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THE STRONGLY DEFORMED NUCLEUS ^{100}Sr

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ABSTRACT

Two gamma rays of 129.2 and 288.4 keV observed in the beta decay of 55 ms ^{100}Rb are interpreted as representing the two lowest transitions in the ^{100}Sr ground-state rotational band. The energy ratio of the two levels, 3.23 approaches the value for a rigid rotator. The half-life of the 2^+ state is 5.15 ± 0.20 ns corresponding to a deformation parameter ε of 0.29. The theoretical implications of these results are discussed on the basis of a Nilsson-Strutinsky calculation.

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A new region of deformed nuclei near (Z,N) = (40,60) was found by Cheifetz et al. [1], and further evidence has recently come from spectra [2,3], masses and isotope shifts [4]. In the present paper, we report the observation of the first 2^+ and 4^+ excited levels in ^{100}Sr with 62 neutrons. The level energies as well as the intrinsic quadrupole moment of the ground-state rotational band indicate that this nucleus represents a well-developed axially symmetric rotor. Earlier findings [3] for ^{98}Sr have been confirmed.

The short-lived isotopes of rubidium [5] were studied by gamma-ray and conversion-electron spectroscopy and by nanosecond lifetime measurements. The radioactivity was produced by fission with 600 MeV protons impinging on a thick target of uranium carbide at high temperature [6], and was mass separated on-line at the ISOLDE Facility at CERN. The yield of ^{100}Rb was 10^5 atoms s^{-1}. In order to reduce the contributions from longer-lived daughter products, the activity was collected on a moving tape.

The gamma-ray spectrum from ^{100}Rb is shown in Fig. 1. The intense line of 129.2 ± 0.5 keV must represent the $2^+ \rightarrow 0^+$ transition in ^{100}Sr and the weaker 288.4 ± 0.5 keV line most likely is the $4^+ \rightarrow 2^+$ transition. The lifetime of the 129.2 keV level was measured by delayed coincidences between beta particles and conversion electrons detected in plastic scintillators, 1 mm and 0.2 mm thick. The distribution of delayed coincidences shown in Fig. 2 shows a single delayed component corresponding to a half-life of 5.15 ± 0.20 ns. The period did not depend on the gate settings in the beta or electron energies.

Similar measurements were performed on ^{98}Rb; the inset in Fig. 2 shows that in this case two delayed components were obtained. Our findings seem to be in excellent agreement with those of Wollnik et al., Peuser et al. [3] and Pinston [7], and we shall not discuss them any further.

The results of the present experiment point to ^{100}Sr as a well-developed axial rotor. The 2^+ state lies very low, the ratio E_{4^+}/E_{2^+} of 3.23 is the highest yet found in this region and is close to the rigid-rotor value of 10/3, and the B(E2) value translates [8] into an intrinsic quadrupole moment of 3.3 b. From this a deformation parameter ε of 0.29

is derived under the assumption of prolate spheroidal shape. (It is essential to include not only the first-order term in ε, which alone would lead to an ε value of 0.35.)

In comparing with theory, we note initially that several theoretical calculations [9] are able to explain the onset of permanent deformations around N = 60. The chameleon character [10] of the zirconium isotopes is explained by the proton number 40 being a sub-shell gap for spherical shapes, while 38 emerges as a substantial gap in the Nilsson diagram for deformations ε = 0.3-0.4. The calculations, however, have difficulties in accounting for the suddenness of the transition (see the inset in Fig. 1) from the spherical shape at N = 56 (the $d_{5/2}$ sub-shell closure) to the strong deformations encountered at N = 60.

The new calculation shown in Fig. 3 and with parameters as given in the caption gives rise to a family of potential-energy curves that agree well with experiment : ^{94}Sr with 56 neutrons comes out with a rather deep spherical minimum, ^{96}Sr is "soft", and ^{98,100}Sr are deformed with a (prolate) minimum at ε = 0.30, the one for ^{100}Sr being deeper. The proton shell energy curve shown in the lower part of Fig. 3 for Z = 38 explains why either very large or very small values of ε are favoured. The deformations at the oblate and prolate minima for ^{100}Sr lead to quadrupole moments that are 70% and 110 % respectively, of the experimental value. This indicates that ^{100}Sr has prolate deformation. An additional argument for this is the high moment of inertia which, if oblate deformation were assumed, would correspond to 82% of the rigid-body value.

The role of the minima calculated for oblate deformations (Fig. 3) is not clear : they are almost as deep as the minima at prolate deformations, and they are certainly expected [9] to connect with these via the gamma degree of freedom. Thus, our calculations would have the heavy strontium isotopes be soft vibrators in the gamma direction, while the high experimental E_{4^+}/E_{2^+} ratio excludes a strong triaxiality.

The moment of inertia of the ^{100}Sr ground-state rotational band is 67% of the prolate deformed rigid-body value, about the same as for ^{20}Ne and well above the values of 50-55% found in the rare earths and actinides.

It is tempting to speculate that this is due to weaker pairing correlations than in the heavier nuclei, maybe associated with the Z = 38 "deformed gap" mentioned above. Further indications for reduced pairing effects come from the mass measurements by Epherre et al. [4], who find that the rubidium isotopes with N > 50 have pairing energies much smaller than expected.

In summary, a new region of strongly deformed nuclei is emerging. Theory accounts qualitatively for the main features of what has been observed, but not for all. More experiments are needed, especially atomic hyperfine structure measurements that unambiguously can tie down the Nilsson assignments of the odd nucleons.

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FIGURE CAPTIONS

Fig. 1 : β-coincident gamma spectrum of ^{100}Rb. The gamma lines at 90.7 129.2 and 288.4 keV all decay with the 55 ms half-life of the parent nucleus, ^{100}Rb [5]. The inset shows the systematics of 2^+ energies for heavy Sr and Zr isotopes.

Fig. 2 : Time spectrum observed at ^{100}Sr from β-ray conversion electron coincidences measured by two thin plastic scintillators. The experimental resolution was 1.8 ns FWHM. The corresponding spectrum obtained for ^{98}Sr is shown in the inset.

Fig. 3 : The upper part of the figure shows potential energy curves for Sr isotopes as a function of the deformation parameter ε. The lower part shows the corresponding proton shell energy for Z = 38 as calculated by the Strutinsky prescription. A modified oscillator potential has been used with the following parameters : $\kappa_p = \kappa_N = 0.08$, $\mu_p = 0.30$, $\mu_N = 0.22$. Only quadrupole deformation (ε) have been considered, but it has been verified that the hexadecapole degree of freedom (ε_4) is unimportant for these isotopes. The pairing strength parameter is taken as $G \cdot A \binom{Z}{N} = 19.2 \pm (7.4) \cdot \left(\frac{N-Z}{A}\right)$ (MeV) with $2\sqrt{10\ Z(N)}$ orbitals included in the calculations. Calculations based on the same set of parameters have also been carried out for the heavier elements. While the picture for zirconium is similar to that shown here, molybdenum and ruthenium have smaller deformations and a less abrupt transition to deformed shapes, in agreement with experimental results [1].

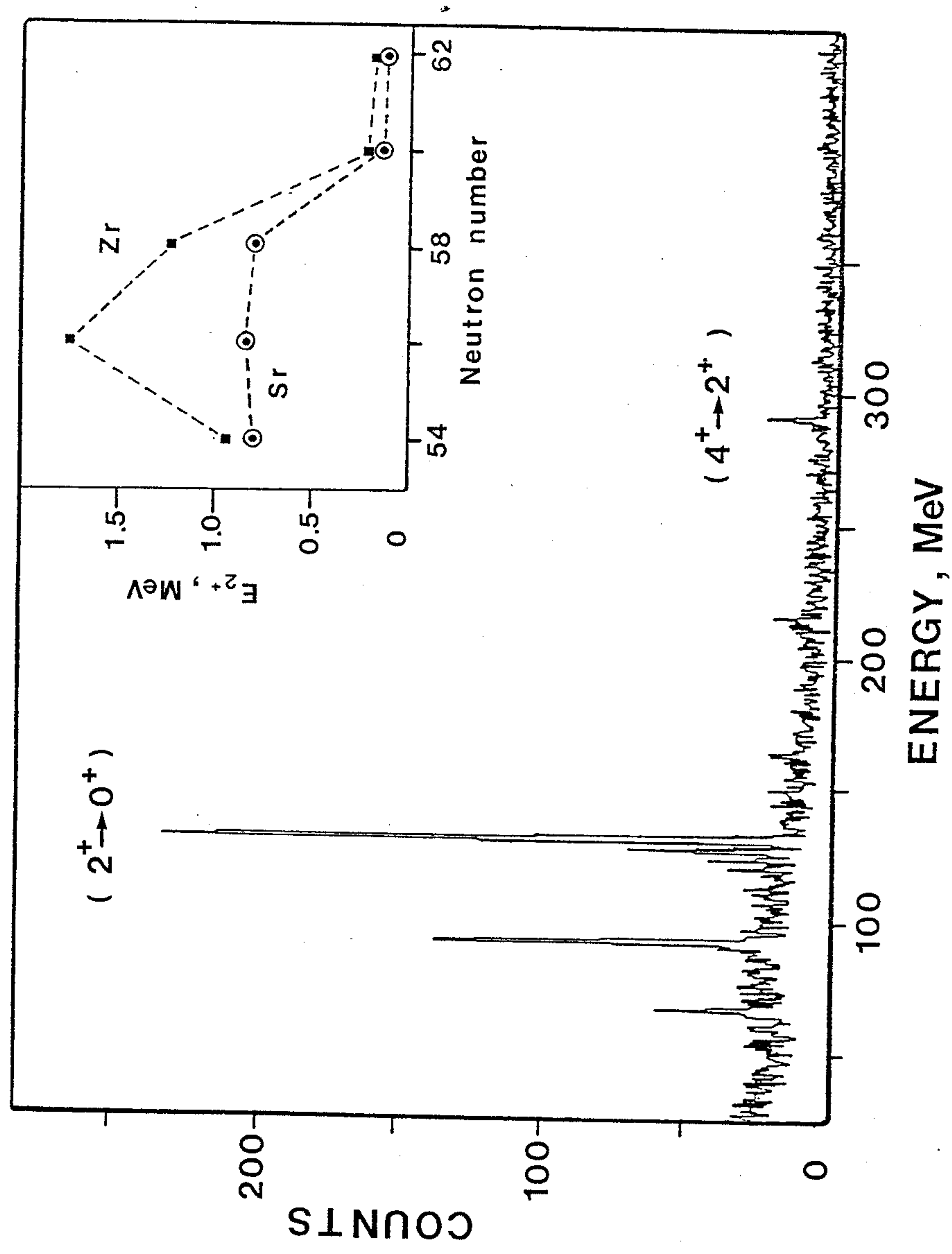
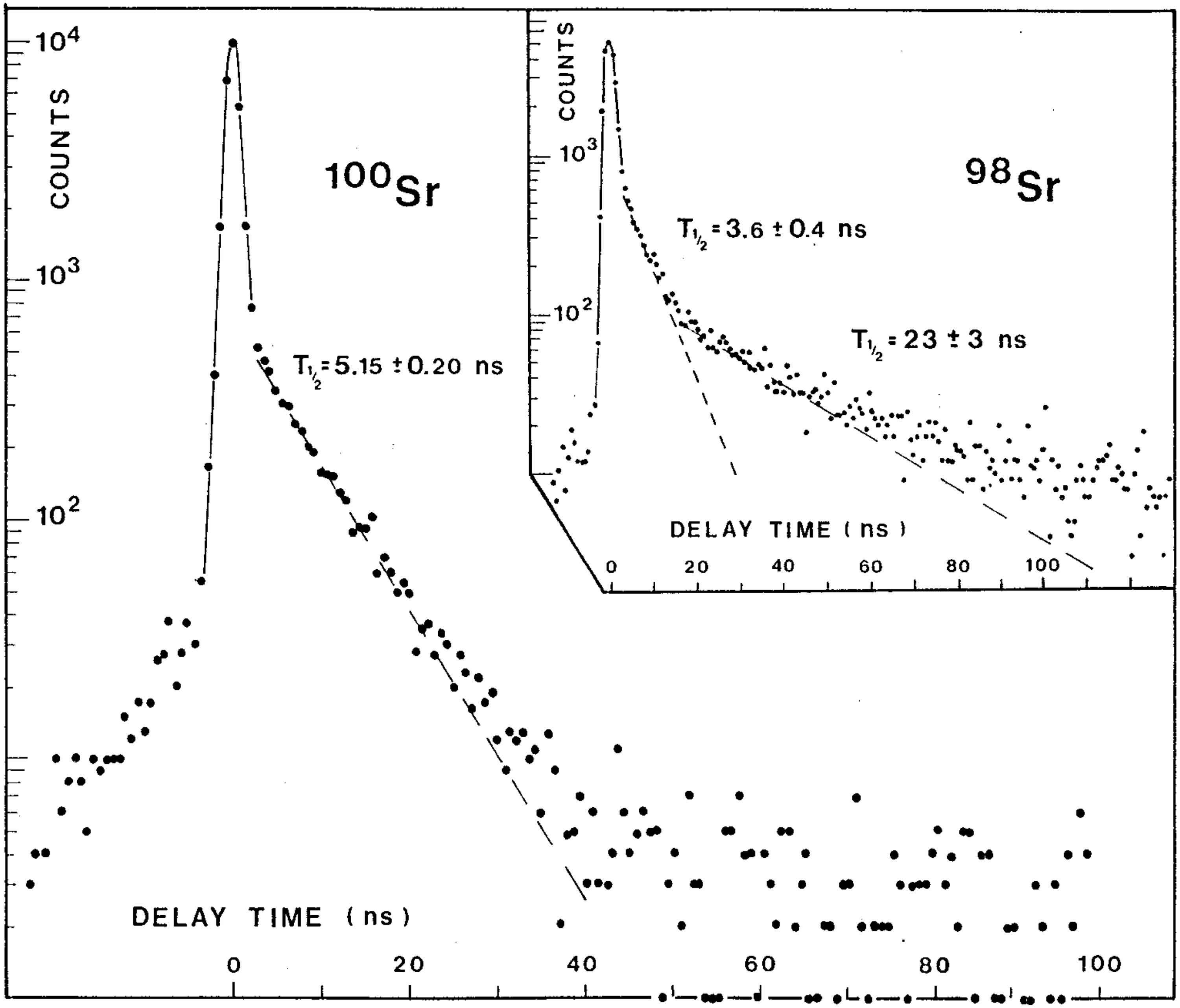
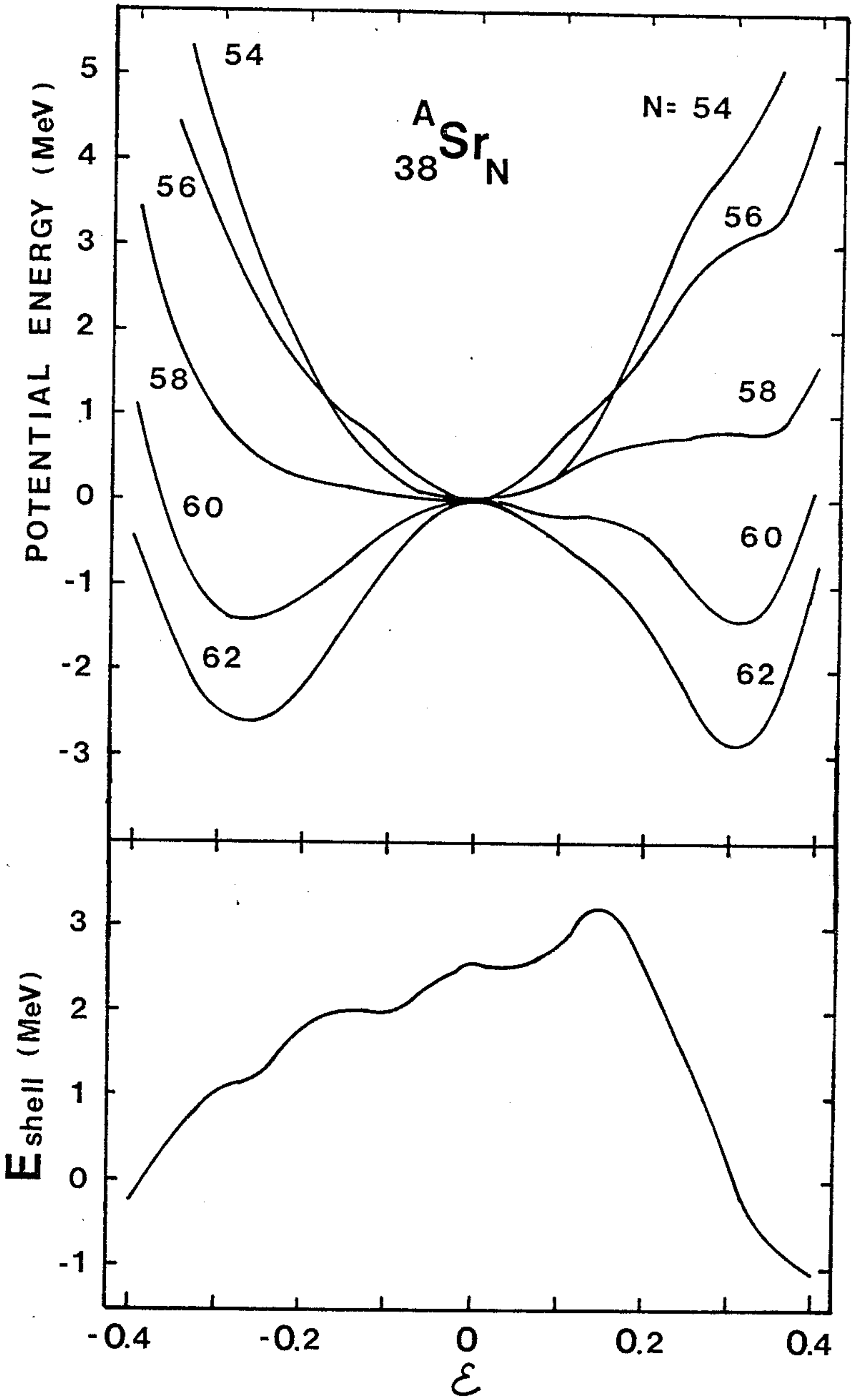


Fig.1



^{100}Sr
$T_{1/2} = 5.15 \pm 0.20$ ns
COUNTS
10^4
10^3
10^2
DELAY TIME (ns)
0
20
40
60
80
100
^{98}Sr
$T_{1/2} = 3.6 \pm 0.4$ ns
$T_{1/2} = 23 \pm 3$ ns

Fig.2



POTENTIAL ENERGY (MeV)
$^{A}_{38}Sr_{N}$
N= 54
54
56
58
60
62
5
4
3
2
1
0
-1
-2
-3
E_{shell} (MeV)
3
2
1
0
-1
-0.4
-0.2
0
0.2
0.4
ε

Fig.3