сообщения
объединенного
института
ядерных
исследований
дубна

E7-89-72

β-DELAYED NEUTRON EMISSION OF THE ISOTOPES ^{20}C, ^{40,41,42}P, ^{43,44}S

1989

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1. Introduction

A recent experiment at GANIL has shown [1] that the reaction of an intermediate-energy ^{48}Ca beam provides a very efficient tool for the production of neutron-rich nuclei. The counting rates for a number of isotopes far from stability in the range from fluorine to argon were found to be high enough to start the investigation of the main properties of nuclei which were not studied before.

In several previous experiments [2,3] at the LISE spectrometer [4] the observation of β-delayed neutrons has been successfully used as a method for measurements of the β half-life $T_{1/2}$ and the neutron emission probability P_n for very neutron-rich nuclei. Applying this method to the products of the fragmentation of a ^{48}Ca beam should then give the opportunity to extend the previous studies to more neutron-rich isotopes and to heavier elements. The possible investigation of the isotope ^{44}S, was particularly interesting due to its importance in stellar nucleosynthesis [5].

In this paper the first measurements of $T_{1/2}$ and P_n values for the isotopes ^{20}C,^{40,41,42}P and ^{43,44}S are presented. Additionally, the cases of ^{17}B , ^{18}C and ^{35}Al are reexamined. These nuclei were produced in the interaction of a 55 MeV/n ^{48}Ca beam with a ^{181}Ta target.

2.Experimental technique

In the present experiment essentially the same set-up was used as described in [2]. Therefore, only the main features of this system will be recalled.

The separation and identification of heavy-ion reaction products were provided by means of the magnetic analysis in the doubly achromatic spectrometer LISE combined with ΔExE and time-of-flight measurements. The fragments were implanted in a four-stage solid-state detector telescope (0.3 mm , 0.3 mm , 1 mm surface barrier and 5.5 mm Si(Li)). They were surrounded by a tumbler-shaped 3 mm NE102A plastic scintillator for β-ray detection and placed inside a 4Π neutron detector. The latter was composed of three vessels containing a total of 30 litres of NE213 liquid-scintillator.

The isotope under study was identified by the measurement of the time-of-flight through the spectrometer and the energy-loss in either one of the 0.3 mm silicon detectors, and selected by appropriate windows. In such an event the primary cyclotron beam was switched off for a time interval corresponding to the expected β-half-life in order to allow a registration of β-neutron coincidences at low background. Thus, in the subsequent off-line analysis it was possible to correlate β-delayed neutrons to the implanted nucleus.

The measurements were made for two settings of the magnetic rigidity of the LISE spectrometer. The values of $B\rho=3.23$Tm and $B\rho=2.768$Tm corresponded to an optimum transmission of light isotopes with $Z<12$ and of ^{44}S, respectively.

3. Results and discussion

During the off-line data analysis, special care was devoted to the selection of the n-γ discrimination thresholds and the width of the β-neutron coincidence windows. The decay curves for newly investigated isotopes are shown in fig. 1 and the numerical values for $T_{1/2}$ and P_n are given in tables 1 and 2, respectively. The solid lines through the experimental data points in the decay curves correspond to a least-square fitting procedure [2] assuming a single exponential decay component and constant background.

The proper operation of the whole experiment could be checked through the observation of delayed neutrons from the isotope ^{15}B which is a strong emitter (P_n = 100% [6]). The observed half-life of $T_{1/2}$ = 10.4 ms is in perfect accordance with previous measurements [2,6]. Furthermore, the number of observed β-neutron coincidences per implanted ^{15}B provides the efficiency calibration of the detector for the absolute P_n values given in table 2. However, it should be considered that our NE 213 detectors had a neutron-energy threshold of E_n = 350 keV. Thus, this method relies on the assumption that the cut-off portion in the neutron spectra is the same for the investigated decays and for ^{15}B.

The results for the isotopes ^{18}C and ^{35}Al are matching well to our previous experiment [2]. For the case of ^{17}B we also find agreement between the present data and the one of [3] obtained by means of a completely different neutron detection technique. For the other cases, namely ^{20}C, ^{40,41,42}P and ^{43,44}S the present experiment yields first information on the β-decay of these nuclei of which only the existence was known before.

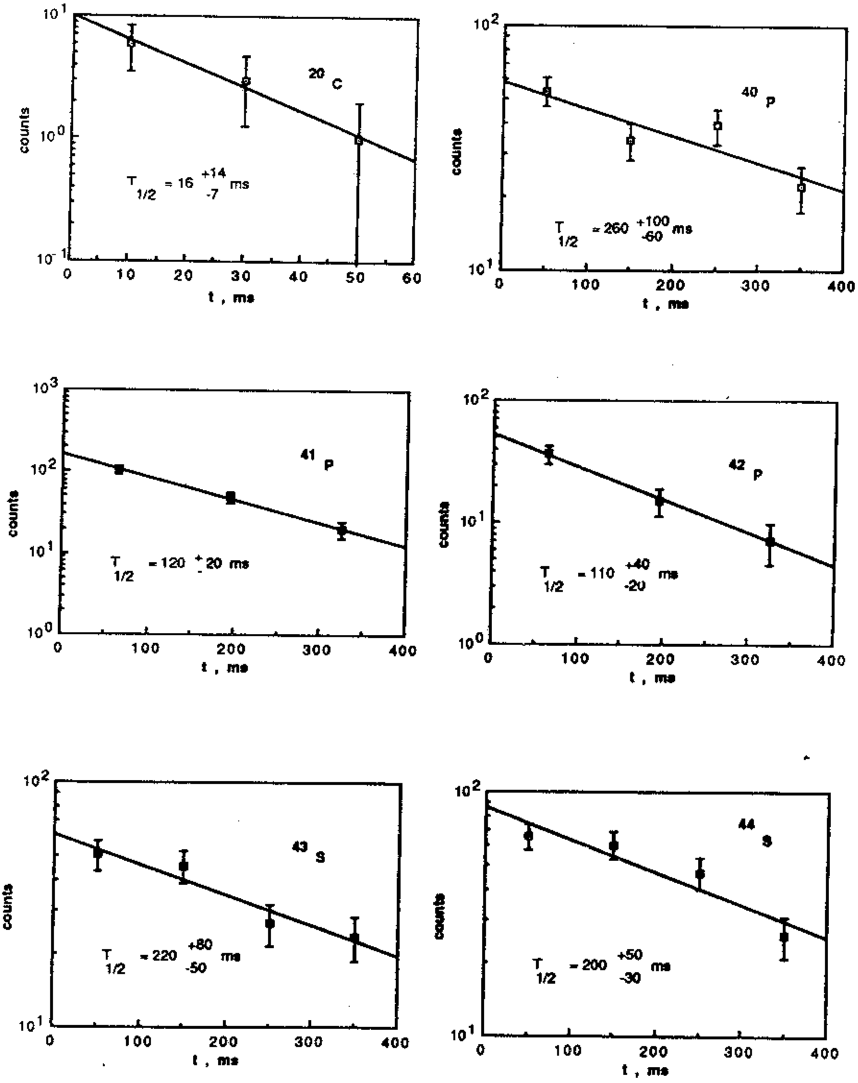


Fig. 1. Experimental decay curves for ^{20}C, $^{40,41,42}P$ and $^{43,44}S$. Constant background is substracted and the solid lines corresponds to a single-component fit.

Table 1: Experimental and theoretical half-lives

^{A}Z	$T_{1/2}$ (ms) exp. values this work	$T_{1/2}$ (ms) exp. values others	a)	b)	c)	d)	e)
^{15}B	$10.3^{+0.6}_{-0.5}$	10.4 ± 0.3 f)	52	24	-	-	-
^{17}B	6 ± 2	5.0 ± 0.5 g)	28	8	-	-	-
^{18}C	78^{+20}_{-15}	66^{+25}_{-15} f)	136	64	124	89	-
^{20}C	16^{+14}_{-7}	-	66	14	9	5.8	-
^{35}Al	170^{+90}_{-50}	130^{+100}_{-25} g)	251	119	33	93	70
^{40}P	260^{+100}_{-60}	-	283	376	17.8	160	23
^{41}P	120 ± 20	-	309	186	26.2	178	21
^{42}P	110^{+40}_{-20}	-	212	102	13.9	162	12
^{43}S	220^{+80}_{-50}	-	549	484	211	741	264
^{44}S	200^{+50}_{-30}	-	493	243	313	351	269

a) gross theory of β-decay by Takahashi [7],

b) improved gross theory by Tachibana et al. [8]

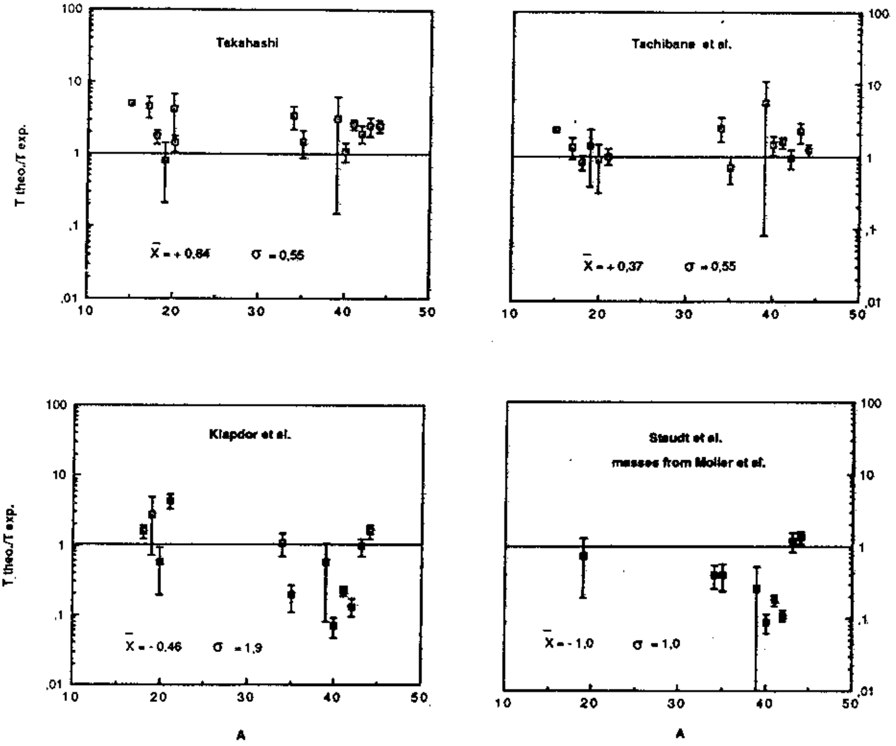
c) microscopic model by Klapdor et al. [9]

d, e) microscopic calculation by Staudt and Klapdor [10] using mass formulas from [11] and [12], respectively

f), g) experimental values taken from [2] and [3], respectively

We have also listed in table 1 the different theoretical predictions which are available. They include the "old" gross theory of β-decay by Takahashi [7], its recent refinement by Tachibana et al. [8] and the microscopic model of Klapdor et al. [9]. Furthermore, results are reported from the new calculation by Staudt and Klapdor [10] which is based on a proton-neutron quasi-particle random-phase approximation [13].

The relative merit of the different predictions for $T_{1/2}$ is shown in fig. 2 where the ratio of theoretical to experimental results is plotted versus the isotopic mass A. $\bar{x}$ denotes the mean value of the logarithm of this ratio and σ its standard deviation. Several features are prominent from this comparison:



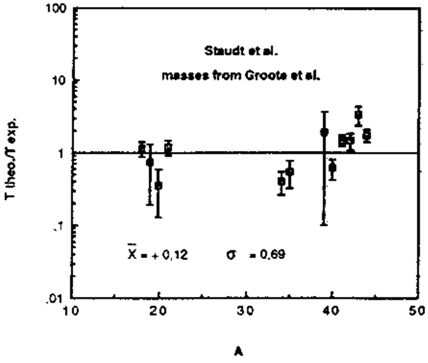


Fig.2 . Ratio of theoretical to experimental β half-lives versus the mass number A. The error bars correspond to (statistical) experimental errors. Additionally to data from the present work experimental half-lives for $^{19,20}N$, ^{34}Al and ^{39}P from [2] are presented. In the calculations by Staudt et al. [10] experimental masses from [14] are taken for ^{19}N and ^{34}Al. The significance of the comparisons is given by $\bar{x}$ and σ defined in the text.

The "old" gross-theory overestimates the experimental half-lifes giving $\bar{x} = +0.84$. This systematic deviation (the standard deviation has the small value of $\sigma = 0.55$) is clearly corrected for in the second-generation calculation by Tachibana et al. without deteriorating the scatter of the individual data points. In this case $\bar{x}$ becomes $\bar{x} = +0.37$ which indicates a remaining tendency for overshooting the experimental data.

On the contrary the microscopic model by Klapdor et al. yields a rather good mean value of $\bar{x} = -0.46$. Here, however, the standard deviation $\sigma = 1.9$ is indicating several large discrepancies to the experimental half-lives, which makes the predictions from this model less reliable.

Table 2: Experimental and theoretical β-delayed neutron emission probabilities

^{A}Z	P_n (%) exp. values this work	P_n (%) exp. values others	P_n(%) theor. values a)
^{15}B	(100) b)	100 c)	75
^{17}B	70 ± 30	85 ± 15 d)	132
^{18}C	50 ± 10	25 ± 4.5 e)	51
^{20}C	50 ± 30	-	73
^{35}Al	40 ± 10	87^{+37}_{-25} e)	63
^{40}P	30 ± 10	-	28
^{41}P	30 ± 10	-	57
^{42}P	50 ± 20	-	44
^{43}S	40 ± 10	-	6
^{44}S	30 ± 10	-	11

a) from [7], b) set by definition (see text), c) from [6],
d) from [3], e) from [2]

The new microscopic calculations by Staudt and Klapdor show an important dependence on the input mass-formula. For the present set of isotopes we obtain $\bar{x} = 0.12$ ($\sigma = 0.69$) and $\bar{x} = -1.0$ ($\sigma = 1.0$) for the v. Groote et al. [11], and Möller and Nix [12] formulas, respectively. The excellent result for the case of the masses from v. Groote et al. suggests that the new model possesses a remarkable predictive power for neutron-rich nuclei far from stability. On the other hand, the use of the Möller and Nix masses apparently leads to a strong underestimation of the experimental half-lives which would be even higher if the two values for $^{43,44}S$ were not lowering the mean deviation. On the contrary, these two isotopes yield the biggest deviation for the calculation using the masses by v. Groote et al. This could point to specific problems in taking correctly into account the $N = 28$ shell closure effects.

One should bear in mind, however, that the above considerations are based on a relatively small number of measurements and that our first experimental results stem from a survey type experiment with relatively low counting statistics. Clearly, the way is now opened for more specific studies of light neutron-rich isotopes, which, at term, should yield a large and more precise data base.

These remarks hold true for the delayed neutron emission probabilities given in table 2. Notwithstanding eventual difficulties due to particular behaviour of the β-strength function of a specific nucleus, and because of the low counting statistics, one observes generally a correct order of magnitude in the gross-theory predictions without an indication for divergence far off stability.

4. Conclusions

The present work was aimed at a first study of basic decay properties of very neutron-rich light nuclei. Isotopes for which only the existence was known up to now were produced as projectile-like fragments from a ^{48}Ca beam. The separation by means of the recoil spectrometer LISE allowed their subsequent study independent of their chemical nature and without limitation in the β-half-life induced by decay loss during the transfer. These two problems which are rather common for ion-source based isotope separators can be considered as being overcome by the present experimental method. The new half-lives indicate, albeit on a still small data base for light nuclei, the reliability of the two new theoretical calculations which approaches the quality of large-scale shell-model predictions. Since both models, i.e. the improved gross theory [8] and the second-generation microscopic model [10], have the ambition (and merit) to provide predictions up to the neutron drip-line, tests still further away from stability are an important challenge for the experimentalist. In this context one may also note the astrophysical importance of nuclear β-decay far from stability [15]. This region is now, for the light nuclei, within experimental reach.

Acknowledgements

We would like to thank A. Staudt for very fruitful discussions. Furthermore we would like to acknowledge F. Geoffroy, A. Latimier and J. Tillier for their technical assistance.

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Received by Publishing Department
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