ACTA PHYSICA DEBRECINA XLVII, 185 (2013)

(^{3}HE,T) REACTIONS ON ^{40}CA NUCLEUS, INVESTIGATION OF SOFT SDR RESONANCES

L. Stuhl[1], A. Krasznahorkay[1], M. Csatlós[1], T. Adachi[2], H. Fujita[2,3], Y. Fujita[2,3], A. Algora[1,4], J. Gulyás[1], J. Daeven[5,6,7], E. Estevez-Aguado[4], C. J. Guess[5,6,7], K. Hatanaka[2], K. Hirota[2], D. Ishikawa[2], E. Litvinova[8,9], T. Marketin[8,10], H. Matsubara[2], R. Meharchand[5,6,7], F. Molina[4], H. Okamura[2], H.J. Ong[2] G. Perdikakis[5,6,7], B. Rubio[4], C. Scholl[11], T. Suzuki[2], G. Susoy[12], A. Tamii[2], J. Thies[13], R. Zegers[5,6,7], J. Zenihiro[2]

[1] ATOMKI, Institute for Nuclear Research, Hung. Acad. of Sci., Hungary,
[2] Research Center for Nuclear Physics (RCNP), Osaka University, Osaka, Japan
[3] Department of Physics, Osaka University, Osaka, Japan
[4] Inst. de Fisica Corpuscular, CSICâĂŞUnivers. de Valencia, Valencia, Spain
[5] National Supercond. Cyclotron Lab., Michigan State Univ., Michigan, USA
[6] Joint Institute for Nuclear Astrophysics, Michigan State Univ., Michigan, USA
[7] Department of Physics and Astronomy, Michigan State Univ., Michigan, USA
[8] GSI Helmholtzzentrum fÃijr Schwerionenforschung, Darmstadt, Germany
[9] Inst. für Theor. Phys., Goethe Univ. Frankfurt am Main, Germany
[10] Physics Department, University of Zagreb, 10000 Zagreb, Croatia
[11] Institut für Kernphysik, Universität zu Köln, 50937 Köln, Germany
[12] Department of Physics, Istanbul University, Istanbul 34134, Turkey
[13] Institut für Kernphysik, Universität Münster, 48149 Münster, Germany

Abstract

Experimental data from 40Ca(3He, t)40Sc charge exchange reaction at 420 MeV beam energy are presented. The achieved 15 keV energy resolution with the information of angular distribution allowed extraction of dipole strenght in 40Sc isotope below 15 MeV excitation energy. Detailed informations for Due to detailed information many individual excited levels were identified. We have found 89 new excited levels out of the 106 ones observed in the ^{40}Sc. 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.

I. Introduction

It was realized already by A. Bohr [1], who discussed the general properties expected for a full (nn, pp and np) component 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. These ideas were further developed by Bés and Broglia and culminated in an article [2], where a detailed analysis of isovector pairing vibrations is presented.

Studies involving isospin effects have undergone a resurgence in recent years as such when similar nuclei become more readily accessible. Moreover, in case of 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., [3] presented an experimental analysis of the pairing vibrations around Ni with emphasis on odd-odd nuclei. These results clearly indicate a collective behavior of the isovector pairing vibrations. The $\hbar\omega$ of such vibrations is estimated to be 0.8 MeV [3] for ^{40}Ca. Cedervall et al., [4] obtained evidence for a spin-aligned neutron-proton paired phase from the level structure of Pd. The possibility of mixed-spin pairing correlations in heavy nuclei was also discussed by Gezerlis et al., [5].

The aim of this work was is to study the fragmentation of the dipole strengths into low-lying excited states in the Sc isotopes. 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 and the method of the analyzis was published recently [6].

The ^{40}Ca(^{3}He,t)^{40}Sc reaction has been studied earlier by Schulz et al., [7] at 28 MeV bombarding energy and by Loiseaux et al., [8] 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 (π1f7/2)(ν1d3/2), (π1p3/2)(ν1d3/2) and (π1f7/2)(ν2s1/2) proton-neutron multiplet states are identified and the effect of configuration mixing is discussed. A similar experiment has been performed by Hansper et al., [9] at 26.1 MeV, using a magnetic spectrometer with an energy resolution of 15 keV. Accordance 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 spin-isospin excitation has been investigated earlier by Tabor et al., [10] in the ^{40}Ca(^{3}He,t)^{40}Sc reaction at 130 and 170 MeV. The angular distribution was measured for to investigate 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, the 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 a summary of a simple proportionality between the cross sections and the dipole strength values.

During the last few years much interest has been devoted to the experimental investigation of electric dipole strength distribution, in connection with the neutron-skin thickness [11] and with the so-called Pygmy Dipole Resonance (PDR) in eveneven nuclei. In a macroscopic picture this resonance is described as an out-of-phase oscillation of a neutron-skin against an inert core. Therefore, properties such as integrated strength and mean excitation energy of the PDR should strongly depend on the N=Z ratio.

The microscopic nature of the pygmy dipole resonance in the stable Ca isotopes has been investigated for the first time by Hartmann et al. [12], in high resolution photon scattering experiments for the first time. So far, no high resolution studies have not been performed, however, for the dipole strengths distribution excited in charge exchange reactions.

II. Experiment

The experiment was performed at the Research Center for Nuclear Physics (RCNP) at Osaka University in Japan. The ^{3}He 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 beam was achromatically transported to the self supporting metallic ^{40}Ca target. The properties of the target can be found in Table I. The typical beam current was 25 nA.

Target	^{40}Ca
Thickness (mg/cm)	1.63
Enrichment	99.97 (0.4)
	0.007 (1) ^{4} Ca
	0.002 (1) ^{43}Ca
	0.016 (1) ^{44}Ca
	$<$0.001 ^{4} Ca

Table 1: The properties of the ^{40}Ca target

The energy of tritons was measured with a magnetic spectrometer using complete dispersion matching technique [13]. The realization of the matching parameters was examined by using the "faint beam method" [14]. Outgoing tritons were momentum analyzed by momentum in the Grand Raiden Spectrometer (GRS) [15] at two different angle positions: 0° and 2.5° with an opening angle of ± 20 mrad horizontally and ± 40 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.

III. Analysis

We analyzed the spectra using the program package: Gaspan, which was developed for the evaluation analysis of gamma- and particle-spectra. We could fit for the given energy range many peaks in the given energy range at the same time. The peaks were fitted with Gaussians line shape with exponential tails and second order polynomials were used in second order for to describinge the background. The excitation energies of the isobar analog state and 10 well known excited states were used for determining the precise energy calibration. The applied energy values are shown in Table 2.

Energy (keV)	ΔE	J$^\pi$
772.1	1.6	(2$^-$)
1670.7	1.9	(1, 2)$^-$
3790	9	1
3900	100	(1,2)$^-$
4368	8	0
4658	11	1
5574	40	1
6426	60	1
9000		(0,1,2)$^-$

Table 2: The well known excited states in ^{40}Ca used for calibration.

In order to distinguish separate the different transitions, the experimental spectra were studied in eight angular regions: 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 relative intensities are also determined for the all different angular bins too. The angular distributions were determined for each of the known levels, and also for the new peaks. They were normalized to the corresponding opening angles, which were determined by the experimental data setup.

We obtained the angular distributions, first of all firstly for the peaks , which have well known spin and parity were well known in the literature. According to their characteristic angular distributions three different groups can be recognized. In order to deduce the spin and parity, an A$_n$ parameter was introduced, which is the ratio of the intensity ratio the of first region divided by the average of intensity of the 3rd and 4th region. To determine the threshold of A$_n$, the distribution of the parameter was investigated. We obtained two distinct groups, for J$^\pi$ = 1 , 3 and for J$^\pi$ = 0$^-$,1$^-$,2$^-$. The angular distributions of the newly identified levels are very similar to those levels having the same multipolarity known from the literature [16].

The angular distributions were determined for each new peaks. Due to the excellent energy resolution of around 15 keV, the spectra contains highly detailed information, which allows the identification of many individual levels up to about 16 MeV excitation. The lowest lying states in ^{40}Sc are identified as members of the $\pi 1 \qquad \nu 1_{3}^{\;\;-}$ $(J^{\pi} = 2^{-} \quad 5^{-})$ 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 where the spins of the proton and the neutron hole is are parallel. The isospin of such state is T=1 and T =-1.

We have found 89 new excited levels out of the 106 ones observed in the ^{40}Sc. We reproduced in 40 cases the values of the well-known excited levels in 40 cases and determined 79 new ΔL 1 states. Their energies were deduced with a the precision of 10-25 keV. Tables below show the energies of levels and the intensities of the newly identified ΔL 1 levels.

Acknowledgments

This research was supported by the European Union and the State of Hungary, co-financed by the European Social Fund in the framework of the TÁMOP 4.2.4.A/2-11-1-2012-0001 National Excellence Program (Nemzeti Kiválóság Program Hazai hallgatói, illetve kutatói személyi támogatást biztosító rendszer).

This work was also supported by the Hungarian OTKA Foundation No. K 106035.

References

[1] A. Bohr, B.R. Mottelsson, *Nuclear Structure, Vol. 2* Benjamin-New York, p 645 1969

[2] D.R. Bes et al., Phys. Rep. C **34**, 1 (1977)

[3] A.O. Macchiavelly et al.,Phys. Lett. B **480**, 1 (2000)

[4] B. Cederwall et al.,Nature **469**, 68 (2011)

[5] A. Gezelris, G.F. Bertsch, Y.L. Luo, Phys. Rev. Lett. **106**, 252502 (2011)

[6] L. Stuhl et al., Acta Physica Polonica B **42**, 667 (2011)

[7] N. Schulz W.P. Alford, A. Jamshidi Nucl. Phys. A **162**, 349 (1971)

[8] J.-M. Loiseaux et al.,Phys. Rev. C **4**, 1219 (1971)

[9] V.Y. Hansper et al.,Phys. Rev. C **61**, 028801 (2000)

[10] S.L. Tabor et al., Phys. Rev. C **25**, 1253 (1982)

[11] A. Krasznahorkay et al., Phys. Rev. Lett. **82**, 3216 (1999)

[12] T. Hartmann et al., Phys. Rev. Lett. **93**, 192501 (2004)

[13] H. Fujita et al., Nucl. Instrum. Methods A **484**, 17 (2002)

[14] Y. Fujita et al., J. Mass Spectrom.Soc. Jpn. **48**, 306 (2000)

[15] M. Fujiwara et al., Nucl. Instr. Meth. Phys. Res. A **422**, 484 (1999)

[16] E.-W. Grewe et al., Phys. Rev. C. **76**, 054307 (2007)

Table 3: Newly identified L 1 and for the calibration used states in ^{40}Sc

E	ΔE	E $_t$	ΔE $_t$	J$^\pi$ $_t$	Int	ΔInt.
772.1	9	772.1	1.6	2^-	54280	1282
836.5	10				583	67
863	12				266	42
894.7	10	893.5	2	(-)	10	2
1113.6	10				23	8
1345.3	10				144	31
1546.8	9				17	4
1604	11				2140	190
1672.6	9	1670.7	1.9	1^-,2^-	8610	237
1699.9	9	1703.2	2.2		9920	237
1802.1	9	1797	2.4	(3^-)	189	50
1926.8	9	1933	3		982	57
2116	11				106	25
2155.9	10				432	75
2179.5	9				8367	522
2230	12				207	47
2338	11				323	39
2375.3	9	2370	4	(4^-)	1882	84
2609	15				2	10
2890.6	9				17	57
2925	10	2940	12	1	427	94
3134	13	3144	17	1	2195	180
3179	11				252	49
3248.7	9				0	0
3289.6	10				43	23
3336.6	9				816	185
3359	11				902	186
3536.7	10				1232	163
3615	11				433	91
3676.7	10				623	102
3710.5	10				2714	170
3873.2	10	3864	41		1890	251
3890.8	10	3900	10	1^-,2^-	7570	669
3999.2	10				1109	150
4066.4	9				11620	476

Table 4: Newly identified L 1 and for the calibration used states in ^{40}Sc

E	ΔE	E$_t$	ΔE$_t$	J$^\pi{}_t$	Int	ΔInt.
4149.6	10	4132	20	1	410	130
4208.1	9				269	81
4368.4	9	4368	8	0	1480	225
4398.7	10				19680	525
4462	13				2736	222
4509	12				550	214
4665.4	10	4658	11	1	1400	914
4688.6	10				4890	965
4838.2	10				1546	130
4882.4	10				1325	130
4994	11				3892	183
5074	11				1043	101
5256.7	10				3161	171
5438	11				2019	342
5523	11				1168	103
5589.2	9	5574	40	1	470	191
5653	10				5210	490
5819.9	10				4180	373
5874	11				4585	360
5938	11				702	316
5979	11				360	314
6135	11				1264	266
6246.4	10				2840	626
6279.1	10				1920	843
6339.6	10				1376	179
6402.4	10				1587	191
6455.8	10	6426	60	1	383	196
6497.6	11				805	217
6710	16				1605	178
6877	18				646	245
6991	16				2305	171
7208	19				1865	209
7261	16				1746	165
7309	16				2602	187
7413	16				1610	140

Table 5: Newly identified L 1 and for the calibration used states in ^{40}Sc

E	ΔE	E_t	ΔE_t	J^π_t	Int	ΔInt.
7560	15				1840	166
7621	15				3990	277
7663	14				4780	1034
7829	14				3150	1042
7987	14				5300	1200
8053	15				3020	566
8111	14				3730	537
8194	15				4160	706
8351	16				2010	704
8496	15				3710	752
8548	15				2180	407
8626	16				3020	553
8768	22				730	700
8831	22				0	0
8988	25	9000	30		2360	502
9249	22				2430	581
9314	21				3320	701
9378	21				3600	702
9440	21				4010	833
9553	22				2530	551
9611	21				2900	611
9735	22				3160	755
9965	24				2740	532
10100	20				3850	702
10427	19				3510	675
10506	20				2220	780
10661	17					
10860	14				880	230
11211	15				960	180
11541	13				398	205
12479	12				464	102
12077	24				150	100
13049	23					
13039	23					
14965	23					
15674	24					