

## Microscopic structure of the Gamow–Teller resonance in $^{208}\text{Bi}$

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The microscopic structure of the Gamow–Teller resonance at  $E_x = 15.6$  MeV in  $^{208}\text{Bi}$  has been investigated by observing its direct proton decay to the neutron–hole states in  $^{207}\text{Pb}$  following its excitation via the  $^{208}\text{Pb}(^3\text{He},t)$  reaction at  $E(^3\text{He}) = 450$  MeV and  $\theta = 0^\circ$ . The total width of the resonance as well as total and partial escape widths, associated with proton decay, have been determined. The total escape width was found to be only  $4.9 \pm 1.3\%$ . A re-examination of several recent theoretical estimates becomes desirable in view of the limited agreement with this value.

The observation of charge-exchange collective excitations via the  $(p, n)$  reaction in the early eighties and in particular of the predicted [1] Gamow–Teller resonance (GTR) constituted a landmark in the study of giant resonances [2–4]. The observation of the GTR was facilitated at bombarding energies  $> 100$  MeV and at small momentum transfer because the  $(p, n)$  charge-exchange reaction preferentially excites spin-flip  $\Delta L = 0$  states under such conditions [5]. This was verified experimentally [6–9] by studying the dependence of the ratio  $(V_{\sigma\tau}/V_t)^2$  of the effective nucleon–nucleon interaction on bombarding energy. This ratio was found to increase strongly as a function of bombarding energy reaching a maximum at around 300 MeV. At higher energies it decreases gradually up to the highest bombarding energy measured, i.e.  $E_p = 800$  MeV. Also, the approximate proportionality between the  $0^\circ$  cross sections and the  $B(\text{GT})$  values [3,8] allowed the determination of the

total GT strength as a function of excitation energy and mass number. Even though our knowledge of the systematics of the GT strength (i.e. the dependence of excitation energy, total width, fraction of the sum rule on mass number) has improved considerably over the last decade, very little is known about the microscopic structure of the GTR.

The microscopic structure of the GTR, which can be described as a coherent sum of one-proton particle one-neutron hole configurations, can in principle be investigated by studying its proton decay. However, no attempts have been made to study proton decay of the GTR following excitation via the  $(p, n)$  reaction at intermediate energies for two obvious experimental reasons. Firstly, the relatively low neutron detection efficiency yields very low coincidence rates in  $(p, n\bar{p})$  experiments, made even more severe by the expected small branching ratios. Secondly, the resolution achieved in detecting high energy neutrons

( $E_n > 100$  MeV) is relatively poor which, combined with the necessity to use thick targets, yields typically more than 1 MeV for the final-state resolution for proton decay to hole states in the residual nucleus. This makes it almost impossible to infer the microscopic structure of the GTR.

The ( ${}^3\text{He}, t$ ) reaction is a more suitable alternative to investigate the microscopic structure of the GTR since, similar to the ( $p, n$ ) reaction at intermediate energies ( $\geq 100$  MeV/ $u$ ), it preferentially excites spin-isospin-flip modes [10,11]. Furthermore, it has the advantage that tritons can be detected at  $0^\circ$  with a magnetic spectrometer with essentially 100% efficiency and with resolution superior to that achievable in the ( $p, n$ ) reaction. Indeed, the ( ${}^3\text{He}, t\bar{p}$ ) reaction has been used at lower bombarding energies ( $\simeq 30$  MeV/ $u$ ) to investigate the microscopic properties of the IAS, which is strongly excited at these energies [12,13]. These energies are, however, too low to appreciably excite the spin-flip GTR with the ( ${}^3\text{He}, t$ ) reaction. This explains the difficulties encountered with the first attempt to measure the proton decay of the GTR at a bombarding energy of (27 MeV/ $u$ ) [12,14]. The observed decay from the excitation energy region near the GTR to neutron-hole states in  ${}^{207}\text{Pb}$  [12] would, if assumed to be entirely from this resonance, account for the total decay of the GTR. This result is surprising because it implies a vanishing spreading width  $\Gamma^\downarrow$  incompatible with the calculated [15,16] value  $\Gamma^\downarrow \approx 4$  MeV and the measured [4] total width  $\Gamma = 4.33 \pm 1.00$  MeV. Furthermore, the observed strong decay into the high-spin  $1_{13/2}$  neutron-hole state cannot be explained [12,14].

In this letter we report on the first successful measurement of the proton decay of a GTR and the determination of its microscopic structure. This is made possible by the availability of a higher energy  ${}^3\text{He}$  beam (150 MeV/ $u$ ) at which the GTR is strongly and preferentially excited. The experiment was performed at the Research Center for Nuclear Physics (RCNP) facility in Osaka. A 450 MeV  ${}^3\text{He}^{++}$  beam extracted from the ring cyclotron [17] was achromatically transported without any momentum defining slits onto a  ${}^{208}\text{Pb}$  target of 5.2 mg/cm<sup>2</sup> thickness and of 99.86% isotopic enrichment. The ejectile tritons were detected in the new spectrometer Grand Raiden [18], which has a  $K$ -value of 1400 MeV. The spectrometer was set at  $-0.3^\circ$  with vertical and horizontal opening an-

gles of 40 mrad each. The  ${}^3\text{He}^{++}$  beam is bent more strongly than the tritons because of its lower magnetic rigidity. It is fully intercepted by a specially designed Faraday cup in the first dipole magnet. A run with an empty target frame showed that absolutely no background from slit scattering or from scattering from the Faraday cup could be observed.

Singly-charged  ${}^3\text{He}^+$  particles are formed in the target with low yield due to atomic charge-exchange processes. They have about the same rigidity as the ejectile tritons populating the ground state ( $g.s.$ ) of  ${}^{208}\text{Bi}$  and can therefore be used as a good calibration standard for the energy and also for the scattering angle since they enter the spectrometer at exactly  $0^\circ$ .

The ejectile tritons were detected with the focal-plane detection system [19] which has two 2-dimensional position-sensitive multi-wire drift chambers (MWDC) backed by two  $\Delta E$ -scintillation counters for particle identification. The horizontal and vertical scattering angles at the target were determined by ray-tracing techniques from the horizontal and vertical positions determined with the focal-plane detection system with uncertainties of not more than 2 mrad and 10 mrad, respectively. Because of the strongly forward-peaked angular distributions of the GTR and the IAS, software cuts on the deduced scattering angles can be used in later off-line analyses to enhance the contribution of these two  $\Delta L = 0$  transitions compared to transitions of higher multipolarity and/or continuum background due to the quasi-free charge-exchange process. The former have minima in their angular distributions at  $0^\circ$ , and the latter has a rather flat angular distribution near  $0^\circ$ .

Fig. 1 shows two such singles spectra where the "full" opening solid angle of 1.6 msr is reduced to 0.28 msr centered at  $0^\circ$  (fig. 1a) and at  $1^\circ$  (fig. 1b), respectively. The software gates define horizontal and vertical opening angles of 14 mrad and 20 mrad, respectively. The figure shows that near  $0^\circ$  the IAS and the GTR are prominent in the spectrum, along with the expected  ${}^3\text{He}^+$  peak. The non-resonant background is assumed to result from quasifree charge exchange. The figure displays the decomposition into the GTR, IAS, and the non-resonant background. The non-resonant continuum background (dash-dotted curve in fig. 1a) has been calculated according to the prescription given in ref. [20]. The uncertainty in defining its strength accounts for the

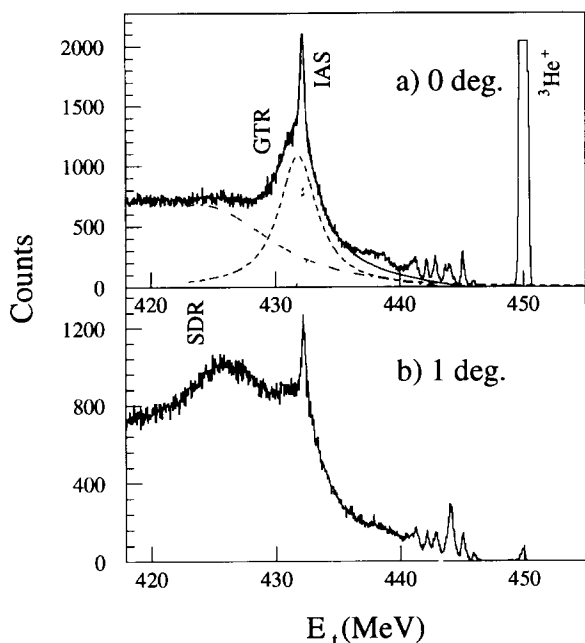


Fig 1 Triton energy spectra from  $^{208}\text{Pb}(^3\text{He}, t)^{208}\text{Bi}$  obtained at  $E(^3\text{He}) = 450$  MeV and at  $\theta = 0^\circ$  (a) Spectrum gated on the smallest scattering angles near  $\theta = 0^\circ$  from  $-7$  to  $+7$  mrad horizontally and from  $-10$  to  $+10$  mrad vertically. Here, IAS, GTR and  $^3\text{He}^+$  peak are prominent. The dashed, dotted, and dash-dotted lines represent fits obtained for GTR, IAS, and non-resonant background, respectively. (b) Spectrum gated on scattering angles near  $\theta = 1^\circ$  with horizontal and vertical openings identical to that of (a). Spin-flip  $\Delta L = 1$  resonances (denoted by SDR) are enhanced, whereas IAS and GTR are strongly suppressed, and the  $^3\text{He}^+$  peak is absent.

uncertainty of the total width of the GTR and for most of the uncertainty of the branching ratios for GTR proton decay (see below). The total width of the GTR was determined from fitting the GTR bump in this spectrum to be  $\Gamma = 3750 \pm 250$  keV. For the spectrum centered at  $1^\circ$  the  $^3\text{He}^+$  peak is absent and, moreover, the contributions of the IAS and the GTR are strongly reduced in agreement with expectations based on their angular distributions. However, the contributions from the  $\Delta L = 1$  spin-flip excitations (denoted by SDR) are enhanced for this spectrum. This will be discussed in more detail in a forthcoming paper [21].

Protons from the decay of the GTR were measured in coincidence with tritons detected at  $0^\circ$  in eight

solid-state detectors (SSD) arranged in two rings containing 4 SSDs each. The detectors in the outer ring were set at 8.8 cm from the target at  $\theta = 132^\circ$ , whereas those in the inner ring were at 10.1 cm and  $157^\circ$ , respectively. The SSDs in both rings were positioned at  $\phi = 45^\circ, 135^\circ, 225^\circ$  and  $315^\circ$ . Each SSD had an area of  $490 \text{ mm}^2$ . The detectors in the outer and inner rings were collimated to cover solid angles of  $\Delta\Omega = 57.8$  and  $47.0$  msr, respectively. During the experiment, in which up to 5 nA of beam current was used, the count rate in each of the SSDs never exceeded 5 kHz.

Time-of-flight spectra were generated for each SSD by starting and stopping a time-to-digital converter module with timing signals from the focal-plane scintillator and the SSD, respectively. The time spectra (not shown here) had a ratio of prompt to random events of about 10. Two-dimensional scatter plots of proton-decay energy measured in SSD versus excitation energy in  $^{208}\text{Bi}$  were generated for prompt and random events by gating on prompt and random peaks in the time spectra. Furthermore, these 2-dimensional spectra were generated with a gate on the core solid angle near  $0^\circ$  (see fig 1a and discussion above). This ensured that the contributions of the IAS and GTR were dominant. A prompt 2-dimensional spectrum obtained under the above conditions is shown in fig 2a. The loci for decay of the IAS, GTR and higher-lying resonances to the g.s. and the low-lying neutron-hole states in  $^{207}\text{Pb}$  (i.e.  $3p_{1/2}, 2f_{5/2}, 3p_{3/2}, 1i_{13/2}, 2f_{7/2}$ ) can be observed. The total resolution of the proton and triton sum energy was about 400 keV. This was not sufficient to completely resolve the decay to the 1st and 2nd excited states of  $^{207}\text{Pb}$ . This can also be seen in the final-state spectrum obtained by projecting the loci in fig 2a on the excitation-energy axis of  $^{207}\text{Pb}$ . This is shown in fig 2b which is gated on the combined region of the GTR and IAS. Here, the various peaks correspond to decay to states in  $^{207}\text{Pb}$ . A triton energy spectrum is shown in fig 2c. It was obtained by gating on decays to the neutron-hole states in  $^{207}\text{Pb}$  and subtracting random coincidences. It is worth noting that in this spectrum the yield of the IAS relative to that of the GTR is much bigger compared to the singles spectrum because the IAS has a much larger branching ratio for proton decay to  $^{207}\text{Pb}$ . At excitation energies higher than that of the GTR, it is observed that the spin-flip  $\Delta L = 1$  resonances which are excited even

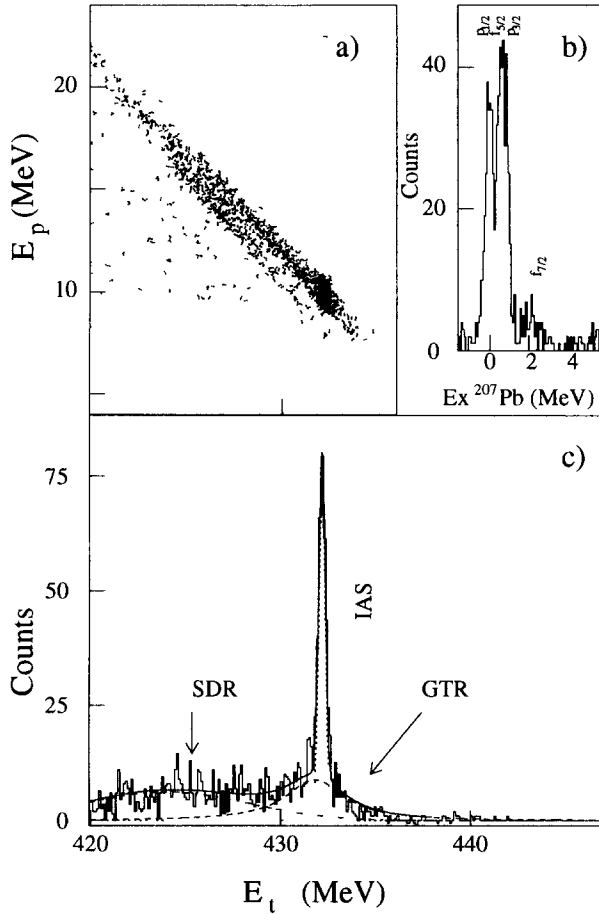


Fig 2 (a) Two-dimensional scatter plot of proton energy versus triton energy [or excitation energy in  $^{208}\text{Bi}$ ] gated on scattering angles centered at  $0^\circ$  (see fig. 1a) The loci indicate decay of states in  $^{208}\text{Bi}$  by protons to final neutron-hole states in  $^{207}\text{Pb}$  (b) The final-state spectrum of neutron-hole states populated in  $^{207}\text{Pb}$  as obtained from projecting loci of fig 2a onto the  $^{207}\text{Pb}$  excitation-energy axis (c) Triton energy spectrum gated on proton decay to neutron-hole states in  $^{207}\text{Pb}$  after subtraction of random coincidences. The dashed, dotted, and dash-dotted lines represent the fits obtained for GTR, IAS, and SDR, respectively

near  $0^\circ$  (after the cut on the core solid angle) also decay by proton emission to the neutron-hole states in  $^{207}\text{Pb}$  [21]. The continuum due to quasifree charge exchange, leading to emission of protons at very forward angles, is strongly suppressed (and therefore can be neglected) because coincidence is required with protons emitted at very backward angles. Thus the spectrum only contains the three contributions

mentioned above.

The total width of the IAS, or the GTR, can be written as

$$\Gamma = \Gamma^\uparrow + \Gamma^\downarrow,$$

where  $\Gamma^\downarrow$  is the spreading width. In heavy nuclei, this leads to neutron decay. Statistical decay in the GTR region in  $^{208}\text{Bi}$  favours neutron to proton decay by about three orders of magnitude as a consequence of the high Coulomb barrier  $\Gamma^\uparrow$  is the escape width connected with the microscopic one-proton particle one-neutron hole structure of the GTR. This leads to direct proton decay to the neutron-hole states of  $^{207}\text{Pb}$ . The escape width can thus be written as

$$\Gamma^\uparrow = \Gamma_p^\uparrow = \sum_i \Gamma_{p_i}^\uparrow, \quad (1)$$

where  $\Gamma_{p_i}^\uparrow$  is the partial proton escape width associated with decay to the  $i$ th neutron-hole state of  $^{207}\text{Pb}$ . The ratio of  $\Gamma^\uparrow$  to the total width  $\Gamma$  can be obtained from the ratios of the coincidence double-differential cross sections to the singles cross section as follows

$$\begin{aligned} \frac{\Gamma_{p_i}^\uparrow}{\Gamma} &= \frac{\int (d^2\sigma_{p_i}/d\Omega_t d\Omega_p) d\Omega_p}{d\sigma/d\Omega_t} \\ &= \frac{4\pi d^2\sigma_{p_i}/d\Omega_t d\Omega_p}{d\sigma/d\Omega_t} \end{aligned} \quad (2)$$

Here, it is implicitly assumed that the double-differential and singles cross sections have been integrated over the excitation energy of the resonance. Furthermore, use has been made in eq. (2) of the fact that the decay of the GTR and IAS is expected to be isotropic.

The measured branching ratios and partial proton escape widths of the IAS and the GTR to the  $3p_{1/2}$ ,  $2f_{5/2}$ ,  $3p_{3/2}$ , and  $2f_{7/2}$  neutron-hole states were determined from the present data. These were determined from the peak areas of the IAS and GTR in spectra similar to that in fig. 2c obtained by gating on the various final hole states in  $^{207}\text{Pb}$  as described above. For the GTR they are given in columns 7 and 8 of table 1, respectively. Since the resolution was not sufficient to separate the decay to the  $2f_{5/2}$  and  $3p_{3/2}$  neutron-hole states in  $^{207}\text{Pb}$ , the sum of the partial decay widths is given. This was also the case in the earlier experiment [12]. The present results for the IAS:  $51.4 \pm 5.6$  keV ( $\Gamma_{p_{1/2}}^\uparrow$ ),  $79.4 \pm 9.4$  keV ( $\Gamma_{f_{5/2}}^\uparrow + \Gamma_{p_{3/2}}^\uparrow$ )

Table 1

Theoretical and experimental partial and total (escape) proton widths,  $\Gamma_{p_i}^\dagger$  and  $\Sigma_i \Gamma_{p_i}^\dagger$ , in keV for the decay of the GTR in  $^{208}\text{Bi}$  into neutron-hole states in  $^{207}\text{Pb}$ . Also given are the measured branching ratios [The uncertainties of the absolute partial widths include only the contributions from the partial branching ratios]

Neutron-hole pstates in $^{207}\text{Pb}$	$E_x$ (keV) <sup>a)</sup>	theor			exp <sup>b)</sup>	$\Gamma_{p_i}^\dagger/\Sigma_i \Gamma_{p_i}^\dagger$ % <sup>c)</sup>	exp <sup>c)</sup>
		ref [14] <sup>d)</sup>	ref [14] <sup>e)</sup>	ref [26]			
$3p_{1/2}^{-1}$	0	123.7	114.1	33	$570 \pm 70$	$31.8 \pm 6.1$	$58.4 \pm 11.2$
$2f_{5/2}^{-1}$	570	192.8	108.7	18	incl in $p_{3/2}$	incl in $p_{3/2}$	incl in $p_{3/2}$
$3p_{3/2}^{-1}$	898	239.5	181.1	21	$1130 \pm 300$	$55.2 \pm 8.5$	$101.5 \pm 15.6$
$1i_{13/2}^{-1}$	1633	7.1	6.3	0.04	$1780 \pm 500$	$4.5 \pm 5.0$	$8.3 \pm 9.2$
$2f_{7/2}^{-1}$	2340	16.6	4.8	0.02	$850 \pm 300$	$8.5 \pm 4.0$	$15.6 \pm 7.4$
$1h_{9/2}^{-1}$	3413	7.9	2.9	0.26			
total		587.6	421.9	72	$\sim 4330$	100 <sup>f)</sup>	$184 \pm 49$

a) Nucl. Data Sheet

b) ref [12], see also ref [14]

c) present experimental results, the total width of the GTR is  $\Gamma = 3750 \pm 250$  keV

d) obtained with SGII interaction

e) obtained with SIII interaction

f) The relative value for the total escape width from the present experiment is  $\Sigma_i \Gamma_{p_i}^\dagger/\Gamma = 4.9 \pm 1.3\%$

and  $3.5 \pm 1.6$  keV ( $\Gamma_{f_{7/2}}^\dagger$ ) are in very good agreement with the earlier experimental values [22] of  $51.9 \pm 1.6$  keV,  $(26.4 \pm 2.0 + 64.7 \pm 3.4)$  keV and  $4.2 \pm 0.6$  keV, respectively. This nice agreement for the values determined for the IAS lends credence to the extracted values for the GTR which are in complete disagreement with the earlier experimental results listed in column 6. This confirms that the earlier measurement has not been able to reliably measure the decay of the GTR due to the weak excitation of the GTR (no GTR bump could be observed) and to proton emission from other reaction processes.

Columns 3–5 display theoretical predictions. Columns 3 and 4 list the partial proton escape widths calculated by Van Giai et al [14] in the Tamm-Dancoff approximation with explicit coupling to the continuum. These calculations were performed within the framework of a self-consistent microscopic theory where the single-particle states and the residual particle-hole interaction are derived from the same Skyrme force. Two different forces were considered, but only that used for the calculations of column 4 yielded an escape width for the IAS compatible with the experimental value. The calculations of Yoshida and Adachi [23] and of Urin et al [24,25] also

reproduce the data for the IAS reasonably well. A good understanding of the microscopic structure and thus of the partial proton escape widths of the IAS therefore exists [22]. However, all theoretical results for the GTR, including those obtained by Muraviev and Urin [26] in RPA with coupling to the continuum (column 5) do not reproduce the data. Only the theoretically predicted dominance of the decays into the three lowest single-neutron hole states is confirmed by the new data. The cause of this discrepancy is not clear. However, it is worth noting that the above calculations do not include coupling to  $2p$ – $2h$  states or to  $\Delta$ -hole excitations which are needed to explain the observed quenching of the GTR [27]. If this quenching of the GTR strength of (50–60)% is taken into account, improved agreement between the results of Van Giai et al [14] obtained with the SIII interaction and the data can possibly be obtained.

In conclusion, the proton decay of the GTR in  $^{208}\text{Bi}$  has been measured successfully for the first time yielding the total and partial escape widths for decays into single-neutron hole state in  $^{207}\text{Pb}$ . The total branching ratio for proton emission is only  $(4.9 \pm 1.3)\%$ . The theoretical results of Van Giai et al [14] obtained with the SIII Skyrme interaction and those of Muraviev

and Urin [26] obtained in the RPA framework are factors of  $\sim 2.5$  too high/low compared to our new data. Further theoretical work seems to be needed to re-examine the underlying assumptions (effective interaction, coupling to continuum, etc.) to understand the microscopic structure of one of the most basic modes of collective excitations. It is clear, though, that the tensor coupling to  $2p$ - $2h$  states in the continuum and/or to the  $\Delta$ -hole excitations, hence quark-degrees of freedom, introduce a major uncertainty.

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## References

- [1] J I Fujita and K Ikeda, Nucl Phys 67 (1965) 145, K Ikeda, S Fujiwara and J I Fujita, Phys Lett 3 (1963) 271
- [2] D E Bainum et al, Phys Rev Lett 44 (1980) 1751
- [3] C D Goodman et al, Phys Rev Lett 44 (1980) 1755
- [4] D J Horen et al, Phys Lett B 95 (1980) 27
- [5] F Petrovich and W G Love, Nucl Phys A 354 (1981) 499c
- [6] N S P King et al, Phys Lett B 175 (1986) 279
- [7] W P Alford et al, Phys Lett B 179 (1986) 20
- [8] T N Taddeucci et al, Nucl Phys A 469 (1987) 125
- [9] B S Flanders et al, Phys Rev C 40 (1989) 1985
- [10] C Ellegaard et al, Phys Rev Lett 50 (1983) 1745
- [11] I Bergqvist et al, Nucl Phys A 469 (1987) 669
- [12] C Gaarde et al, Phys Rev Lett 46 (1981) 902
- [13] H J Hofmann et al, Nucl Phys A 433 (1985) 181 and references therein
- [14] N Van Giai et al, Phys Lett B 233 (1989) 1
- [15] P F Bortignon, R A Brogna and F Zardi, in Proc Int Conf on Spin Excitations in Nuclei (Telluride, 1982), eds F Petrovich et al (Plenum, New York, 1984) p 415
- [16] H R Fiebig and J Wambach, Nucl Phys A 386 (1982) 381
- [17] I Miura et al, RCNP Ann Rep (1991) p 149
- [18] M Fujiwara et al, Nucl Instr Meth Phys Res A, to be published
- [19] T Noro et al, RCNP Ann. Rep (1991) p 177
- [20] J Janecke, Phys Rev. C 48 (1993) 2828 and references therein
- [21] H Akimune et al, to be published
- [22] S Y van der Werf, M N Harakeh and E N M Quint, Phys Lett B 216 (1989) 15 and references therein
- [23] S Yoshida and S Adachi, Z Physik A 325 (1986) 441
- [24] V G Guba and M G Urin, Nucl Phys A 460 (1986) 222
- [25] O A Rumyantsev and M G Urin, Phys Rev C (in print)
- [26] S E Muraviev and M G Urin, Nucl Phys A (in print)
- [27] F Osterfeld, Rev Mod Phys 64 (1992) 491 and references therein