NEUTRON RICH NUCLEI STUDIED WITH THE (^{14}C,^{16}O) REACTION

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Abstract

Measurements of the masses and excited state energies of neutron rich nuclei ^{62}Fe, ^{68}Ni, ^{74}Zn and ^{80}Ge have been performed with the (^{14}C,^{16}O) reaction. The masses are compared with the Myers and Garvey-Felson predicted values. The position of the first 2^+ state is reviewed for the even-even isotopes of the four elements.

The acceleration of ^{14}C beams opens new perspectives in nuclear spectroscopy. The (^{14}C,^{16}O) reaction, a two proton pick-up process kinematically favored for its positive Q value, provides an adequate tool for studying proton pair correlations[1]. On neutron-rich targets, this pick-up leads to residual nuclei with still larger neutron excess. The (^{18}O,^{20}Ne) reaction has already been investigated as an alternative to the obviously difficult (n,^{3}He) reaction but the low lying states of ^{20}Ne are strongly populated and they obscure the residual nuclei spectra. Moreover those low-lying states in ^{20}Ne as well as the ones in ^{18}O are strongly coupled to the ground-states introducing coupled-channel effects. The (^{14}C,^{16}O) reaction does not suffer from those two inconveniences.

In this contribution we shall report on two proton pick-up on the most neutron rich isotopes ^{64}Ni, ^{70}Zn, ^{76}Ge and ^{82}Se. With their large neutron excess - N-Z from 8 to 14 - these target nuclei lie isolated from the main part of the valley of stability. Due to the slope of this ridge $\Delta Z/\Delta N = 1/2$ in the (Z,N) diagram, the two-proton pick-up reaction leads to residual nuclei four neutron heavier than its last stable isotope. Such nuclei is out of the range for practical neutron stripping. Further more the final nuclei lie in a region of the chart of the nucleides far from the alkalies and not yet investigated by fission fragments spectroscopy.

EXPERIMENTAL SET-UP

The set-up (fig 1) was already described elsewhere. The ray tracing [2] at the exit of the magnet is performed within an angular aperture of 5° lab. and with a 0.2° accuracy. The overall solid angle is 5 msr. The ion identification is unambignously achieved with a ΔE_1,ΔE_2, E ionisation chamber [3].

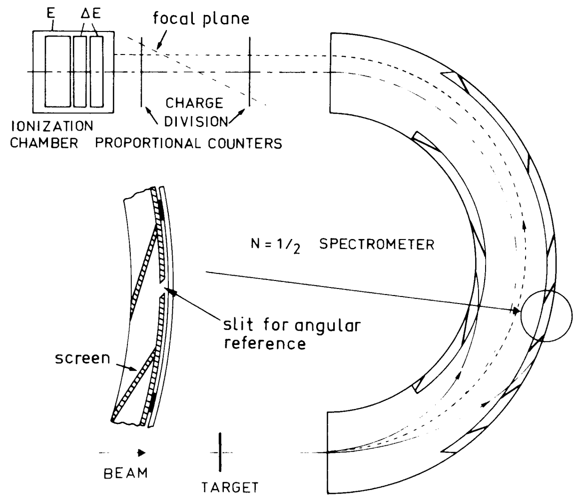

Fig. 1 - Experimental set-up

A new device has been added in order to perform measurements at very small angles including 0°. The magnet vacuum chamber is equiped with two isolated systems of beam catchers and screens designed to eliminate background effects in the focal space. This system also provides a measurement of the beam intensity. In the experiment the ratio of the average magnetic rigidity of the analysed particles to the magnetic rigidity of the most abondant charge state of the incident beam was ~ 0.76 and with optimized beam transport adjustements, we did not observe any significant increment of the background in the focal space, when the analyser was set at 0°.

The targets were made of isotopically enriched elements evaporated on 20 $\mu g/cm^2$ thick ^{12}C backing and the Se target deposit was covered with a 10 $\mu g/cm^2$ layer of carbon. The ^{70}Zn targets were separated from enriched element at the CSNSM separator and collected on a 30 $\mu g/cm^2$ ^{12}C backing. The target thicknesses lie from 50 $\mu g/cm^2$ for ^{80}Se to 130 $\mu g/cm^2$ for ^{70}Zn.

RESULTS

a) spectra

The ^{16}O energy-spectra corrected for the kinematical effects are shown in fig.2 Wide peaks are observed for ^{16}O and ^{12}C contaminants, whose kinematical factors are

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larger than the heavy target ones. For all the targets, the ground state is the most excited level as expected, since on the neutron rich-nuclei, the energy-matching occurs for negative excitation energy around E_x=-10MeV[4]. Excited states are observed for the first time in ^{62}Fe and ^{74}Zn spectra, however.

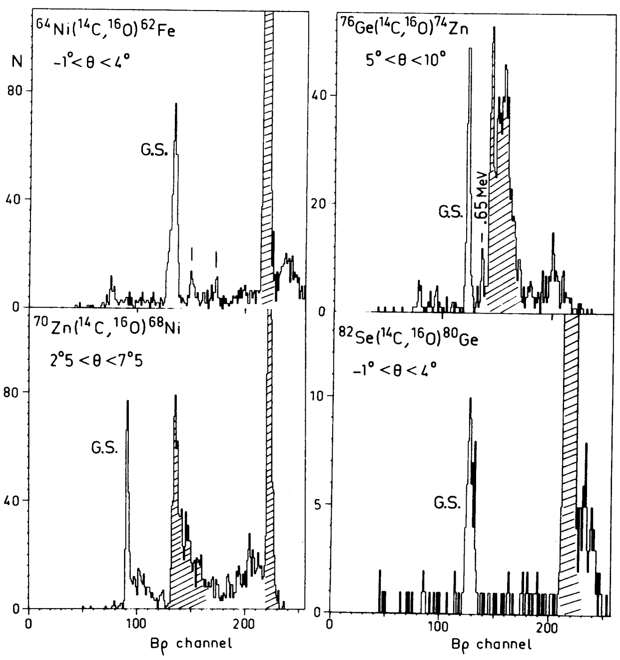

Fig. 2 - Bρ spectra measured for the exotic nuclei.

The unknown masses and excitation energies are determined using a calibration based on the (^{14}C, ^{16}O) reaction itself, measured on ^{62}Ni and ^{74}Ge targets and on the ^{16}O and ^{12}C contaminants at different angles. The three-parameters calibration curve Bρ /F = f (F) where F is the frequency of the magnetic resonance set in the spectrometer is fitted by a least square method. The larger deviation between the curve and the reference points (there are 9 of them) is $\frac{\Delta B\rho}{B\rho} \sim 10^{-4}$ which corresponds to an uncertainty of 20 keV in the mass measurement. The other sources of error are the channel determination connected with the statistics in the peak, the target thickness (~ 10 keV) and the magnetic field stability (~ 10 keV).

For ^{62}Fe and ^{68}Ni, the present measurements have been combined with previous results[5] reducing the final error bars.

b) <u>angular distributions</u>

The angular distributions have been plotted for the observed levels between 0° and 13° C.M. (fig. 3).

Since the transfer takes place at the surface of the nucleus we observe a diffraction pattern, generated by the bright ring of nuclear surface oriented perpendicular to the incident beam. As in optics, there is a concentration of intensity in a very forward angular range. The first minimum is given by that for the function Jo (Rθ/ƛ) which takes place at very small angles for heavy ion projectiles of low energy . The concentration of the cross-section is observed to be more effective for a ΔL= 0 transition. It can be

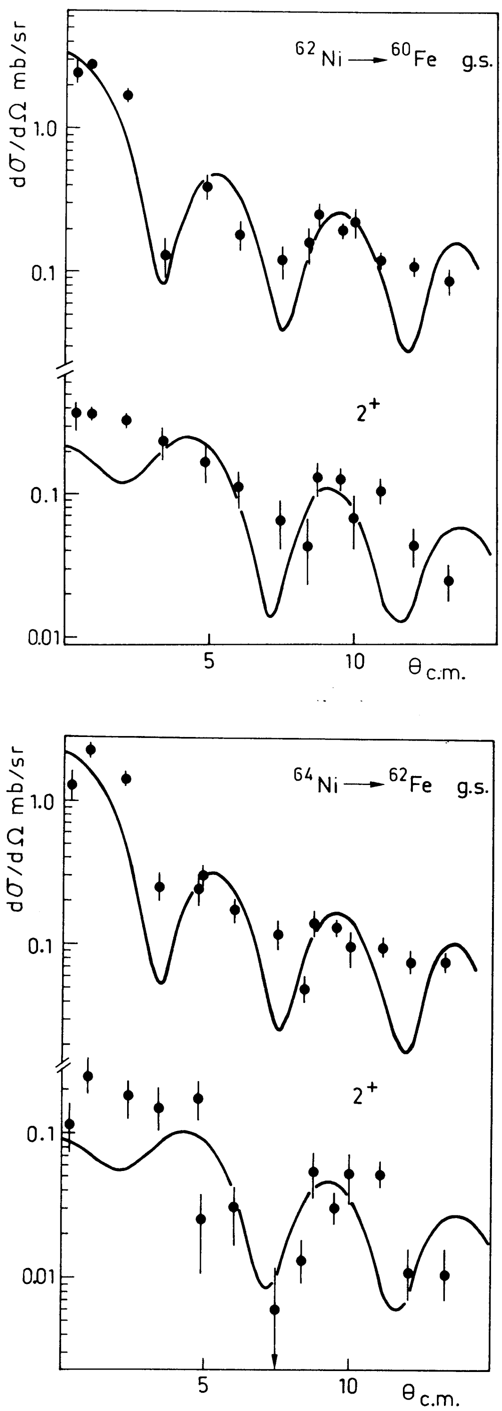

Fig. 3 - Angular distributions for ^{60}Fe - reference nuclei - and for ^{62}Fe with the results of the DWBA

understood in the framework of the DWBA approximation where $\frac{d\sigma}{d\Omega}$ is written as

$$\sum_M |T^M_J|^2 \quad (i)$$

; where $J = \Delta L$ is the transferred angular momentum, equal to the spin of the final level here and

$$T^M_J(\theta) = (-1)^M \sum_{L_iL_f} \langle \quad | \quad \rangle P^M_{L_f}(\theta) I^J_{L_iL_f} \quad (ii)$$

Since for $L = 0$ the sum (i) reduces to the T^0_0 term containing very few terms $P^0_{L_f=L_i}$ (ii) (as the entrance L_i window is narrow), the diffraction shape is observed very clearly. But for $\Delta L \neq 0$, the window is broadened ($L_f = L_i \pm \Delta L$). Furthermore, when increases, the other magnetic substates ($M \neq 0$) enter in expression ii) and i) and smear out of the diffractive pattern. This makes the small angular range very significant for heavy ion transfers.

The caracteristic shape of the $L = 0$ angular distribution is used for spin assignement. On the basis of a comparison between the angular distribution of ^{60}Fe and ^{62}Fe (fig 3) the spin value of 0 can be eliminated for the first ^{62}Fe excited state. A similar argument is applicable for the 2nd excited state of ^{62}Fe and the excited state of ^{74}Zn. All those states are very likely to be 2^+ states.

In ^{68}Ni an excited states was reported previously with poor statistics[4]. In this experiment using a separated Zn target, this state is hardly visible because of the inhomogeneity of the target.

DWBA calculations have been performed with the Saturn-Mars code using the optical potentials of ref. 1. Within the restrictive assumption of a cluster form factor the fits allow one to extract the product of spectroscopic factors $CS_1{}^2 CS_2{}^2$. The results are very similar (table 1) although slowly increasing with the number of proton-pairs available in the f - p shell (except for the ^{70}Zn to ^{68}Ni transition). A systematic analysis of those spectroscopic factors will be published later.

(Final) Nuclei	Qo MeV	Spin	Ex MeV	$d\sigma . d\Omega^{-1}$ mb.sr^{-1} θ=5°	$CS_1{}^2\ CS_2{}^2$
^{60}Fe	+ 2.46	0^+	0	0.200	0.19
		2^+	0.84	0.093	0.18
^{62}Fe	- 0.48	0^+	0	0.137	0.26
		2^+	0.86	0.032	0.19
^{68}Ni	+ 1.85	0^+	0	0.120	0.16
^{72}Zn	+ 2.47	0^+	0	0.248	0.33
		2^+	0.69	0.116	0.64
		2^+	1.68	0.042	
^{74}Zn	+ 0.22	0^+	0	0.102	0.33
		2^+	0.65		
^{80}Ge	- 0.40	0^+		0.116	0.66

Table I

c) the masses

The masses of the residual nuclei are calculated with the conservation laws applied to a two-body reaction. They are shown in table II with the results of previous measurements [6,7,8]. Except for the mass of ^{62}Fe from ref 8 for which the uncertainties may have been optimistically estimated. They are compatible with the previous values. The ^{62}Fe and ^{68}Ni spectra were measured with (^{18}O,^{20}Ne) pick-up reaction. The nuclei of ^{74}Zn and ^{80}Ge are observed unambiguously for the first time and the error bar on their masses is clearly reduced.

In table II are the values predicted by the liquid drop model of Myers[11] and the values calculated with the Garvey-Kelson[12] formula. Those last values are in excellent agreement with our results.

On fig. 4, we have plotted the differences between the calculated and measured

Nuclei	$T = \frac{N-Z}{2}$	Previous Measurements (MeV)	This work (MeV)	Predictions (MeV) Myers	Garvey-Kelson Formula
^{62}Fe	5	58.87 ± 0.20 [6] 58.93 ± 0.05 [7] 58.94 ± 0.02 [8]	58.83 ± 0.04	59.10	59.20
^{68}Ni	6	63.47 ± 0.03 [8]	63.53 ± 0.03	64.78	63.78
^{74}Zn	7	65.67 ± 0.14 [9]	65.57 ± 0.04	67.48	65.43
^{80}Ge	8	69.43 ± 0.310 [10]	69.38 ± 0.06	71.40	69.66

Table II

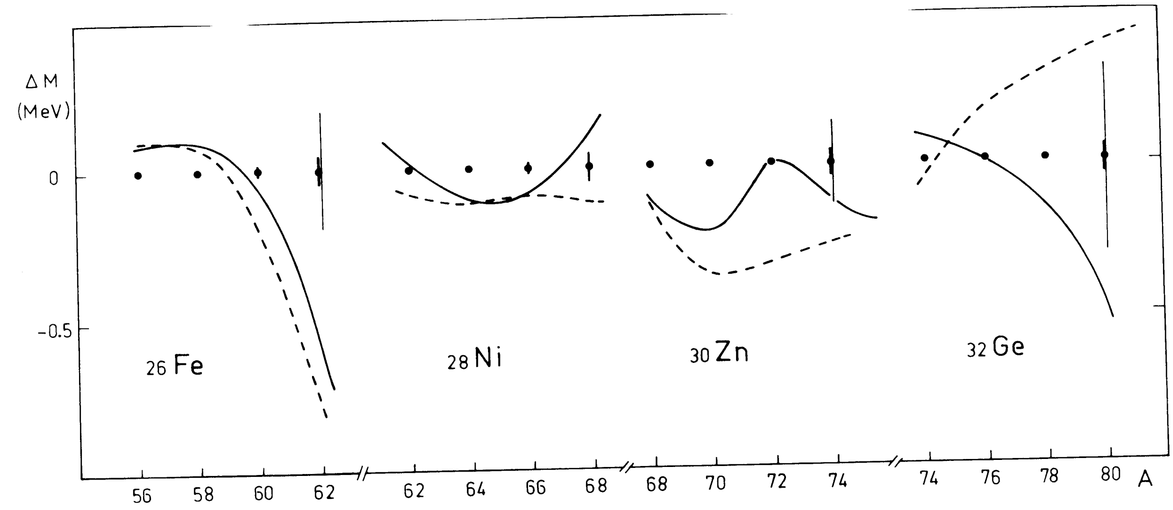

Fig. 4 - Differences between the calculated masses and the measured masses for the even isotopes of the four elements. The previous errorbars are shown with a thin line and the present errorbars with a thick line. The full line refers to the values of Janecke Garvey-Kelson and the dotted line to the ones of Liran-Zeldes[11)]

masses versus the atomic number A. It is interesting to note that those differences are small and nearly constant for the full f 7/2 proton shell Ni and for Zn isotopes. They increase with the distance to the bottom of the stability valley with negative sign for Fe and symetrically for Ge isotopes.

In Myers model the shell corrections are included explicitely but Garvey-Kelson are not specially accounting for shell closure in their extrapolations and the optimum agreement obtained for Z = 28 may result from compensating terms on each side of the shell closure.

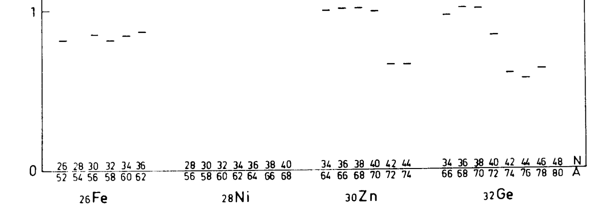

Fig. 5 - First 2^+ excitation energy shown as a funct on of A, the atomic number.

d) the 2^+ states and the shape of the nuclei

A simplified picture of the collectivity of even-even nuclei is given by the 2^+ excitation energy. Wether one has vibrations or rotations, a lower energy indicates a softer nuclei or one with a greater permanent deformation.

It is worth to combine the systematic survey of the 2^+ measured excitation energy (fig. 5) with the results of the collective Hartree-Fock Bogoliubov calculations, obtained by Girod[13)] with the D1 interaction of Gogny[14)] shown on fig. 6. The Ni isotopes are found to be soft except the ^{68}Ni

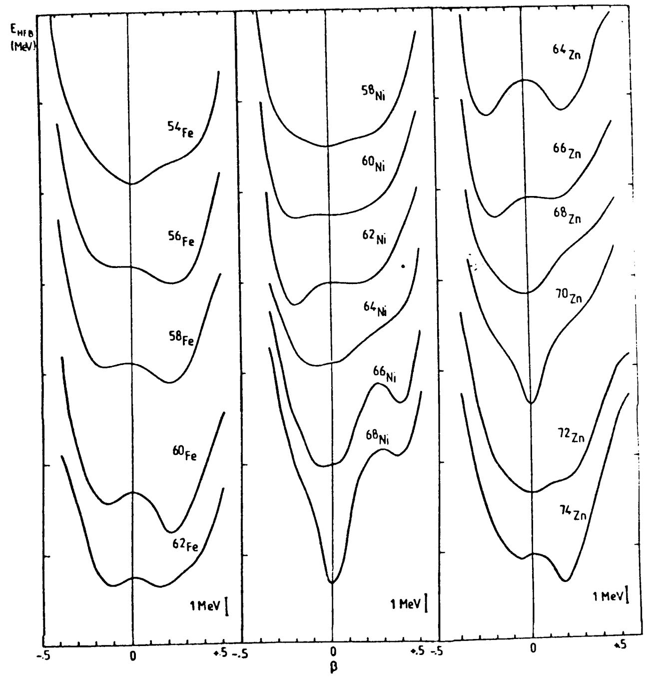

Fig. 6- Results of Hartree-Fock Bogoliubov calculations

nuclei for which ,with 40 neutrons,a defined rigidity occurs. With the same number of neutrons,the ^{70}Zn also happens to be rigid. On fig.5 there is an indication for a change in the deformation when N increases from 38 to 42 compatible with the H.F.B. results. In the Ge isotopes a similar change has been reported for this neutron number both experimentally (fig.5 and ref.15) and in H.F. calculations [16].

The Fe isotopes are all calculated to be soft,although the 2^+ excitation energy of the ^{56}Fe (N=28) isotope is larger than in the other isotopes .

A more detailed analysis of those results is under process.

SUMMARY

We have studied the (^{14}C,^{16}O) reaction on a few neutron rich targets of the f-p shell in order to measure masses and spectra of very neutron rich nuclei.

The analyse of the forward angular distributions have provided indications on the spin of the final levels.

The measured masses have been compared to different predictions.The location of the first 2^+ has been discussed in connection with the H.F.B.results.

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DISCUSSION

J.C. Hill: What is your estimate of typical cross-sections for the (^{14}C,^{16}O) and (^{14}C,^{15}O) reactions in this mass region?

M. Bernas: For (^{14}C,^{16}O) forward angular cross-sections we found a few $mbsr^{-1}$. For the (^{14}C,^{15}O) (one charge exchange) a reduction by a factor of 5 may be expected, but it depends on the total Q value of the considered reaction.

P. Armbruster: Are there HF-calculations available in the mass region (Z=28, N=40) and do they indicate the onset of deformation your measurements indicate?

M. Bernas: On the last figure are shown results of calculations HFB performed with D1 force. A shape transition may be indicated for Zn isotopes on each side of N=40. One may note that those nuclei are all soft nuclei except ^{68}Ni and ^{70}Zn, for which the orbitals may be more apart as their deformation looks smaller and their shape more defined. It could explain why this overlap of their wavefunction is shown to be smaller (Table 1).

O.W.B. Schult: Do you have an idea about the cross-section of a reaction where you effectively remove four protons from the target like e.g. in a (^{14}C, ^{18}Ne) process?

M. Bernas: The worst situation is a reduction by a factor of 10 for each extra proton pick-up, but it could be tried first in the stability valley.