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Proposal to the ISOLDE Committee

Beta decay study of $n\hbar\omega$ excitations in neutron-rich (fp) nuclei
Test of the empirical nuclear interaction

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Abstract : We propose to study the beta decay of some very neutron-rich isotopes : $^{52-53}$K, $^{34-35}$Al, $^{65-67}$Mn, and identify positive and negative parity states in the Ca, Si and Fe daughter nuclei which are of particular interest in shell-model calculations. Results will allow to determine unambiguously some of the components of the effective interaction which, until now, can strongly diverge between different calculations. For these neutron-rich nuclei, beta decay rates will be established by neutron and gamma spectroscopy. The experimental device will allow β–γ, γ–γ and β-n-γ coincidences with Ge γ counters and neutron detectors optimized for the delayed neutrons specifications.

We ask for a total of 27 shifts for on-line data taking plus 3 additional shifts for beam optimization and calibration.

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I - Introduction

Strong modifications of the shell model potential are predicted near the edge of the neutron drip-line [1]. For nuclei which are attainable with the present production techniques, neutron-skin effects have been observed by interaction cross sections measurements [2]. These skin properties should have only an indirect influence on the level structure and, in first approximation the shell model calculations, very successful in sd, fp and sd-fp nuclei near stability, should allow reliable predictions for very neutron rich nuclei and fail only near the neutron drip line. We want to address this point in more details and in the case of very neutron-rich (sd) and (sd-fp) nuclei, make use of the beta decay process to populate different configurations either with particles in the lowest available shell ($0\hbar\omega$) or with one or more excitations in the upper major shell ($1\hbar\omega$, $2\hbar\omega$...).

We present a plan to study, with the same experimental techniques, selected cases of n-rich nuclei of particular interest, where significant tests of the calculations can be made. With the present production conditions at ISOLDE, three regions of the N, Z plane have been selected on the grounds of nuclear structure effects suitable for the comparison with theory. The corresponding motivations are given in the next section.

II - Physical motivations

II-A. Study of the $^{52\text{-}53}$K → Ca beta decay

Nuclei with $40 < A < 56$, near the stability line, are well described in the framework of the shell model. For these nuclei, the valence particles are mostly f7/2 and the interactions V_{ff} and V_{fr} (with r = f5/2, p3/2, p1/2) can be fixed from previously known data. However, when the number of neutrons increases, the situation becomes more complex which explains why the interaction V_{rr} can be found very disparate with different calculations.

Heavy Ca isotopes, because of the simplicity of the wave-functions, correspond to the optimal choice to fix unambiguously the interaction in this mass region.

The present information on ^{52}K and ^{52}Ca result from a 1985 measurement [3] at ISOLDE/SC. For A=53, only $T_{1/2}$ and P_n were measured at the CERN/PS in 1983 [4]. Since then, detailed shell model calculations of positive and negative parity states have been performed for these nuclei [5,6]. Some of these theoretical results are reported in Fig 1, where the excitation energy of the positive parity states of even calcium isotopes (50<A<56), or of negative parity states of odd isotopes (49<A<55), are represented and compared to experimental values, where available. Two calculations are illustrated, which differ by the choice of the interaction : the calculation by W.A.Richter et al. [5] using a two-body interaction for a truncated fp configuration space (TBLC8), and the calculation by E.Caurier [7] adopting a slightly modified Kuo-Brown interaction (KB3). From Fig.1, it appears that predicted properties are strongly dependent on the choice of the interaction. In particular, we note :

- in odd Ca nuclei, the excitation energy of the lowest negative parity levels differs strongly in the two calculations, with, for exemple an important contribution of the $5/2^-$ shell at low energy in one case, replaced by the $1/2^-$ shell in the other.

- in even-even nuclei, we note correlated gaps resulting from a sub-shell closure occuring for different A values, according to the interaction.

As a consequence, the experimental investigation of neutron-rich K isotopes decays is planned to allow a detailed comparison between calculations and experiments on three points :

II-A-1) The low energy level structure of ^{52}Ca and ^{53}Ca as the level pattern for these two isotopes deviates with the type of interaction used for the calculation. Information given by the decay of ^{52}K and ^{53}K [J^π predicted to be 2^- and $3/2^+$ respectively] will give a constraint for the theory.

It should be noted that these lower states [π=(+) for ^{52}Ca and π=(-) for ^{53}Ca] have opposite parity to the beta parent nucleus. They can only be populated by first-forbidden transitions which, far from stability with increasing beta decay energy, represent a sizeable fraction of the beta strength.

II-A-2) The states of ^{52}Ca and ^{53}Ca above 1hω excitation with the same parity as the parent K isotope. These levels are populated by allowed Gamow-Teller transitions. The strength and location of the GT transitions is important for astrophysical models. A comparison of the experimental results will also be made with shell model calculations involving (sd + fp) configurations. Another component of the nuclear interaction, related to different shells, will then be documented.

II-A-3) The decay properties of ^{53}Ca. The ^{53}Ca → ^{53}Sc decay is unknown, as the ^{53}Sc → ^{53}Ti one. ^{53}Sc (Z=21, N=32) ground state has to be $J^\pi = 7/2^-$ from straightforward shell model considerations while ^{53}Ca (Z=20, N=33) ground state is either $J^\pi=5/2^-$ or $J^\pi=1/2^-$. With the first option, we expect a strong beta transition from ^{53}Ca to ^{53}Sc g.s. which is strongly forbidden with the second option. ^{53}Ca is then an interesting case where low levels properties can discriminate between the values proposed by the theoretical predictions.

II-B. Study of ^{34,35}Si from ^{34,35}Al beta decay

As noted before, theoretical descriptions become more difficult when going away from the stability line. The lack of experimental data in "key" nuclei leads to different plausible interactions. For example, in the region $14 \leq Z \leq 20$, $20 \leq N \leq 28$, we know the individual energies in ^{39}K and ^{41}Ca, but we are left with two fundamental questions : how are evolving single particles (holes) energies, when we add neutrons (N, 20 → 28), or when we subtract protons (Z, 20 → 14). The answers are given by the spectrum of ^{47}K (which is known) and of ^{35}Si (which is unknown). We propose then to study ^{35}Si, in the ^{35}Al → ^{35}Si decay, and to re-investigate the ^{34}Al → ^{34}Si decay in the improved PS/Booster conditions.

The previous study of ^{34}Si at ISOLDE/SC by ^{34}Al beta decay, has provided an interesting example of an even-even nucleus with a strong 2hω contribution in the first 2^+ state at 3328 keV [8]. This result was interpreted as the effect of inversion of excitation energies between 0hω and 2hω states near Z=12, N=20. In a recent experiment at MSU [9] with a ^{34}Si radioactive beam, the location of the 2^+ state has been confirmed and the corresponding B(E2) has been measured [B(E2↑) = 85(33) e^2fm^4]. This value is very low and differs considerably with the result found by Motobayashi et al [10] for the neighbouring N=20, ^{32}Mg, isotone [for ^{32}Mg, B(E2 ↑) = 454(78) e^2fm^4]. The weak B(E2) value for ^{34}Si is interpreted as the result of the poor connection between the 2^+ state, dominated by a large fp-shell intruder component, and the ground state, well described with an sd-shell configuration. In ^{32}Mg, both 0^+ and 2^+ belong to the intruder configuration and the resulting B(E2) value is high.

In ^{34}Si, calculations [9,11] suggest the existence of an excited 0^+_2 state at 2.02 MeV, belonging to the 2ħω configuration and linked to the 2^+_1 state at 3.33 MeV by a large B(E2). The ratio of the B(E2 ↑) values for the excitation of the 2^+_1 state from the two 0^+ states compensates for the ratio of the energy factor, and the branching ratio of the $(2^+_1 \rightarrow 0^+_2)/(2^+_1 \rightarrow 0^+_1)$ should amount to more than 2%. The experimental confirmation of this 0^+_2 level would be an important step for the description of (sd)(0ħω) and (fp)(2ħω) states at N=20.

The study of ^{35}Si (Z=14, N=21), populated by the beta decay of ^{35}Al, will provide a test for the evolution of single particle states far from stability with the location of the lowest $3/2^-$ level (Fig.2). It should be noted that the population of a $3/2^-$ state in ^{35}Si from beta decay of $J^\pi=5/2^+$ ^{35}Al, involves a first forbidden transition; however, this transition should be observable as the beta decay rate is favoured by the large beta energy available ($Q\beta \approx 13.7$ MeV).

II-C. Study of $^{65-67}$Fe from $^{65-67}$Mn beta decay.

The study of neutron rich nuclei around N = 20 has revealed a restricted region ($10 \leq Z \leq 12$, $19 \leq N \leq 21$) of strong deformation, where the ground state corresponds to an intruder (2p2h) state.

A possible analogy can be made between the ^{66}Mn(Z=25, N=41) → ^{66}Fe(Z=26, N=40) decay and the well-known case : ^{32}Na(Z=11, N=21) → ^{32}Mg(Z=12, N=20). In both cases, the final nucleus has a proton number near half-shell value and a neutron number corresponding to a filled shell. The strong contribution of intruder states (2ħω) in ^{32}Mg has been explained in different calculations [13] and is related to the strong interaction between the four (sd) protons and (fp) neutrons. The resulting gain in energy produces the well-known "inversion" of normal and intruder states in the ^{32}Mg low level scheme.

Is a similar situation existing around N = 40 ? What is the situation in ^{66}Fe, ^{64}Cr (equivalent to ^{32}Mg, ^{30}Ne) ? resulting from the interaction between the (f7/2, p3/2) protons and neutrons in upper shells (g9/2, d5/2) ? The lack of reliable experimental data does not allow to answer.

A detailed investigation of the level structure of the Fe isotopes, through the Mn → Fe beta decay, has been made possible very recently at ISOLDE with the UC target and the laser ion source developments[12]. In 1997, the first information on the beta decay of Mn isotopes up to A=68 has been obtained (half-lives measured via delayed neutrons, [14]). These developments allow nuclear spectroscopy in a new portion of the N, Z plane where inversion of 0hω and 2hω states can occur.

A study of the low level structure of ^{66}Fe has to be made in order to search for collective properties, related to [2 particles -2 holes] configurations or evidence for N=40 shell gap. This study should be complemented by the search of intruder states in neighbouring odd-even isotopes : ^{65}Fe and ^{67}Fe, populated by $^{65,\ 67}$Mn beta decay.

It should be noted that the nuclear structure effects in this mass region have to be understood for a safe evaluation of solar systems r-abundances with the high entropy model (J.Witt et al [15] and K. Takahashi et al. [16]) as this is the seed region for the r-process developping out of an α-rich freeze out.

III - Experimental : Production, Detection

III-A. Production

For the experiments involving neutron-rich K and Al isotopes, an UC target will be used, associated with a surface ionization source. Yields at ISOLDE/Booster for direct production of the K isotopes are :

^{51}K	5x 10^3 at/μC
^{52}K	8x 10^2 at/μC
^{53}K	10 at/μC

for ^{52}Ca and ^{53}Ca, we expect in addition of the fraction populated by ^{52,53}K beta decay, a direct production which is favoured by longer half-lives (4.6 s and 90 ms for ^{52}Ca and ^{53}Ca respectively).

For Al production, needed for the studies of Al → Si transitions, a long release time has been observed in the ISOLDE target/ion source usual set-up. But our previous work at ISOLDE/SC with UC targets was in many cases dominated by a fast Al contamination (for exemple with ^{31}Al, $T_{1/2}$ = 644 ms , in our study of ^{31}Na decay [17]). We took advantage of this contamination to study the beta decay of the neutron-rich isotope ^{34}Al ($T_{1/2}$ = 60 ms) at ISOLDE/SC with a yield at the measuring point of 10 at/s[8]. For ^{35}Al , whose half-life is longer by a factor 2 ($T_{1/2} \approx$ 150 ms), we expect to be able to find at ISOLDE/Booster the yields measured for ^{34}Al at ISOLDE/SC.

How could Al beams of short-half life isotopes be observed (and used) previously as a long release time has been measured in dedicated target tests ? A possible explanation has been proposed by the separator group in which a fluoration of the Al ions could occur between the target and the ion-source, preventing competing trapping effects.

by the separator group in which a fluoration of the Al ions could occur between the target and the ion-source, preventing competing trapping effects.

For Mn production, we will use the UC target combined with the laser ion source. From target tests measurements made in 1997 [14] up to A = 69, the ^{64}Mn beta yield (without correction for daughter activities) amounts to 9.6 10^4 beta/microCoulomb. With the half-life values for ^{64}Mn to ^{67}Mn (^{64}Mn : 87ms, ^{65}Mn : 86ms, ^{66}Mn : 62ms, ^{67}Mn : 41 ms), we should have more than 10 at/s for the last Mn isotope under study (^{67}Mn). More information on this point should be obtained during the November 1997 test.

III-B. Detection

The experimental set-up, assembled around the collecting point of the tape-system used currently for fast decay studies, will involve the following detectors :

- A $4\pi-\beta$ detector, for triggering $\beta-\gamma$ coincidences and for providing a start signal for neutron time of flight measurements.

- Several γ-counters (Ge of large volume, 70% relative efficiency). The number of γ-counters (2, 3 ?) will be limited by the solid angle available at the collecting point, considering that all γ-measurements should be associated with neutron detection.

- Neutron counters. Two types of neutron detectors will be used (Fig.3). Large liquid scintillators (3.75 liter/cell) will be used in close geometry to identify, with the best possible efficiency, n-γ events. The intrinsic efficiency of the large scintillator cells is $\approx$ 50 % for 1 MeV neutrons. An array of 12 low-threshold neutron detectors [18] will also be used with a fligth path compatible with the production yield of the isotope under study. With a 40 cm path, the total neutron detection solid angle is close to 50 msr. The intrinsic efficiency of the neutron detectors is around 15 % with a smooth varition between 50 keV and 3 MeV. Neutron-gamma coincidences will be registered for the identification of the delayed neutron branches feeding excited states in the final nucleus. Both types of neutron detectors have been already successfully used for IS/308 and IS/338.

IV - Beam time request

The information given by the proposed experiment will be useful for the interpretation of some of the first REX experiment as it will provide complementary data on nuclear properties of n-rich light nuclei of interest for the shell model analysis.

UC target with surface ionization source :

For the study of very neutron-rich potassium isotopes, we ask 9 shifts for determining decay properties of ^{52}K and ^{53}K. The adjustement of the experimental conditions and the calibration of the different counters will require one additional shift. In particular, ^{26}Na, produced with the same target /ion source will be used for relative efficiency determination of the β and γ counters. ^{49}K and ^{51}K will be used for neutron detectors calibration.

For the neutron-rich Al isotopes, one shift is required again for calibration and identification of contaminants. For the γ–γ studies in ^{34}Si and the first observation of ^{35}Si decay modes , we ask for a total of 9 shifts.

U target with laser ion source :

For the first detailed investigation of the decay modes of ^{65}Mn, ^{66}Mn and ^{67}Mn by β–γ, γ–γ, β–n and n-γ measurements, we ask for a total of 9 shifts. Here again, one additional shift is required for calibration of the detectors and tuning of the experiment with the power laser conditions.

Total number of shifts : 30

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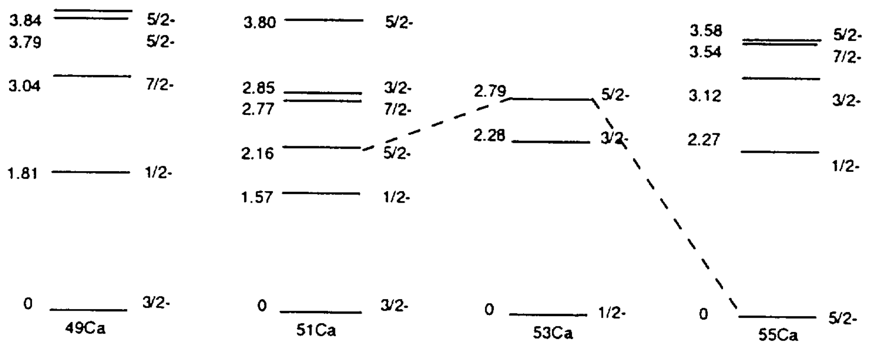
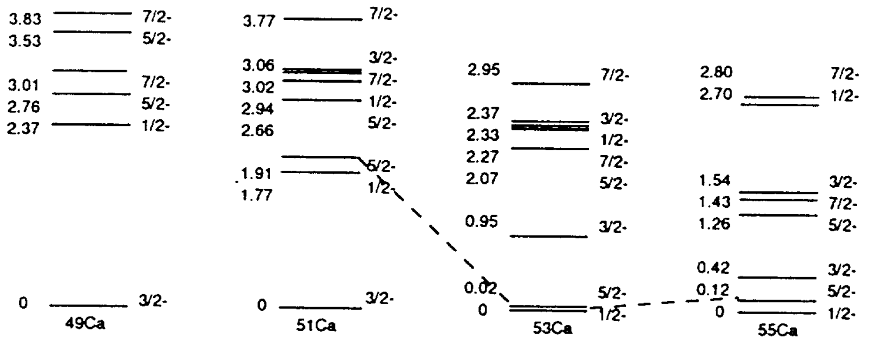


NEGATIVE PARITY STATES IN ODD-EVEN Ca ISOTOPES WITH KB3 INTERACTION (CAURIER, 1995)



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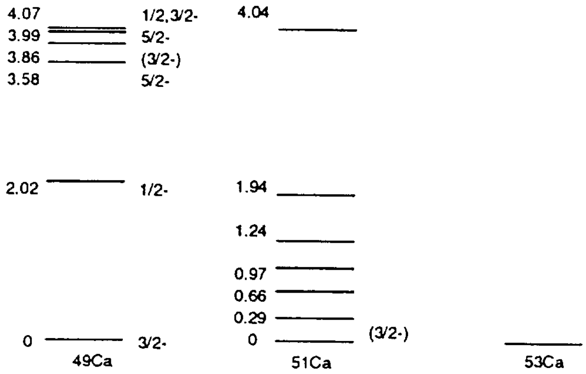
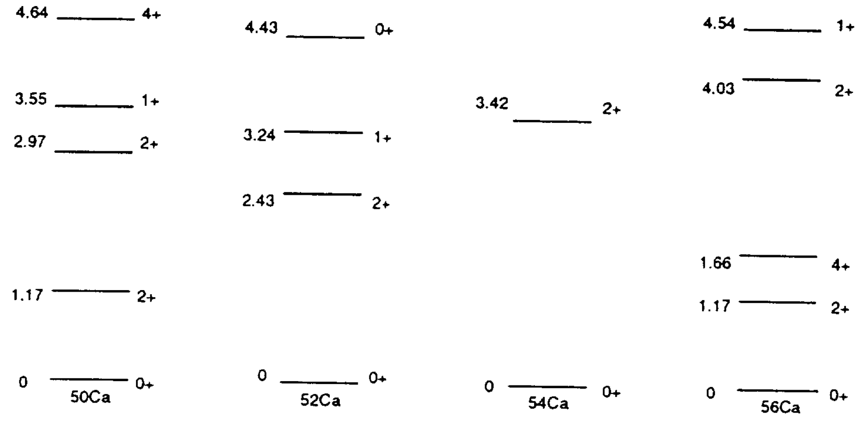
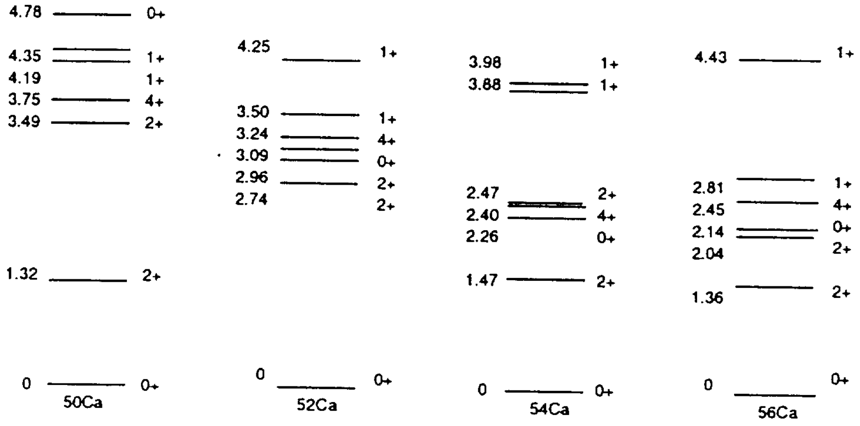


NEGATIVE PARITY STATES IN ODD-EVEN Ca ISOTOPES : EXPERIMENT (NDS)

Figure 1a : Excitation energies in the odd Ca isotopes 49 ≤ A ≤ 55. Predictions with two different interactions are compared with data.



POSITIVE PARITY STATES IN EVEN-EVEN Ca ISOTOPES WITH KB3 INTERACTION (CAURIER, 1995)



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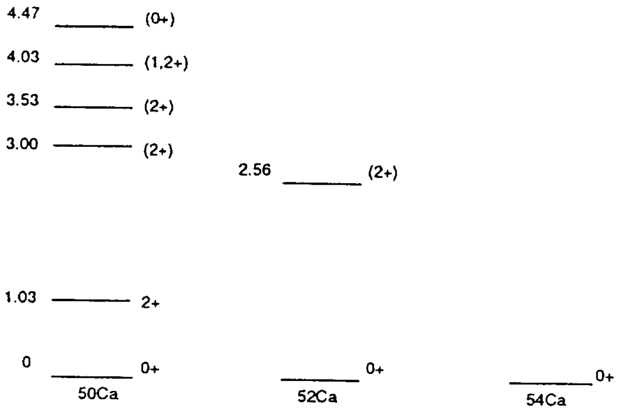

POSITIVE PARITY STATES IN EVEN-EVEN Ca ISOTOPES: EXPERIMENT (NDS & ISOLDE RESULTS)

Figure 1b : Excitation energies in the even Ca isotopes 50 ≤ A ≤ 56. Predictions with two different interactions are compared with data.

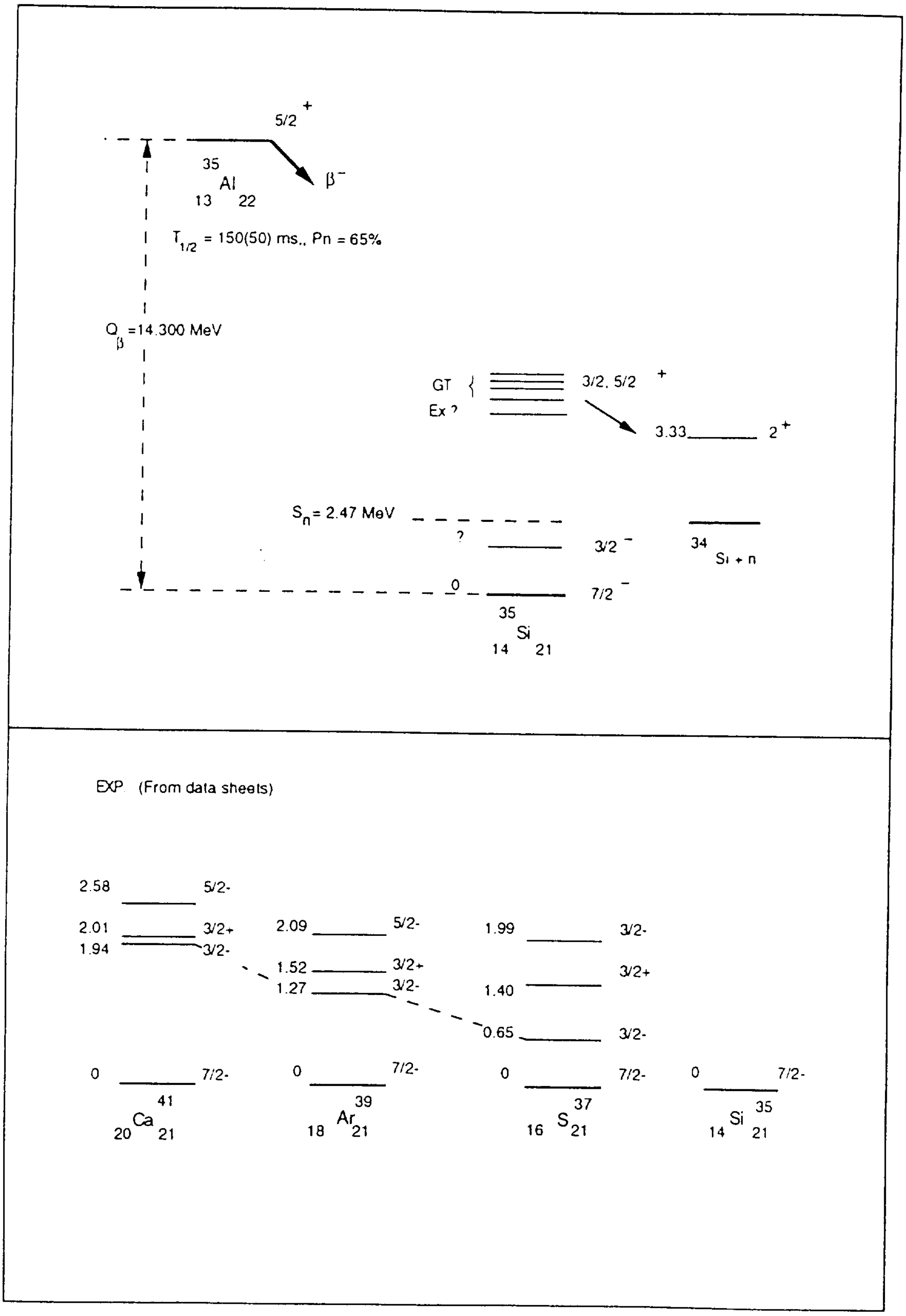

Figure 2 : Schematic decay of ^{35}Al.

Low energy level structure of the N = 21 isotones.

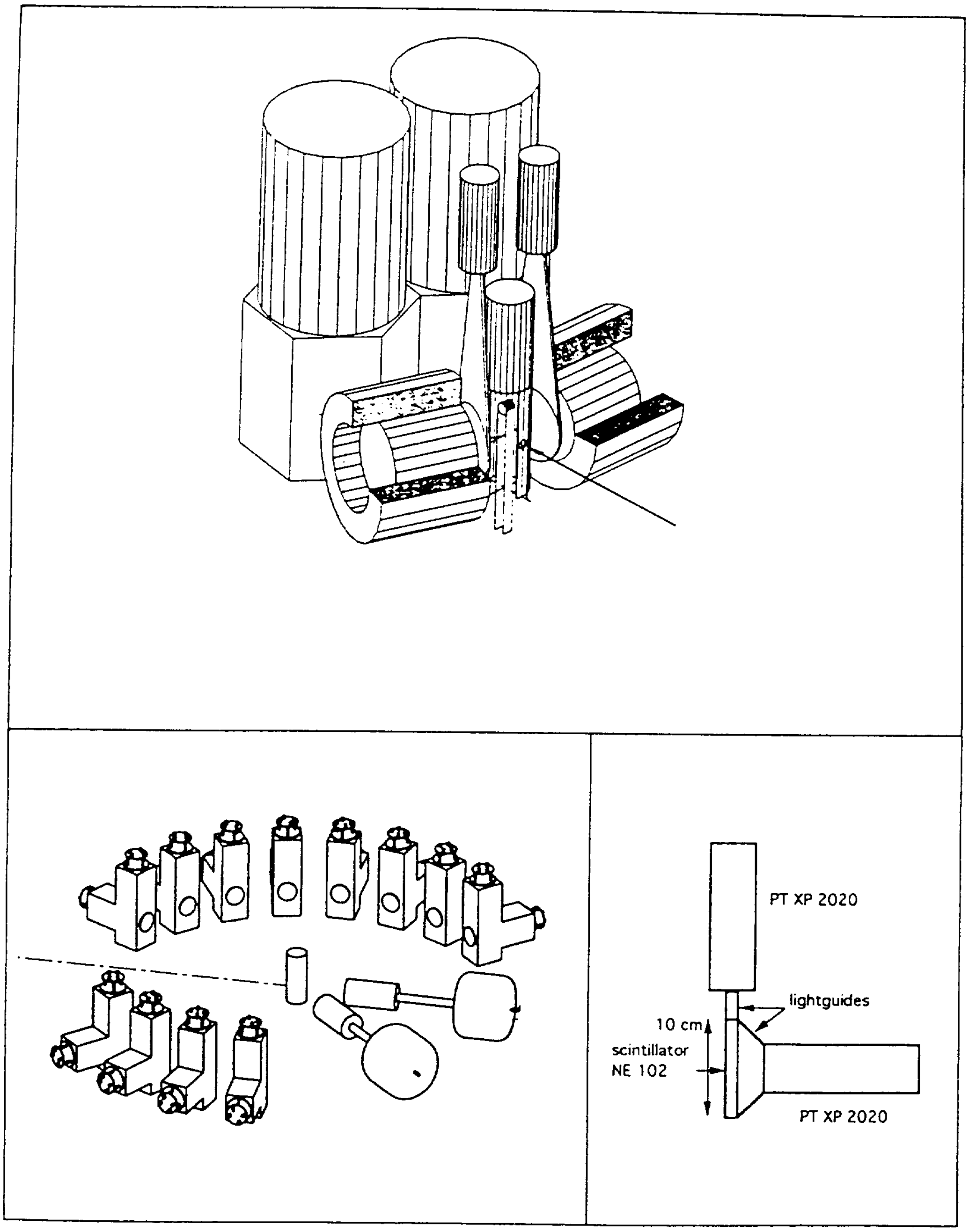

Figure 3 : Schematic view of the experimental set-up used for very neutron rich decay investigation :
a) scintillator cells and gamma counters,
b) array of 12 low threshold neutron detectors associated with gamma detection.

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