Soft spin-dipole resonances in $^{40}$Ca

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Abstract.

High resolution experimental data has been obtained for the $^{40,42,44,48}$Ca($^3$He,t)$^{40}$Sc charge exchange reaction at 420 MeV beam energy, which favors the spin-isospin excitations. The measured angular distributions were analyzed for each state separately, and the relative spin dipole strength has been extracted for the first time. The low-lying spin-dipole strength distribution in $^{40}$Sc shows some interesting periodic gross feature. It resembles to a soft, damped multi-phonon vibrational band with $\hbar\omega = 1.8$ MeV, which might be associated to pairing vibrations around $^{40}$Ca.

1. Introduction

It was realized already by A. Bohr [1], who discussed the general properties expected for a full (nn, pp and np) components that T=1 pairing phonon is appropriate for the region around $^{40}$Ca. Already then, the evidence including both energetics and transfer data. [2] was compelling regarding the major role played by the T=1 pairing in N=Z nuclei. These ideas were further developed by Bès and Broglia and culminated in the review article [3], where a very detailed analysis of isovector pairing vibrations was presented.

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.

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Macchiavelly et al., [4] presented an experimental analysis of the pairing vibrations around
$^{56}$Ni with emphasis on odd-odd nuclei. Their results clearly indicate a collective behavior of the
isovector pairing vibrations. The $\hbar\omega$ of such vibrations is estimated to be 0.8 MeV [4] for
$^{40}$Ca. In a recently published article Cedervall et al., [5] obtained evidence for a spin-aligned
neutron-proton paired phase from the level structure of $^{42}$Pd. Gezerlis et al., [6] discussed also
the possibility of mixed-spin pairing correlations in heavy nuclei.

The aim of the present work was to study the low-lying dipole strength distribution in $^{40}$Ca
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 [7].

The $^{40}$Ca($^3$He,t)$^{40}$Sc reaction has been studied earlier by Schulz et al., [8] at 28 MeV
bombarding energy and by Loiseaux et al., [9] 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. 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., [10] 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.,[11] 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 $\beta$-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., [12] 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 structures.

2. Experimental methods and results

The experiment was performed at the Research Center for Nuclear Physics, Osaka University.
The energy of the $^3$He beam of 420 MeV was achromatically transported to self supporting
metallic $^{40}$Ca, $^{42}$Ca, $^{44}$Ca, $^{48}$Ca targets with thicknesses of 1.63 − 1.87 mg/cm$^2$. The typical
beam current was 5 nA. The energy of the tritons was measured with a magnetic spectrometer
"Grand Riden", using complete dispersion matching techniques [13]. The energy resolution was
about 20 keV. The spectrometer was set at 0° and 2.5° with respect to the beam direction with
an opening angle of ±20 mrad horizontally and ±20 mrad vertically defined by a slit at the
entrance of the spectrometer. A few typical triton spectrum is shown in the left side of Fig. 1.

The spectra were analyzed using the program package: Gaspan. 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 quality of the fit was always good.
The excitation energies of the IAS’s and a few well known excited states are used for determining
the precise energy calibration. We determined the precise level energies and intensities for each
isotope. The spectra were studied in eight distinct angular regions for all scandium isotopes.
The angular distributions were determined for each known, and new peaks. A few examples for
the angular distributions are displayed at the right hand side of Fig. 1.

The lowest lying states in $^{40}$Sc are 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 $T_z=-1$. 

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Figure 1. Left side: Part of the triton spectra measured at $\theta = 2.5^\circ$ for the different Ca targets indicated in the figures, showing preferentially the $\Delta L=1$, dipole transitions. Right side: examples for the angular distributions measured in the $^{40}\text{Ca}(^{3}\text{He},t)^{40}\text{Sc}$ reaction for $\Delta L=0$ (a), for $\Delta L=1$ (b) and for some not identified (c) transitions.

Such proton neutron multiplet has been observed also in the mirror nucleus of $^{40}\text{Sc}$ namely in $^{40}\text{K}$ 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 $^{40}\text{Ca}$ 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 $^{40}\text{Sc}(T=-1)$, in $^{40}\text{Ca}(T=0)$ and in $^{40}\text{K}(T=1)$ [14].

All three multiplets turned out to be very similar. The sequence of the $J^{\pi}$'s are $4^{-}, 3^{-}, 2^{-}$ and $5^{-}$. The energy differences between the members of the bands agree(s) within 1-2 keV.

In $^{40}\text{Sc}$ no other multiplet states has been identified yet. However, using the strong similarity of the low-lying excited states in $^{40}\text{K}$ and $^{40}\text{Sc}$ we may identify some additional multiplet states. The next multiplet in $^{40}\text{K}$ is $(\pi 1d_{3/2})^{-1}(\nu 1d_{3/2})^{-1}$ with $L=2$ and $J^{\pi}$'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 $^{41}\text{Sc}$ than in $^{39}\text{K}$ such a multiplet should be also lower in $^{40}\text{Sc}$ than in $^{40}\text{K}$. The triplet state observed around 1.7 MeV is a good
candidate for the \((\nu1d_{3/2})^{-1}(\pi2p_{3/2})\) multiplet in \(^{40}\text{Sc}\). This assignment is supported also by the angular distribution of the states.

The dipole strengths distributions deduced from our experimental data for \(^{40}\text{Sc}\), \(^{42}\text{Sc}\), \(^{44}\text{Sc}\), and \(^{48}\text{Sc}\) are compared in Fig. 2.

3. Conclusions
Concerning the dipole strength distributions shown in Fig. 2 two observation can be made:

(i) there is a relatively strong peak at about 10 MeV in each distributions,
(ii) some periodic structure of the distribution is showing up, especially for \(^{40}\text{Sc}\).

Both features are very common for all isotopes, which suggests the presence of some core excitations in \(^{40}\text{Ca}\).

In order to understand the experimental results relativistic RPA (RRPA) calculations have been performed with NL3 [15] [16] interactions. The results are shown in Fig. 3. RRPA predicts low-lying strength with nearly periodic peaked structure caused by the dipole isospin-flip and spin-isospin-flip transitions governed by the pion and effective rho-meson exchange interactions. The obtained strength, however, shows no enhancement of the strength at lowest energies. Thus, it is expected that correlations beyond RRPA can be responsible for the observed enhancement.

It was realized that the periodic structure observed in the dipole strengths distribution can be associated with the multiparticle-multihole \(0^+\) states observed previously in \(^{40}\text{Ca}\), and also shown in the left part of Fig. 4.

Coupling the \(2^-\) state of the ground state multiplet (which is the strongest channel in the \(^{(3}\text{He},t)\) reaction) to the different low-lying \(0^+\) states in \(^{40}\text{Ca}\), 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 SDR distribution.

Figure 2. Relative dipole strengths distributions for \(^{40}\text{Sc}\) (a), \(^{42}\text{Sc}\) (b), \(^{44}\text{Sc}\) (c), and \(^{48}\text{Sc}\) (d) as a function of the excitation energy.
Figure 3. Isospin-flip and spin-isospin-flip dipole strength functions obtained within the Relativistic RPA with NL3 and DD-ME2 interactions.

Figure 4. Left part: Spin-dipole excited states observed in the $^{40}\text{Ca}({}^{3}\text{He},t)^{40}\text{Sc}$ reaction at $\Theta = 2.5^\circ$. 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 $^{40}\text{Ca}$ are marked. Right part: Part of the level scheme of $^{40}\text{Ca}$ showing only the $0^+$ levels, the level density of the $0^+$-states and the shell model prediction for the multiparticle-multihole configurations [19].

Such low-lying $0^+$ states in $^{40}\text{Ca}$ can also be considered as parts of the Giant Monopole Resonance (GMR). The GMR was investigated by Yangblood et al., [17] and indeed observed a bump around 10 MeV, although the centroid of the GMR was found to be at 19 MeV.
We expect also coupling of the $2^-$ state to the GMR. The high energy dipole strength distribution was investigated by Gaarde et al. [18] in the $^{40}\text{Ca}(p,n)$ 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.,[19] the energy of the 4, 6 and 8 particle-hole states is also shown in Fig. 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 $^{40}\text{K}$ excited in the $^{40}\text{Ca}(n,p)$ reaction. For the N=Z $^{40}\text{Ca}$ nucleus the sum rule for the $\beta^-$ and $\beta^+$ strengths reduces to $S^-_{\text{SDR}} = S^+_{\text{SDR}}$ [20]. So the cross section of the $^{40}\text{Ca}(p,n)$ and the $^{40}\text{Ca}(n,p)$ reactions should be the same. For isospin symmetry considerations one expects the same strengths distribution as well for the (p,n) and (n,p) type reactions.

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.,[21], 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 GDR.

Acknowledgments

The authors acknowledge the RCNP cyclotron staff for their support during the course of the present experiment. This work has been supported by the Hungarian OTKA Foundation No. K72566 and by the Helmholtz Alliance EMMI.

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