all these isotopes at lower transition energies below the neutron threshold.

Workshop on Photon Strength Functions and Related Topics
June 17-20 2007
Prague, Czech Republic

*Speaker

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike Licence. http://pos.sissa.it/

PoS(PSF07)010

1. Introduction

In the study of the energy dependency of γ-ray transition probabilities from highly excited states it is usual to introduce a quantity called γ-ray strength function. The γ-ray strength function is a measure of the average electromagnetic properties of the nuclei and is fundamental for understanding the nuclear structure. Experimentally, the main information on the γ-ray strength function determination is obtained from photoabsorption cross-section measurements [1]. High energy γ-ray transitions ($E_\gamma \sim$ 10-15 MeV) are dominated by the giant electric dipole resonance (GEDR). However there persists a serious lack of information at low γ-ray energies. In these regions an experimental technique developed by the Oslo Cylotron Group provides valuable information.

In the present work, the γ-ray strength function for the closed proton shell nuclei $^{205-207}$Pb and a doubly closed shell nucleus ^{208}Pb have been measured using the Oslo method. These nuclei have all a closed proton shell, $h_{11/2}$, and the neutrons are in the $i_{13/2}$ shell. The method uses a subtraction technique for obtaining primary γ-ray spectra [6] and Brink-Axel hypothesis [2, 3], which states that the giant dipole resonances, with approximately equal properties, can be built on the excited states. The factorization of the primary γ-ray matrix can be used to deduce the nuclear level density and the γ-ray strength function simultaneously. The applicability of the Oslo method in closed shell nuclei, where statistical properties are less favorable, has been tested in the present work.

2. Experimental Setup and Data Analysis

The experiments were performed at the Oslo Cyclotron Laboratory (OCL) using a $\sim$ 2 nA beam of 38-MeV ^{3}He ions. The self-supporting targets were ^{206,208}Pb metallic foils of thickness 1.40 and 4.71 mg/cm^2, respectively. The bombardment of ^{3}He on the Pb target opens a number of reaction channels, such as (^{3}He,^{3}He'), (^{3}He, α), (^{3}He, $xn\alpha$). The interesting reactions here are;

- ^{208}Pb(^{3}He,^{3}He)^{208}Pb
- ^{208}Pb(^{3}He, α)^{207}Pb
- ^{206}Pb(^{3}He, ^{3}He)^{206}Pb
- ^{206}Pb(^{3}He, α)^{205}Pb

The particles are detected by eight collimated Si ΔE and E type detectors, making an angle of 45° with the beam line, which are 145μm and 1500μm thick, respectively. For the γ-rays 28 5"x5" NaI detectors are used , called CACTUS [4], having a total efficiency $\sim$ 15 % of 4π.The CACTUS array surrounds the target and Si particle detectors.

From the known Q values and reaction kinematics the ejectile energy can be transformed into initial excitation energy of the residual nuclei. Using the particle-γ coincidence technique, each γ-ray can be assigned to a cascade depopulating an excitation energy state in the residual nucleus. The data are then sorted into total γ-ray spectra originating from different excitation energy bins. The γ-ray spectra are also corrected for the response of the NaI detectors. Every spectrum is unfolded using a Compton-subtraction method which preserves the fluctuations in the original spectra and

PoS(PSF07)010

does not introduce further spurious fluctuations [5]. The primary γ-rays are filtered out from the unfolded spectra by using the subtraction method given in [6]. The main assumption of the method is that the γ-decay pattern from any excitation bin is independent whether the state is populated via scattering or neutron pick-up reaction, or through γ decay from the excited levels following the initial nuclear reaction. This assumption is trivially fulfilled if one populates the same levels with same weights within any excitation energy bin, since decay branching ratios are the properties of the levels and do not depend on the population mechanism.

Finally, the primary-γ spectra can be factorized according to the generalized Axel-Brink hypothesis [2, 3] into nuclear level density ρ and γ-ray transmission coefficient τ:

$$P(E_i, E_\gamma) \propto \rho(E_i - E_\gamma)\tau(E_\gamma). \tag{2.1}$$

In the Oslo method the functions ρ and τ are determined by an iterative method [7] through the adjustment of all data points until a global χ^2 minimum with the experimental matrix $P(E_i, E_\gamma)$ is reached. Through transformation it can be shown [7] that,

$$\tilde{\rho}(E_i - E_\gamma) = A\exp[\alpha(E_i - E_\gamma)]\rho(E_i - E_\gamma) \tag{2.2}$$

$$\tilde{\tau}(E_\gamma) = B\exp(\alpha\, E_\gamma)\; \tau(E_\gamma), \tag{2.3}$$

give the same fit to the experimental data.

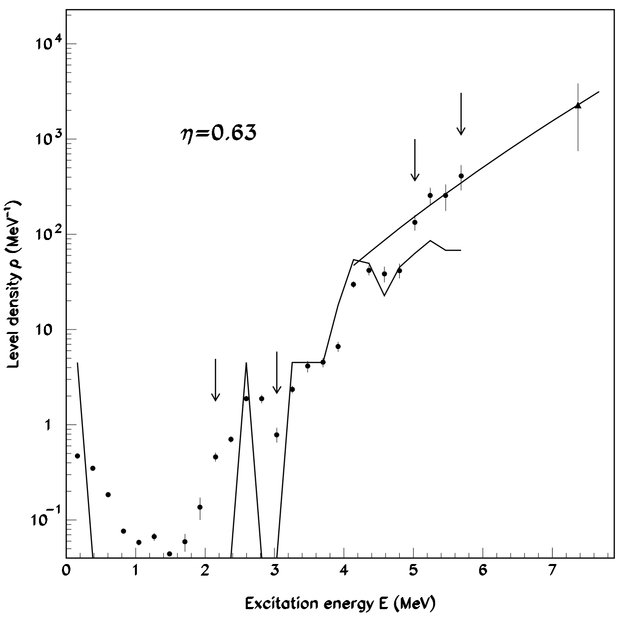

Figure 1: The normalization of experimental nuclear level density (closed circles) in ^{208}Pb. The arrows indicate the fitting of data points at low excitation energy with known levels (zigzag line). To bridge the gap between the calculated level density at B_n and experimentally determined data points, the BSFG model based level density is drawn (solid line).

The free parameters A, B and α are normalized to get a physical solution. The A and α parameters are determined by the absolute normalization of the level density ρ. Fitting the data points

PoS(PSF07)010

at low excitation energy and at the neutron separation energy to the number of discrete levels and neutron-resonance spacing data, respectively, gives the normalization. The extraction procedure and the error analysis are covered in detail in [7]. Figure 1 demonstrates the normalization of level density in the ^{208}Pb. The experimental data points are normalized by adjusting the parameters A and α such that a least χ^2 fit is obtained for the data points between the arrows. At low excitation energies the data points fit well with the known levels. However, an extrapolation is drawn between the last few data points and level density at neutron separation (ρ_{B_n}) by using the back-shifted Fermi gas (BSFG) model [8, 9]. The constant η is the adjustment parameter for ρ_{BSFG} such that $\eta \rho_{BSFG} = \rho_{B_n}$ at $E_i = B_n$.

3. Experimental Extraction of Radiative Strength Function

The γ-ray transmission coefficient τ in Eq. (2.1) is expressed as a sum of all the radiative strength function f_{XL} of electromagnetic character X and multipolarity L,

$$\tau(E_\gamma) = 2\pi \sum_{XL} E_\gamma^{2L+1} f_{XL}(E_\gamma). \tag{3.1}$$

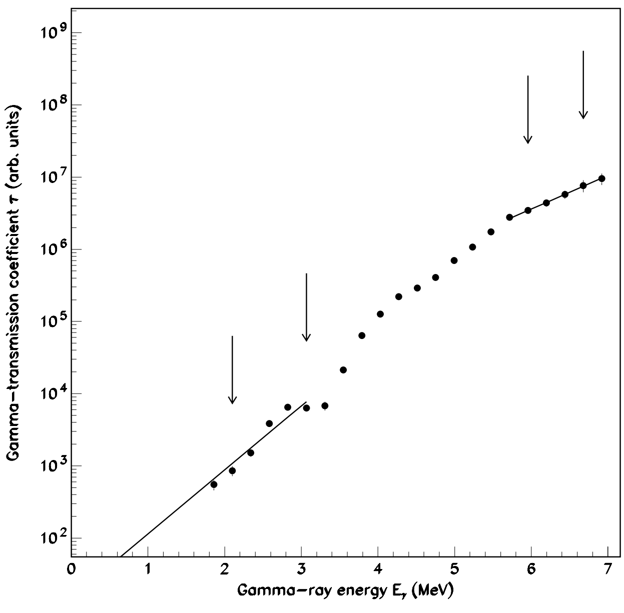

Figure 2: The un-normalized γ-ray transmission coefficient $\tau(E_\gamma)$ for ^{207}Pb. The extrapolations are made to calculate the normalization integral of Eq. (3.3). The arrows indicate the lower and upper fitting regions for the extrapolations.

The slope of the experimental γ-ray transmission coefficient τ is determined through the normalization of the level density. The level density normalization of ^{208}Pb has been shown in Fig.1. The main contributions to the derived τ function are assumed to be the $E1$ and $M1$ γ-ray transitions.

PoS(PSF07)010

It is also assumed that the numbers of accessible levels of positive and negative parity are equal for any energy and spin. Thus the observed τ is expressed as,

$$B\tau(E_\gamma) = [f_{E1}(E_\gamma) + f_{M1}(E_\gamma)]E_\gamma^3. \tag{3.2}$$

The unknown factor B determines the absolute normalization of the γ-ray strength function. In Fig.2, $\tau(E_\gamma)$ for ^{207}Pb is shown. The factor B must be found from other experimental data, such as the experimental average total radiative width of neutron resonances $\langle\Gamma_\gamma\rangle$ at neutron separation energy.
It is already assumed that γ decay is dominated by $E1$ and $M1$ transitions and that number of positive and negative parity states are equal. The expression of width [10] for initial target spin $I \pm 1/2$ and parity π at $E = B_n$ reduces to,

$$\langle\Gamma_\gamma\rangle = \frac{1}{2\pi\rho(B_n, I \pm 1/2, \pi)} \int_0^{B_n} dE_\gamma B\tau(E_\gamma)\rho(B_n - E_\gamma) \sum_{J=-1}^{1} g(B_n - E_\gamma, I \pm 1/2 + J). \tag{3.3}$$

where $D = 1/\rho(B_n, I, \pi)$ is the average resonance spacing of s-wave neutron resonances. The level density ρ is expressed as the product of total level density summed over all spins and spin distribution g, given by [8]

$$g(E_i, I) = \frac{2I+1}{2\sigma^2} exp(\frac{-(I+1/2)^2}{2\sigma^2}), \tag{3.4}$$

here σ is the energy dependent spin cutt-off parameter. The spin distribution is normalized to $\sum_I g \sim 1$ and $\langle\Gamma_\gamma\rangle$ is then the weighted sum of contributions with I as shown equation (3.3).

Because of methodological difficulties in extracting first generation γ-ray spectrum [6], τ and ρ can not be determined experimentally in the interval $E_\gamma < 2$MeV. In addition, the data at the highest γ-ray energies, $E_\gamma > B_n - 1$ MeV suffer from poor statistics, so $\tau(E_\gamma)$ is extrapolated at low and high γ-ray energies as shown in Fig.2.

4. Results and Discussion

The normalized experimental γ-ray strength functions for $^{205-208}$Pb,

$$f(E_\gamma) = \frac{1}{2\pi} \frac{B\tau(E_\gamma)}{E_\gamma^3}, \tag{4.1}$$

are shown in Fig.3. To determine the normalization constant B for ^{205}Pb the experimental value of the average radiative width taken from [11], has been used. For the other three nuclei, ^{206,207,208}Pb, the experimental value of ^{205}Pb has been used and the result is then scaled to agree with the (γ, n) data [12]. The comparison of γ-ray strength function determined by the Oslo method with (γ, n) reaction shows that intermediate resonances have been observed between 4.5 and 7.0 MeV in all the presently investigated lead isotopes. The effect of smearing in the γ-ray strength function is also obvious by the gradual opening of neutron shell closure at N=126. These intermediate resonances are also observed above the neutron threshold and below the giant dipole resonances in $^{206-208}$Pb nuclei. It is, however, difficult to determine the polarity of these intermediate structures since the

PoS(PSF07)010

Oslo method does not provide any such information. Comparing the γ-ray strength functions in these isotopes of lead, it has been seen that the intermediate structures are smeared more out in ^{206}Pb than in ^{208}Pb. In the odd isotopes ^{205,207}Pb these structures are even more smeared. One another interesting fact, evident from Fig.3, is that γ-ray strength function in ^{205}Pb is ten times larger than the other neighboring nuclei. The present results,however preliminary, are encouraging for further comparison of our values of γ-strength function with the standard giant electric dipole resonance (GEDR) model based on Bink-Axel approach [2, 3] and the model of Kadmenskiĭ, Markushev, and Furman (KMF) [14] for determining the radiative strength functions.

PoS(PSF07)010

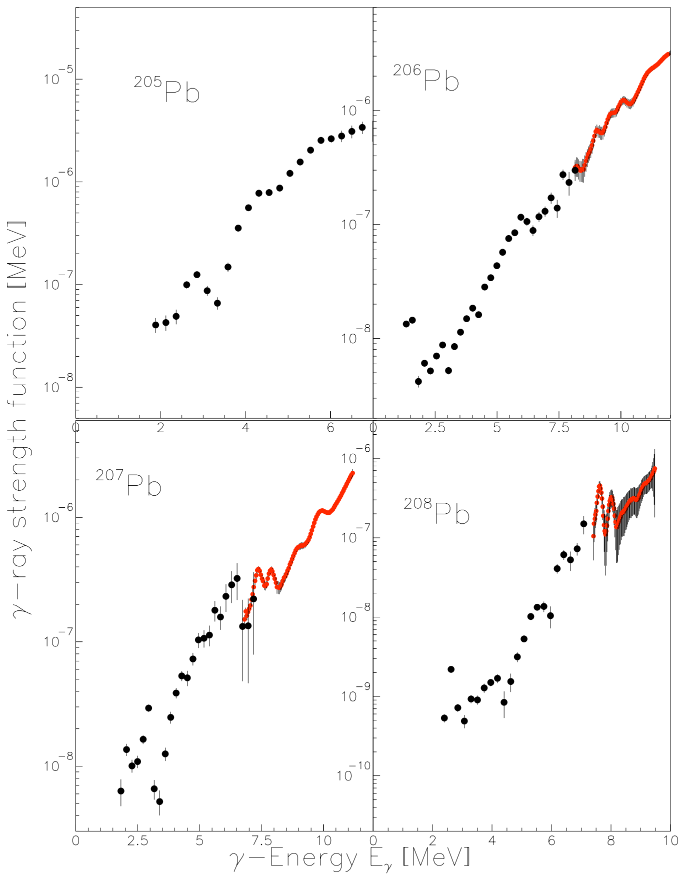

Figure 3: The γ-ray strength functions of $^{205-208}$Pb. The open circles are the normalized Oslo data scaled to the photoabsorption data of (γ,n) reactions [12].

References

[1] S.S. Dietrich and B.L. Berman At. Data Nucl. Data Tables **38**, 199 (1988).

[2] D. M. Brink, Ph.D. thesis, Oxford University, 1955.

[3] P. Axel, Phys. Rev. **126**, 671 (1962).

[4] M. Guttormsen, A. Atac, G. Løvhøiden, S. Messelt, T. Ramsøy, J. Rekstad, T. F. Thorsteinsen, T. S. Tveter and Z. Zelazny, Phys. Scr. **T32**, 54 (1990).

[5] M. Guttormsen, T. S. Tveter, L. Bergholt, F. Ingebretsen, and J. Rekstad, Nucl. Instr. Methods Phys. Res. **A374**, 371 (1996).

[6] M. Guttormsen, T. Ramsøy, J. Rekstad, Nucl. Instr. Methods Phys. Res. **A225**, 518 (1987).

[7] A. Schiller, L. Bergholt, M. Guttormsen, E. Melby, J. Rekstad and S. Siem, Nucl. Instr. Methods Phys. Res. **A447**, 498 (2000).

[8] A. Gilbert, A.G.W. Cameron, Can. J. Phys. **43**, 1446 (1965).

[9] T. Egidy and D. Bucurescu, Phys. Rev. **C72**, 044311 (2005).

[10] A. Voinov, M. Guttormsen, E. Melby, J. Rekstad, A. Schiller, S. Siem Phys. Rev. **C63**, 044313 (2001).

[11] Data extracted using the Reference Input Parameter Library, http://www-nds.iaea.org/RIPL-2/

[12] S.N. Belyaev, A.B. Kozin, A.A. Nechkin, V.A. Semenov, and S.F. Semenko. Yad. Fys. **42**, 1050 (1985).

[13] N. Ryezayeva et al., Phys. Rev. Lett. **89**, 272502-1 (2002).

[14] S.G. Kadmenskiĭ, V.P. Markushev, and V.I. Furman, Yad. Fiz. **37**, 227 (1983)

PoS(PSF07)010