BRIEF REPORTS

Brief Reports are short papers which report on completed research or are addenda to papers previously published in the **Physical Review.** *A Brief Report may be no longer than four printed pages and must be accompanied by an abstract.*

Low-lying dipole strength in ^{207}Pb

A. Nord,[1] S. W. Yates,[2] O. Beck,[1] D. Belic,[1] P. von Brentano,[3] T. Eckert,[1] C. Fransen,[3] R.-D. Herzberg,[3,*] U. Kneissl,[1] H. Maser,[1] N. Pietralla,[3] H. H. Pitz,[1] and V. Werner[3]

[1]*Institut für Strahlenphysik, Universität Stuttgart, Allmandring 3, D-70569 Stuttgart, Germany*

[2]*Department of Chemistry, University of Kentucky, Lexington, Kentucky 40506-0055*

[3]*Institut für Kernphysik, Universität zu Köln, Zülpicher Str. 77, D-50937 Köln, Germany*

(Received 30 January 1998)

Low-lying dipole strength in the neutron-hole nucleus ^{207}Pb has been investigated in nuclear resonance fluorescence (NRF) measurements performed with bremsstrahlung beams with an end-point energy of 4.1 MeV. Known excitations at 898 $(3/2^-)$, 3303 $(1/2^+)$, and 3927 $(3/2^-)$ keV were observed and their absolute total strengths were determined with improved precision. While excellent sensitivity was obtained in this study, no other dipole excitations could be detected in the energy region from 1 to 4 MeV. [S0556-2813(98)02706-X]

PACS number(s): 25.20.Dc, 21.10.Pc, 23.20.−g, 27.80.+w

The lowest states of ^{207}Pb have long provided examples of the success of the nuclear shell model and can generally be understood as single-neutron hole excitations; the $3p_{1/2}{}^{-1}$ ground state as well as low-lying $2f_{5/2}{}^{-1}$, $3p_{3/2}{}^{-1}$, $1i_{13/2}{}^{-1}$, and $2f_{7/2}{}^{-1}$ states have been identified [1]. Weak coupling of the $p_{1/2}{}^{-1}$ ground state with the 3^- octupole phonon of ^{208}Pb at 2614 keV results in a doublet at 2624 $(5/2^+)$ and 2662 $(7/2^+)$ keV [2–4]. Recently, the complete sextuplet ($1/2^+$ to $11/2^+$) from coupling of the $f_{5/2}$ neutron hole, the first excited state of ^{207}Pb, with the octupole phonon of the ^{208}Pb core $(3^-\otimes f_{5/2}{}^{-1})$ has been suggested [5]. Moreover, fast $E1$ transitions were observed to play an important role in the deexcitation of these states. To obtain additional information about low-lying excitations in ^{207}Pb and $E1$ transitions in nuclei near closed shells, more specifically, those involving octupole phonons, a nuclear resonance fluorescence (NRF) study of ^{207}Pb was undertaken.

NRF is a sensitive, selective technique for studying low-lying dipole excitations in nuclei, and the formalism for describing the population of these excitations has been described previously [6]. With beams of continuous bremsstrahlung, the total cross section integrated over a single resonance and the full solid angle is

$$I_{s,f}=g\left(\pi\frac{\hbar c}{E_\gamma}\right)^2\frac{\Gamma_0\Gamma_f}{\Gamma}, \tag{1}$$

where E_γ represents the excitation energy of the photoexcited state, and Γ_0, Γ_f, and Γ are the decay widths of the excited state to the ground state, to a final lower-lying state, and its total width, respectively. The statistical factor, $g=(2J+1)/(2J_0+1)$, depends only on the excited state and ground state spins. The product $g\Gamma_0$ can be extracted from the measured scattering intensities and is proportional to the reduced excitation probabilities,

$$B(\Pi 1)\uparrow = gB(\Pi 1)\downarrow = \frac{9}{16\pi}\left(\frac{\hbar c}{E_\gamma}\right)^3(g\Gamma_0). \tag{2}$$

In numerical form,

$$B(E1)\uparrow = 0.955\frac{g\Gamma_0}{E_\gamma^3}\,[10^{-3}e^2\ \mathrm{fm}^2], \tag{3}$$

$$B(M1)\uparrow = 0.0864\frac{g\Gamma_0}{E_\gamma^3}\,[\mu_N^2], \tag{4}$$

$$g\Gamma_0^{\mathrm{red}} = g\frac{\Gamma_0}{E_\gamma^3}, \tag{5}$$

where the transition energies are in MeV and the ground-state transition widths are in meV. As is clear from these

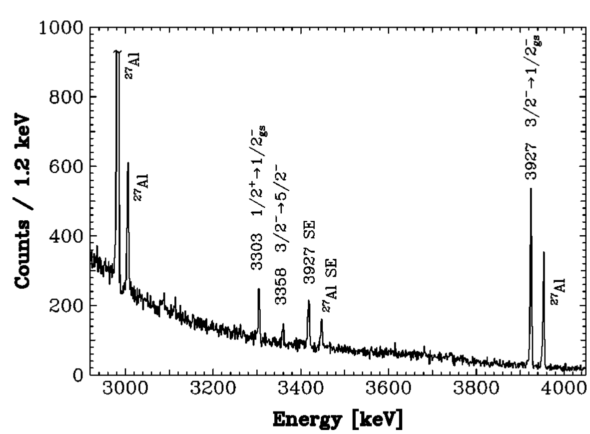

FIG. 1. High-energy portion of the ^{207}Pb(γ,γ') spectrum acquired with a photon energy endpoint of 4.1 MeV. The ^{27}Al calibration peaks, single escape peaks (SE), and the peaks from transitions in ^{207}Pb are labeled.

*Present address: Department of Physics, University of Liverpool, Liverpool, L69 7ZE, UK.

TABLE I. Results from the ^{207}Pb(γ,γ') reaction. Excitation energies E_x, spins and parities J^π, integrated cross sections $I_{s,0}$, ground-state decay widths Γ_0, the products $g\Gamma_0^{\rm red}$ of the spin factor g and the reduced ground-state decay widths $\Gamma_0^{\rm red}$, experimental decay branching ratios $R_{\rm expt}$, and the reduced excitation probabilities $B(M1)\uparrow$ and $B(E1)\uparrow$ are given. For comparison the Γ_0 values determined by Swann [10] are also presented.

E_x (keV)	J^π	$I_{s,0}$ (eV b)	Γ_0 (meV)	$g\Gamma_0^{\rm red\ a}$ (meV/MeV^3)	$R_{\rm expt}$ $^{\rm b}$	$B(M1)\uparrow$ (μ_N^2)	$B(E1)\uparrow$ (10^{-3} e^2 fm^2)	$\Gamma_0^{\rm Swann}$ (meV)
898	3/2$^-$	15.5(17)	1.63(18)	4.49(50)		0.388(43)		
3303	1/2$^+$	12.5(8)	46.0(25)	1.28(7)	0.52(6)$^{\rm c}$		1.22(7)	39(6)
3927	3/2$^-$	132.3(94)	297(19)	9.82(63)	0.19(2)	0.848(55)		340(40)

$^{\rm a}$See Eq. (5).
$^{\rm b}R_{\rm expt}=B(\Pi L;J\to J_f)/B(\Pi L;J\to J_0)=(\Gamma_f/\Gamma_0)(E^3_{\gamma J_0}/E^3_{\gamma J_f})$.
$^{\rm c}$From Ref. [5].

equations, the reduced transition widths are proportional to the reduced dipole excitation probabilities.

The excitation of low-lying states of ^{207}Pb was performed with continuous bremsstrahlung from the 4.3 MV Dynamitron accelerator of the University of Stuttgart [6]. The collimated bremsstrahlung beam was allowed to strike the scattering sample, a 1336 mg metallic Pb disk (92.78% ^{207}Pb) sandwiched between Al disks, where the well-known transitions in ^{27}Al served as an absolute photon flux monitor [7]. Figure 1 illustrates the high-energy region of the spectrum of scattered photons which were detected with high-resolution HPGe γ-ray spectrometers located at angles of 90°, 125°, and 150° with respect to the incident bremsstrahlung beam. Peaks arising from ^{207}Pb and from the Al photon flux monitor are indicated.

In Table I, the results of the present study are summarized. The spins indicated have been firmly determined in previous studies, and the γ-ray angular distributions measured in the present work are consistent with these assignments [8,9]. Also shown in Table I are the results from the NRF measurements of Swann [10]. While his results appear to be in good agreement with those of the present work, it should be noted that the γ-ray branchings given in Table I were not available in the previous work [10].

The dipole strength distribution measured for ^{207}Pb is illustrated in Fig. 2. It is surprising that only three states in ^{207}Pb—at 898, 3303, and 3927 keV—were excited in this reaction, although the sensitivity of the measurement at energies above 2.5 MeV is excellent (see Fig. 3). The sensitivity at about 3.4 MeV corresponds to a dipole excitation strength of $B(E1)\uparrow\approx 0.1\times10^{-3}$ e^2 fm^2. Furthermore, there is little fragmentation of the dipole strength. It should be noted, however, that these are the only well-established [8,9] excited states in ^{207}Pb with spins of 1/2 or 3/2 below 4 MeV.

The population of the 898-keV 3/2$^-$ state can be understood as the $\nu(3p_{1/2})^{-1}\to\nu(3p_{3/2})^{-1}$ $M1$ single-particle transition. The measured $M1$ strength is in excellent agreement with that determined previously [9,11,12].

The 1/2$^+$ state at 3303 keV has been suggested [5,13,14] as the lowest-spin member of the $3^-\otimes f_{5/2}{}^{-1}$ sextuplet and would not be expected to receive significant population in photon scattering measurements. However, as pointed out by Smith *et al.* [14], the wave function of this state is expected to contain a significant fragment of the deep-lying $3s_{1/2}{}^{-1}$ state. The strong population of this state in NRF can thus be attributed to the $\nu(3p_{1/2})^{-1}\to\nu(3s_{1/2})^{-1}$ allowed $E1$ transition.

The most strongly excited state, the 3927-keV 3/2$^-$ excitation, defies a simple interpretation. Weak coupling of the 4085-keV 2$^+$ excitation in ^{208}Pb to the $p_{1/2}$ neutron hole,

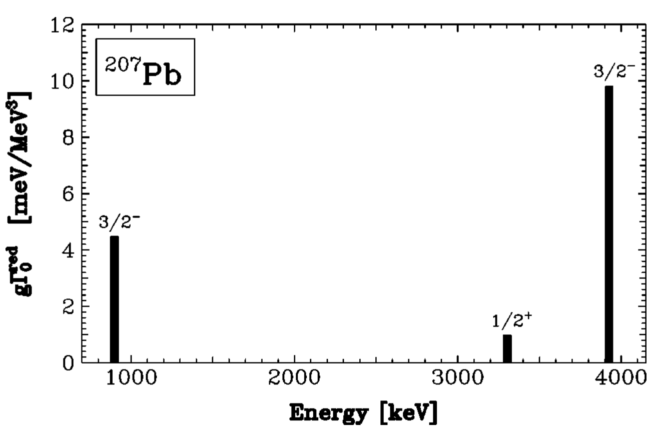

FIG. 2. Dipole strength distribution in ^{207}Pb. Shown are the values $g\cdot\Gamma_0^{\rm red}$ for the 898 (3/2$^-$), 3303 (1/2$^+$), and 3927 (3/2$^-$) keV excitations, the only states observed in this study.

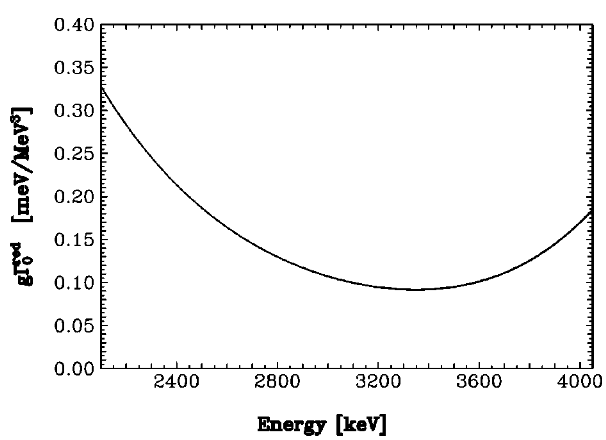

FIG. 3. Plot illustrating the sensitivity of the present ^{207}Pb(γ,γ') measurement. The reduced transition widths can be related to reduced transition probabilities through Eqs. (3)–(5). The sensitivity at 3.4 MeV corresponds to a value of $B(E1)\uparrow\approx 0.1\times10^{-3}$ e^2 fm^2.

the ground state of ^{207}Pb, should lead to a doublet near this excitation energy, but these states have been firmly identified [2,10] as the $3/2^-$, $5/2^-$ doublet at 4104 and 4140 keV. Fragmentation of this strength into the 3927-keV state might serve to explain the strength observed in this study.

In summary, the $^{207}\mathrm{Pb}(\gamma,\gamma')$ reaction has been performed with bremsstrahlung beams with an end-point energy of 4.1 MeV, and the absolute dipole strengths of the populated states were determined. While the sensitivity of this measurement was quite high, only three known excitations were observed below 4 MeV.

We wish to thank M. Kadi for providing his results prior to publication. Support by the Deutsche Forschungsgemeinschaft under Contracts Nos. Br 799/6, Kn 154/21, and Kn 154/30 and by the U.S. National Science Foundation under Grant No. PHY-9515461 is gratefully acknowledged.

[1] P. Mukherjee and B. L Cohen, Phys. Rev. **127**, 1284 (1962).
[2] G. Vallois, J. Saudinos, O. Beer, M. Gendrot, and P. Lopato, Phys. Lett. **22**, 659 (1966).
[3] J. C. Hafele and R. Woods, Phys. Lett. **23**, 579 (1966).
[4] E. Grosse, C. F. Moore, J. Solf, W. R. Hering, and P. von Brentano, Z. Phys. **218**, 213 (1968).
[5] M. Kadi, P. E. Garrett, M. Yeh, and S. W. Yates (unpublished).
[6] U. Kneissl, H. H. Pitz, and A. Zilges, Prog. Part. Nucl. Phys. **37**, 349 (1996), and references therein.
[7] N. Pietralla, I. Bauske, O. Beck, P. von Brentano, W. Geiger, R.-D. Herzberg, U. Kneissl, J. Margraf, H. Maser, H. H. Pitz, and A. Zilges, Phys. Rev. C **51**, 1021 (1995).
[8] M. R. Schmorak, Nucl. Data Sheets **43**, 383 (1984).
[9] M. J. Martin, Nucl. Data Sheets **70**, 315 (1993).
[10] C. P. Swann, J. Franklin Inst. **298**, 321 (1974).
[11] E. Grosse, M. Dost, K. Haberkant, J. W. Hertel, H. V. Klapdor, H. J. Körner, D. Proetel, and P. von Brentano, Nucl. Phys. **A174**, 525 (1971).
[12] O. Häusser, F. C. Khanna, and D. Ward, Nucl. Phys. **A194**, 113 (1972).
[13] R. A. Moyer, B. L. Cohen, and R. C. Diehl, Phys. Rev. C **2**, 1898 (1970).
[14] S. M. Smith, P. G. Roos, C. Moazed, and A. M. Bernstein, Nucl. Phys. **A173**, 32 (1971).