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Investigation of Low-Lying Spin Dipole Response of ^{40,42,44,48}Ca Nuclei in (^{3}He,t) Charge-Exchange Reactions

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Abstract. The microscopic structure of the isovector spin-dipole resonance (IVSGDR) has been investigated at 420 MeV in ^{40,42,44,48}Ca(^{3}He,t)^{40,42,44,48}Sc reactions. By performing the dispersion matching techniques to the magnetic spectrometer system an energy resolution of 15-20 keV was obtained. The measured angular distributions in forward scattering angles allowed the extraction of the dipole strength. The spectra contain highly detailed information, which allowed the identification of many individual levels up to about 15 MeV excitation energy. By using the angular-distribution analysis, the spin and parity values of the newly identified states were determined.The low-lying dipole strengths distributions of all four isotopes show a strong peak below 10 MeV and a periodic-like structure, with period of $\hbar\omega = 1.8$ MeV. The theoretical interpretation of these phenomena is still in progress.

1 Introduction

The spin-isospin excitations in nuclei have been one of the interesting subjects of experimental and theoretical investigations for a long time. The transition is a $1\hbar\omega$ excitation and characterised by quantum-number changes of orbital angular momentum ($\Delta L = 1$), spin ($\Delta S = 1$), and isospin ($\Delta T = 1$) [1]. Nevertheless, our knowledge of the spin dipole (SD) response on $N = Z$ and exotic nuclei is poor, even though it is expected that exotic properties cause new features in this excitation mode.

During the last few years much interest has been devoted to the non-spin-flip channel ($\Delta L = 1$, $\Delta S = 0$, and $\Delta T = 1$), there have been data showing enhancement of low lying dipole strengths. The low-lying dipole response, so-called soft dipole resonance, has been studied in several lighter nuclei [2–4]. The appearance of a collective soft-dipole resonance in general was predicted for heavier neutron-rich systems [5,6] also. The origin of these low-lying dipole excitations, however, has not been fully resolved in experiments. In particular, it is not clear whether some of these states correspond to a collective soft mode, or they all simply result from incoherent single-particle excitations. The degrees of collectivity or the nature of correlations responsible for this excitation is one of the central issues that need to be clarified [7]. Thus, from the experimental side, systematic studies on the spin-dipole strength evolution is necessary for a deeper understanding of the origin of the low-lying strength. The microscopic nature of the low lying dipole resonance in the stable Ca isotopes has been investigated by Hartmann et al. [8] in high resolution photon scattering experiments for the first time. However, so far, no high resolution studies have been performed for the spin dipole strengths distribution in these nuclei. Unfortunately, no theoretical prediction can be found in literature about the SD strength distribution in Ca or Sc isotopes.

The recent advancement of the experimental techniques eventuate the possibility of the precise investigation of microscopic structure of IVSGDR aiming to crawl accurate the structure of nuclei. The impact of isospin symmetry is maximal near the $N = Z$ line where nuclei have equal numbers of neutrons and protons, but at the same time it is interesting to study the evaluation of strengths by increasing the neutron numbers. Especially interest in these nuclei is the role played by the isoscalar ($T = 0$) and isovector ($T = 1$) pairing correlations. Previously, A. Bohr [9] obtained that $T = 1$ pairing phonon is appropriate for the region around ^{40}Ca. Already then, the evidence including both energetics and transfer data was compelling regarding the major role played by the $T = 1$ pairing in $N = Z$ nuclei [10]. The pairing vibration appears as a low-energy collective mode in the case of a residual two-body interaction such that the nucleus should be sufficiently close to the transition point between the single-particle and a superconducting system. Later, the detailed theoretical analysis of the of isovector pairing vibrations was published by Bés and Broglia [11], where an answer for the role of the $T = 0$ collective pairing has not been clarified.

Studies involving isospin effects have undergone a resurgence in recent years as such nuclei become more readily accessible. Moreover, near closed shells, the strength of the pairing force relative to the single-particle level-spacing is expected to be less than the critical value needed to obtain a superconducting solution, and the pairing field then gives rise to a collective phonon. However, despite many experimental efforts, these predictions have not been confirmed yet.

Macchiavelly et al. [12] described an experimental analysis of the pairing vibrations around ^{56}Ni with emphasis on odd-odd nuclei. These results clearly indicate a collective behaviour of the isovector pairing vibrations. The $\hbar\omega$ of such vibrations is estimated to be 0.8 MeV [12] for ^{40}Ca [12]. More recently, Cedervall et al. [13] obtained evidence for a spin-aligned neutron-proton paired phase from the level structure of ^{92}Pd. The possibility of mixed-spin pairing correlations in heavy nuclei was also discussed by Gezerlis et al. [14].

The aim of this work was to study the fragmentation of the spin dipole strengths into low-lying (below 10 MeV) excited states by using the (^{3}He,t) reaction, which was extensively used earlier for the excitation of spin-isospin vibrational states in other isotopes. Some of our preliminary results was published recently [15] and [16].

The ^{40}Ca(^{3}He,t)^{40}Sc reaction has been studied earlier by Schulz et al. [17] at 28 MeV bombarding energy and by Loiseaux et al. [18] at 30.2 MeV bombarding energy using solid state telescopes and a magnetic spectrograph. The energy resolution was 70 keV and 15–20 keV, respectively. In this paper some of the $(\pi 1f_{7/2})(\nu 1d_{3/2})^{-1}$, $(\pi 1p_{3/2})(\nu 1d_{3/2})^{-1}$ and $(\pi 1f_{7/2})(\nu 2s_{1/2})^{-1}$ proton-neutron multiplet states are identified and the effect of configuration mixing is discussed. A similar experiment has been performed more recently by Hansper et al., [19] at 26.1 MeV, using a magnetic spectrometer with an energy resolution of 15 keV. Correspondence of the observed ^{40}Sc levels with the known $T = 1$ states in ^{40}K and ^{40}Ca are based on predictions provided by the isobaric multiplet mass equation.

The ^{48}Ca(^{3}He,t)^{48}Sc reaction was studied earlier by Grewe et al. [20] at 420 MeV bombarding energy with an energy resolution of about 40 keV. Up to about 9 MeV some excited states relevant for the double β-decay were identified. Those levels were observed and investigated also in our present work and they are in good agreement with the levels, observed by Grewe et al.

The spin-isospin excitation has been investigated earlier by Tabor et al. [21] in the ^{40}Ca(^{3}He,t)^{40}Sc reaction at 130 and 170 MeV. The angular distribution was measured for the suspected giant dipole resonance (GDR) structure. The data are reasonably well described by a collective model calculation based on the Goldhaber-Teller model of the GDR. Some weaker $L = 1$ resonances at 2, 4, 6, and 8 MeV has also been observed. However, their energy resolution of about 400 keV did not allow to study their detailed structures. The (^{3}He,t) charge exchange reaction was used to access the dipole strengths distribution as summing a simple proportionality between the cross sections and the dipole strength values.

2 Experimental Method

The measurements were performed at the Research Center for Nuclear Physics (RCNP) at Osaka University, Japan [22]. The ^{3}He^{+2} beam at 420 MeV was provided through the cascade acceleration with the $K = 120$ AVF cyclotron and the $K = 400$ RCNP Ring Cyclotron. The energy of the ^{3}He^{+2} beam was achromatically transported to the thin self-supporting metallic Ca targets. The main properties of the targets are listed in Table 1. The typical beam current was 25 nA.

Table 1. *Properties of targets we used in (^{3}He,t) charge exchange reactions*

Target	^{40}Ca	^{42}Ca	^{44}Ca	^{48}Ca
Thickness (mg/cm^2)	1.63	1.78	1.83	1.87
Enrichment (%)	99.97(0.4)	93.71(0.6)	98.78(0.2)	95.2(0.6)
Contaminants (%)				
^{40}Ca	–	5.08(6)	1.12(2)	1.23(2)
^{42}Ca	0.007(1)	–	0.06(1)	0.2(1)
^{43}Ca	0.002(1)	0.33(3)	0.03(1)	no data
^{44}Ca	0.016(1)	0.869(5)	–	no data
^{46}Ca	<0.001	<0.003	<0.002	<0.002
^{48}Ca	no data	0.014(1)	0.006(2)	–

The energy of tritons was measured with a magnetic spectrometer using complete dispersion matching technique [23]. An energy resolution of 20 keV [full width at half maximum (FWHM)] was realised by applying matching techniques. The realisation of the matching parameters was examined by using the "faint beam method" [24]. Outgoing tritons were momentum analysed within the full acceptance of the Grand Raiden Spectrometer (GRS) [25, 26] at two different angular positions: 0° and 2.5° with an opening angle of ±20 mrad horizontally and ±20 mrad vertically defined by a slit at the entrance of the spectrometer. The results of both settings were combined to achieve angular distributions, by which the character of single transitions could be determined. The outgoing tritons were detected at the focal plane with a system consisting of two multi wire drift chambers (MWDCs) that allow track reconstruction [27] and two plastic scintillators used for the creation of triggers to start the data-acquisition system and particle identification.

3 Data Analysis

We analysed the spectra using the program package: Gaspan, which was developed for the evaluation of gamma- and particle-spectra [28]. In a given energy range all peaks were fitted at the same time. Gaussian line shape with exponential tails and second order polynomials were used for describing the background. The typical value of the chi-square tests varied between 1.05 and 1.17. The excitation energies of the isobaric analogue state and about 10 well known excited states were used for determining the precise energy calibration. We determined the precise level energies and intensities in the excitation energy range 0–15 MeV for each isotope. Part of the differential spectrum (difference between the spectra measured at 0° and 2.5° degrees) of ^{40}Ca(^{3}He,t)^{40}Sc reaction is shown in Figure 1. Prominent states populated in spin dipole transitions are enhanced and indicated by their excitation energies.

In order of distinguish the different transitions, the experimental spectra were studied in eight angular regions, as 0°–0.5°, 0.5°–0.8°, 0.8°–1.2°, 1.2°–1.6°, and 1.6°–2°, 2°–2.5°, 2.5°–3° and 3°–3.5°. The angular distributions were determined for each known and newly identified peaks also. Several examples for the angular distributions are presented on Figure 2.

They were normalised to the corresponding opening angle which was determined by experimental data (experimental opening angle). According to their characteristic angular distributions three different groups can be recognised. In order to deduce the spin and parity, an A$_n$ parameter was introduced, which is the ratio of the intensity of first angular region divided by the average of intensity of the 3^rd and 4^th angular region. To determine the threshold of A$_n$, the distribution of the parameter was investigated. Two different groups of levels were obtained for $J^\pi = 1^+$, 3^+ and $J^\pi = 0^-$, 1^-, 2^-. The relative intensities were determined for the all different angular bins for each identified excited state.

The lowest lying states in ^{40}Sc were identified as members of the $(\pi 1f_{7/2})(\nu 1d_{3/2})^{-1}$ ($J^\pi = 2^- - 5^-$) multiplet. As the (^{3}He,t) reaction at this bombarding energy excites preferentially the spin-flip states, in our case the 2^- state is excited the strongest, in which the spin of the proton and the neutron hole is parallel. The isospin of such state is $T = 1$ and $T_z = -1$. Such proton neutron multiplet has been observed also in the mirror nucleus of ^{40}Sc namely in ^{40}K in which it is also the ground state multiplet with $T = 1$ and $T_z = 1$. The $T_z = 0$ members of the isospin multiplet has been observed in ^{40}Ca at 7.658 MeV above the ground state. Such a shift can be explained by the Coulomb energy difference. The other states of the proton-neutron multiplet with $J^\pi = 3^-$, 4^- and 5^- were also identified in ^{40}Sc ($T = -1$), in ^{40}Ca ($T = 0$) and in ^{40}K ($T = 1$) [29]. All three multiplets turned out to be very similar. The sequence of the J^π's are 4^-, 3^-, 2^- and 5^-. The energy differences between the members of the bands agree(s) within 1–2 keV.

In ^{40}Sc no other multiplet states has been identified yet. However, using the strong similarity of the low-lying excited states in ^{40}K and ^{40}Sc we may identify some additional multiplet states. The next multiplet in ^{40}K is $(\pi 1d_{3/2}))^{-1}(\nu 1d_{3/2})^{-1}$ with $L = 2$ and J^π's are 0^+ (1644 keV), 2^+ (1959 keV), 3^+ (2260 keV) and 1^+ (2290 keV). At about the same excitation energy the $(\pi 1d_{3/2}))^{-1}(\nu 2p_{3/2})$ ($L = 1$, $J^\pi = 0^- - 3^-$) multiplet was also identified. As the $(\pi 2p_{3/2})$ is somewhat lower in ^{41}Sc than in ^{39}K such a multiplet should be also lower in ^{40}Sc than in ^{40}K. The triplet state observed around 1.7 MeV is a

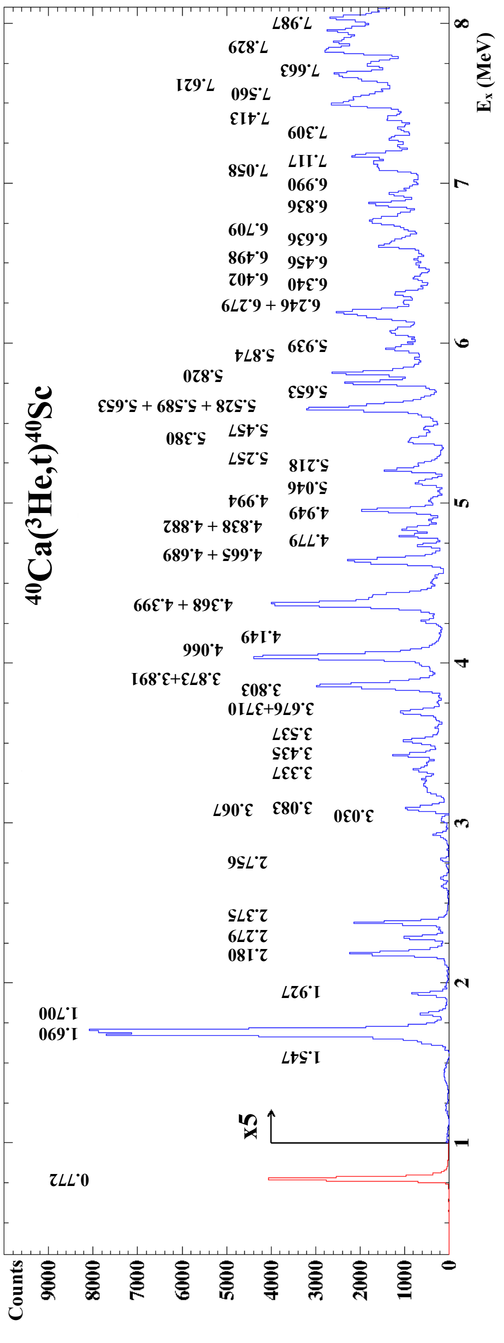

Figure 1. Part of the differential spectrum (difference between the spectra measured at 0° and 2.5° degrees) of ^{40}Ca(^{3}He,t)^{40}Sc reaction in excitation energy region of 0–8 MeV.

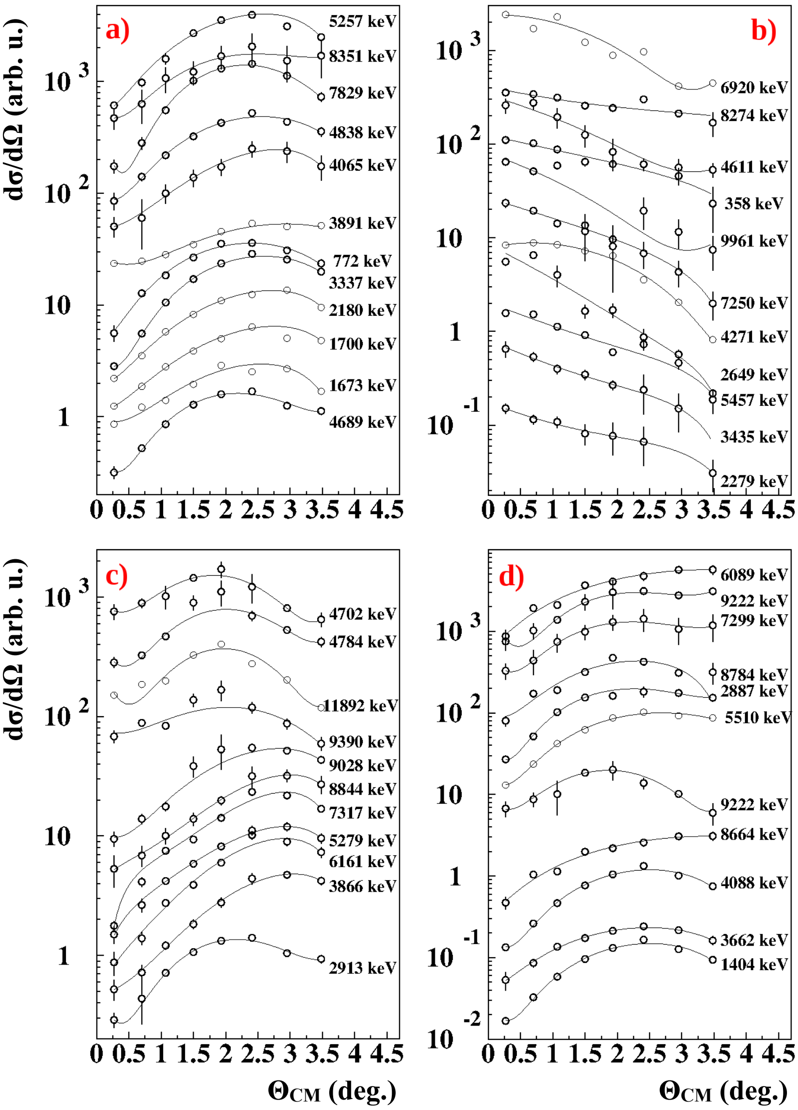

Figure 2. Examples for the angular distributions measured in (^{3}He,t) reaction. The a) part of figure presents few newly determined dipole states in the case of ^{40}Sc, while b) shows $\Delta L = 0$ and 2 transitions in ^{40}Sc (2279, 3435, 5457, 7117), ^{42}Sc (2649, 4271, 7250, 9961) and ^{48}Sc (358, 4611, 8274, 9938) isotopes. Known and newly identified dipole states are also presented in ^{42}Sc c) and ^{48}Sc d) nuclei.

good candidate for the $(\nu 1d_{3/2}))^{-1}(\pi 2p_{3/2})$ multiplet in ^{40}Sc. This assignment is supported also by the angular distribution of the states.

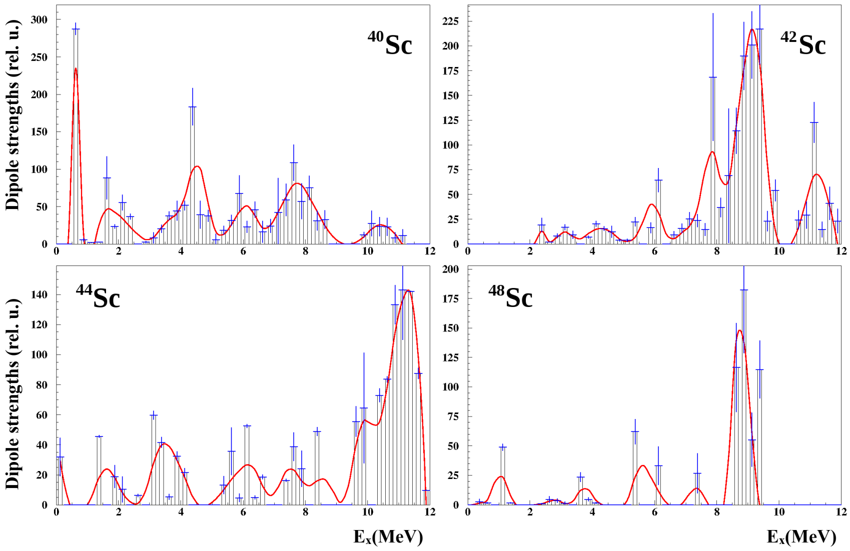

Figure 3. Relative dipole strengths distributions for ^{40}Sc (a), ^{42}Sc (b), ^{44}Sc (c), and ^{48}Sc (d) as a function of the excitation energy.

According to the lack of detailed experimental and theoretical data on transitions in Ca, K isotopes we were not able to perform further microscopic study of the single states and multiplets. The collective behavior of the states were studied in Sc isotopes. The dipole strengths distributions deduced from our experimental data for ^{40}Sc, ^{42}Sc, ^{44}Sc, and ^{48}Sc are displayed in Figure 3.

4 Conclusions

We have observed two characteristic features of the dipole strength distributions: a relatively strong peak around 10 MeV, and a periodic-like structure especially in ^{40}Ca. Both features suggests the presence of some core excitations in the doubly magic ^{40}Ca. It was realised that the periodic structure observed in the dipole strengths distribution can be associated with the multiparticle-multihole 0^+ states observed previously in ^{40}Ca, and also shown in the left part of Figure 4.

Coupling the 2^- state of the ground state multiplet (which is the strongest channel in the (^{3}He,t) rection) to the different low-lying 0^+ states in ^{40}Ca, the centroids of the bumps at 4, 6 and 8 MeV can nicely be reproduced. The density of the states increases rapidly above 8 MeV. The distribution of the 0^+ states is also shown in the right part of the figure. It has a definite peak at around 10 MeV. Coupling this peak to the 2^- state, one gets the 10 MeV peak in the IVSGDR distribution.

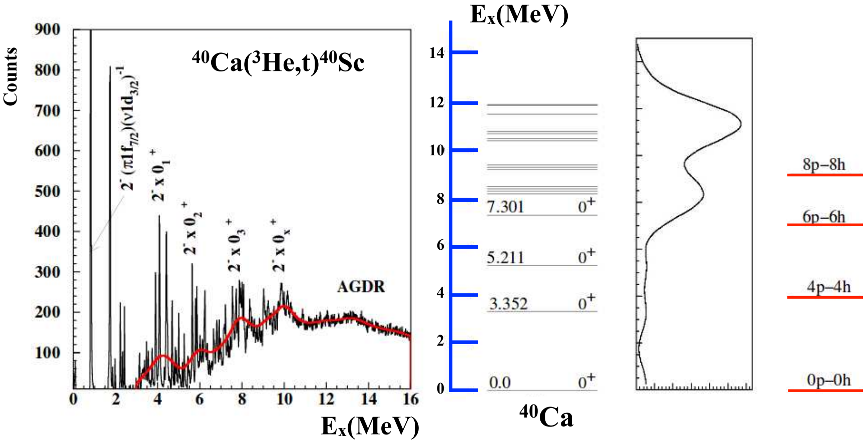

Figure 4. Left part: Spin-dipole excited states observed in the ^{40}Ca(^{3}He,t)Sc reaction at $\Theta = 2.5°$. A folded spectrum (with FWHM=500 keV) is shown in red. The periodic structure of the distribution is clearly visible. The position of the strong 2^- transition of the ground state multiplet as well as the results of their coupling to the lowest lying 0^+-states in ^{40}Ca are marked. Right part: Part of the level scheme of ^{40}Ca showing only the 0^+ levels, the level density of the 0^+-states and the shell model prediction for the multiparticle-multihole configurations [30].

Such low-lying 0^+ states in ^{40}Ca can also be considered as parts of the Giant Monopole Resonance (GMR). The GMR was investigated by Yangblood et al., [31] and indeed observed a bump around 10 MeV, although the centroid of the GMR was found to be at 19 MeV.

We expect also couplingof the 2^- state to the GMR. The high energy dipole stench distribution was investigated by Gaarde et al. [32] in the ^{40}Ca(p,n) reaction at 200 MeV bombarding energy and observed such a strong dipole peak at about 22 MeV. According to the shell model calculations of M. Sakakura et al. [30] the energy of the 4, 6 and 8 particle-hole states is also shown in Figure 4.

Such multiparticle-multihole configurations might be associated to monopole multiphonon states as well. We have a proton-neutron pair connected to such multiphonon states. The resulting 2^- states are also coupled to hundreds of other 2^- states (we are dealing with an odd-odd nucleus), which result in the observed spreading of their strengths.

Similar periodic structure is expected in the dipole strengths distribution of ^{40}K excited in the ^{40}Ca(n,p) reaction. For the $N = Z$ ^{40}Ca nucleus the sum rule for the β^- and β^+ strengths reduces to $S^-_{IVSGDR} = S^+_{IVSGDR}$ [33]. So the cross section of the ^{40}Ca(p,n) and the ^{40}Ca(n,p) reactions should be the same.

Unfortunately, most of the (n,p) reactions were performed at low bombarding energy where the spin-isospin excitations were suppressed. The only reaction, which was studied at intermediate energy (152 MeV) was performed by

Maesday et al. [34], but the energy resolution was about 3 MeV, which smeared out the structure of the spin dipole strengths distribution. They observed only one broad peak, which was identified as the IVGDR.

Acknowledgments

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