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Beta decay of the new isotope ^{101}Sn

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Abstract

The very neutron-deficient isotope ^{101}Sn has been produced in a ^{50}Cr(^{58}Ni, 2p5n) reaction and its decay has been studied for the first time. Energy and time spectra of beta-delayed protons emitted from samples that were prepared by using chemically selective ion sources of an on-line mass separator have been measured. The half-life of ^{101}Sn was determined to be 3±1 s. The results obtained are compared to theoretical predictions.

1 Introduction

In recent years, the ^{100}Sn region has been extensively explored by different experimental and theoretical groups. In this paper we present results of decay studies at mass A=101 performed at the on-line mass separator at GSI. This work is part of a program which systematically investigates decay properties of proton-rich nuclei in the ^{100}Sn region. The main motivation for these studies is to test nuclear models predicting nuclear structure and decay properties of nuclei near the proton drip line and near closed shells. In particular, systematic examinations of neutron-deficient odd-even nuclei yield information on the behaviour of single-particle states when approaching the proton-drip line. The analysis of the single-particle energies in the ^{100}Sn region performed recently by Brown and Rykaczewski [1] indicates that the $g_{7/2}$ and $d_{5/2}$ neutron single-particle states in ^{101}Sn change their order when coming from lighter N=51 isotones. Thus, studies of the decay properties of ^{101}Sn provide an excellent way of verifying this prediction.

According to shell-model calculations [1], in the beta decay of ^{101}Sn the strength of the Gamow-Teller transitions is spread over more than hundred levels in ^{101}In. Most of these transitions lead to states with high probability of proton emission. Consequently, the beta-delayed proton branching ratio is expected to be close to 40%. The high probability of proton emission after the beta decay of ^{101}Sn enables spectroscopic studies even at the very low production rate of this isotope.

2 Experimental technique

^{101}Sn was produced in the ^{50}Cr(^{58}Ni, 2p5n) fusion-evaporation reaction. The on-line separation technique has been used to select ^{101}Sn and suppress other reaction products.

In order to observe beta-delayed protons from the ^{101}Sn decay, the mass separated A=101 beam was alternately stopped in front of one of two identical ΔE-E telescopes. Each of them consisted of 22 μm, 150 mm^2 and 700 μm, 450 mm^2 silicon surface-barrier detectors and enabled background-free detection of protons with an efficiency of about 18%. By switching the separated beam between two telescopes, grow-in and decay of the collected activity could be observed.

Although this detector set-up allowed us to detect short-lived proton activity at mass 101, an unambiguous assignment of this activity was hampered by the presence of isobaric contaminants. In the A=101 chain, protons can originate from the decay of ^{101}Sn or they can follow the decay of ^{101}In. Beta-delayed proton branches for the A=101 isobars closer to the valley of stability are negligible due to much smaller energy windows open for proton emission.

So far, the decay of ^{101}In has been investigated only by means of γ-ray spectroscopy [2] and there is no experimental data available on a possible beta-delayed proton branching. Calculations based on a statistical model [3, 4] yield for the decay of ^{101}In ground-state a beta-delayed proton branching ratio of the order of $2{\cdot}10^{-6}$. A much higher branching ratio, however, can be expected for the decay of the, so far unidentified, $1/2^-$ isomeric state in ^{101}In. Systematics of $1/2^-$ isomers known in neighboring odd-mass indium isotopes [5, 6, 7] locates this state in ^{101}In at an excitation energy of about 650 keV. The statistical model predicts that the beta-decay of this isomer will lead to a branching ratio of $2{\cdot}10^{-5}$ for subsequent proton emission.

In view of the large uncertainties in estimating beta-delayed proton branching ratios and since ^{101}In is expected to be produced in the ^{50}Cr(^{58}Ni, 3p4n) reaction with a cross-section about 200 times higher than ^{101}Sn [8], a firm assignment of the proton activity

observed at mass 101 requires measurements with a chemically selective ion source.

2.1 Tin chemistry with laser ion source

The laser ion source (LIS) of the type described in ref. [9] enables substantial reduction of the isobaric background in measurements at on-line mass separators. The ionization principle of the LIS is based on stepwise resonant excitation of atoms in a hot cavity. The tin atoms were ionized in a cavity heated to a temperature of about 2200 K by a three-step resonant excitation scheme leading to an autoionizing state in the final transition [10]. The beams of three tunable dye lasers pumped by copper vapor lasers with a pulse repetition rate of 10 kHz were focused through a window in the mass separator magnet into the extraction hole of LIS. The laser power introduced into the opening of LIS was sufficient to obtain saturation of all transitions in the applied excitation scheme.

The separation efficiency (η) of the LIS for ^{108}Sn has been determined to 8.5^{+2}_{-3} % [11] which is about 6 times lower than with the FEBIAD ion source [12, 13]. This loss seemed tolerable, since the much lower LIS efficiency for indium (caused by the inevitable surface ionization) provided a tin-over-indium enhancement by a factor of 6 to 7 (see Fig. 1a). The fact that for the rates of the new activity at mass A=101, of ^{103}Sn and of ^{104}Sn the same loss factor of approximately 6 was found, seemed to point clearly to a tin assignment of the A=101 proton activity.

Unfortunately an assignment to ^{101}In , although less probable, cannot be excluded due to the trend in the measured ratio η_{LIS}/η_{FEBIAD} for indium isotopes shown in Fig. 1a. This trend, indicating ratios increasing towards short half-lives, may well be an artefact due to poor statistics. There may, however, be also a real cause: even though

the ionization efficiency clearly does not depend on the half-life, the unknown release efficiency for indium may, for short-lived isotopes, be better in the small-volume LIS than in the larger FEBIAD-E ion source.

Due to this ambiguity and due to the fact that the low A=101 beta-delayed proton rate (about 0.5 protons per hour) obtained with the LIS did not allow for a half-life determination, a further approach, based on the considerably better ionization efficiency of the FEBIAD-E source was necessary (the separation efficiency of this source for a 3 seconds tin isotope amounts to about 15% [13]).

2.2 Tin discrimination with FEBIAD ion source

Even though an efficient tin-over-indium enhancement is not possible in a FEBIAD ion source for short-lived tin isotopes, the reverse is possible [14], namely a practically loss-free indium chemistry by attaching a cold trap to the FEBIAD-E source. This technique utilizes the higher volatility (in terms of desorption speed) of indium compared to tin. With a specially tailored cold trap, the separation efficiency for tin can be substantially suppressed while leaving the one for indium untouched. The suppression of tin was determined in a separate experiment with a stable ^{120}Sn beam from the UNILAC with the implantation technique [13]. The comparison of the release profiles measured by using the ion source with and without cold trap gave a suppression of about 3 to 8 times in the half-life range from 100 to 1 second, as indicated by the hatched area in Fig. 1b. This was confirmed in the main measurements by monitoring (simultaneously to the accumulation of A=101 protons) the rates of ^{103}Sn or ^{104}Sn for a FEBIAD-E ion source without and with the cold trap (subsequently referred to as unselective and tin-

discriminative FEBIAD source, respectively), see Fig. 1b. In order to control that short-lived indium isotopes are not suppressed, the rates of ^{101}In and ^{104}In were additionally monitored. As shown in Fig. 1b they were found to be practically equal for both ion sources.

Thus with the unselective ion source beta-delayed protons of mass 101 could be accumulated at a sufficiently high rate of about 3 protons per hour, while the subsequent measurement with the tin-discriminative source probed into an eventual ^{101}In origin or contribution. With the latter source the proton rate was a factor of 3.2±0.7 lower (see Fig. 1b) indicating clearly that most of the protons originate indeed from ^{101}Sn. The observation that this factor is not 7±1.5 as expected for a 3 seconds tin activity, points to (unless the discrepancy is purely of statistical nature) the presence of protons originating also from the decay of ^{101}In. With this interpretation 18±8 % and 60±13 % of the observed A=101 proton activity can be assigned to the decay of ^{101}In in the case of unselective and tin-discriminative ion source, respectively. These values are consistent with the above-mentioned estimates of production cross-section, release efficiency and beta-delayed proton branching ratio for ^{101}In.

3 Results and discussion

Figure 2 shows the energy spectra of beta-delayed protons accumulated during measurements at mass A=101 with the unselective and the tin-discriminative FEBIAD ion source. Both spectra have been normalized to the same beam dose of 7.6 particle·mC corresponding to an average current of 40 particle·nA of ^{58}Ni^{14+} beam during the 54 hours - measurement with the unselective FEBIAD source.

The energy spectrum of protons emitted after beta decay of ^{101}Sn (blank histogram in Fig. 4) has been obtained as difference of these normalized proton spectra. An analogous background correction has been applied to obtain the time distribution of protons following the decay of ^{101}Sn (see Fig. 3). The analysis of the time spectrum yielded 3±1 s for the half-life of ^{101}Sn assuming a single decay component in the function describing grow-in and decay of the activity.

This half-life is about 2 times longer than predicted by shell model calculations [1] and about 1.5 times shorter than the half-life obtained in pn-QRPA calculations [15] which use the Q_{EC} value from [16]. The observed discrepancies can be connected either with the calculated beta strength distribution (which explicitly relates to the spin of ^{101}Sn) or/and with the assumed decay energy. Since for ^{101}Sn neither of these quantities is known experimentally, a definite verification of theoretical models based only on the examination of experimental and predicted half-lives cannot be made yet.

Another possibility of testing nuclear models is offered by comparison of measured and calculated proton spectra presented in Fig. 4. The hatched histogram shows the shape of the energy spectrum of beta-delayed protons from ^{101}Sn which has been calculated using the statistical model [3, 4], applying the beta-strength distribution from [1] and the nuclear masses predicted in [17]. While the centre of gravity of the calculated proton spectrum is very close to the mean energy of detected protons, the theoretical spectrum is concentrated in much narrower energy range. This observation may indicate why the description of the Gamow-Teller strength distribution predicted in ref. [1] fails to reproduce the experimental half-life of ^{101}Sn.

In the measurements at mass A=101 with the unselective FEBIAD ion source a rate of about 3 protons per hour has been observed. Assuming 40% beta-delayed proton

branching ratio, this value corresponds to a separation yield of about 40 atoms of ^{101}Sn per hour compared to 0.4 and 1 atom of ^{101}Sn per hour in experiments employing projectile fragmentation and in-flight separation at GSI [18] and GANIL [19], respectively. This comparison and the results obtained in recent studies of neutron-deficient isotopes of silver [20] and indium [21] prove that on-line mass separation is competitive with in-flight separation methods in the cases where fast, efficient and chemically selective ion sources are available.

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Fig. 1. Half-life dependence of the ratio of separation efficiencies η for the LIS and FEBIAD ion source (a) as well as for the tin-discriminative (cooled) and unselective FEBIAD source (b), determined for different isotopes of tin and indium. The vertical error bars include the statistical uncertainty of measured rates and the systematical uncertainty of 10% in the beam dose normalization. The half-life uncertainty indicated in Fig. 1a for A=101 point reflects the problem that the half-life could not be determined in that experiment.

Fig. 2. Energy spectrum of beta-delayed protons collected during 54 hours of measurements at mass A=101 with the unselective (a) and the tin-discriminative (b) FEBIAD ion source. The lower histogram includes a normalization factor of 1.92 resulting from the ratio of beam doses during these two measurements.

Fig. 3. Time spectrum of protons emitted after beta decay of ^{101}Sn. The solid curve represents the best fit of the theoretical one-component time distribution to the experimental data.

Fig. 4. Energy spectrum of protons emitted after beta decay of ^{101}Sn (blank histogram). The hatched histogram shows the spectrum of ^{101}Sn protons calculated using statistical model and beta strength distribution obtained in shell model calculations [1] (see text for details). Theoretical and experimental spectra are normalized to equal integral number of counts.

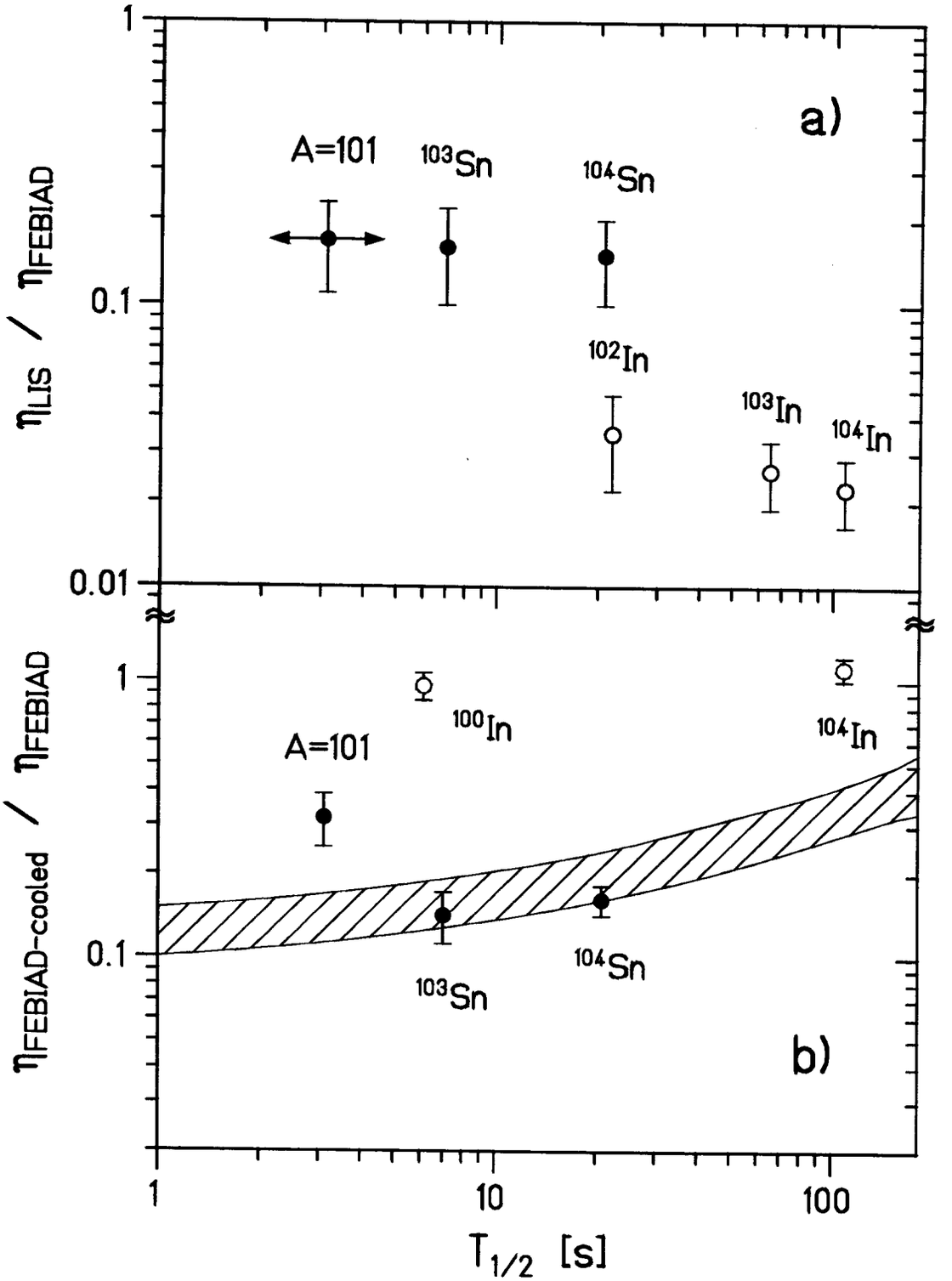
a)
A=101
103Sn
104Sn
102In
103In
104In
0.1
0.01
ηLIS / ηFEBIAD
b)
A=101
100In
104In
103Sn
104Sn
0.1
1
ηFEBIAD-cooled / ηFEBIAD
1
10
100
T1/2 [s]

Fig. 1

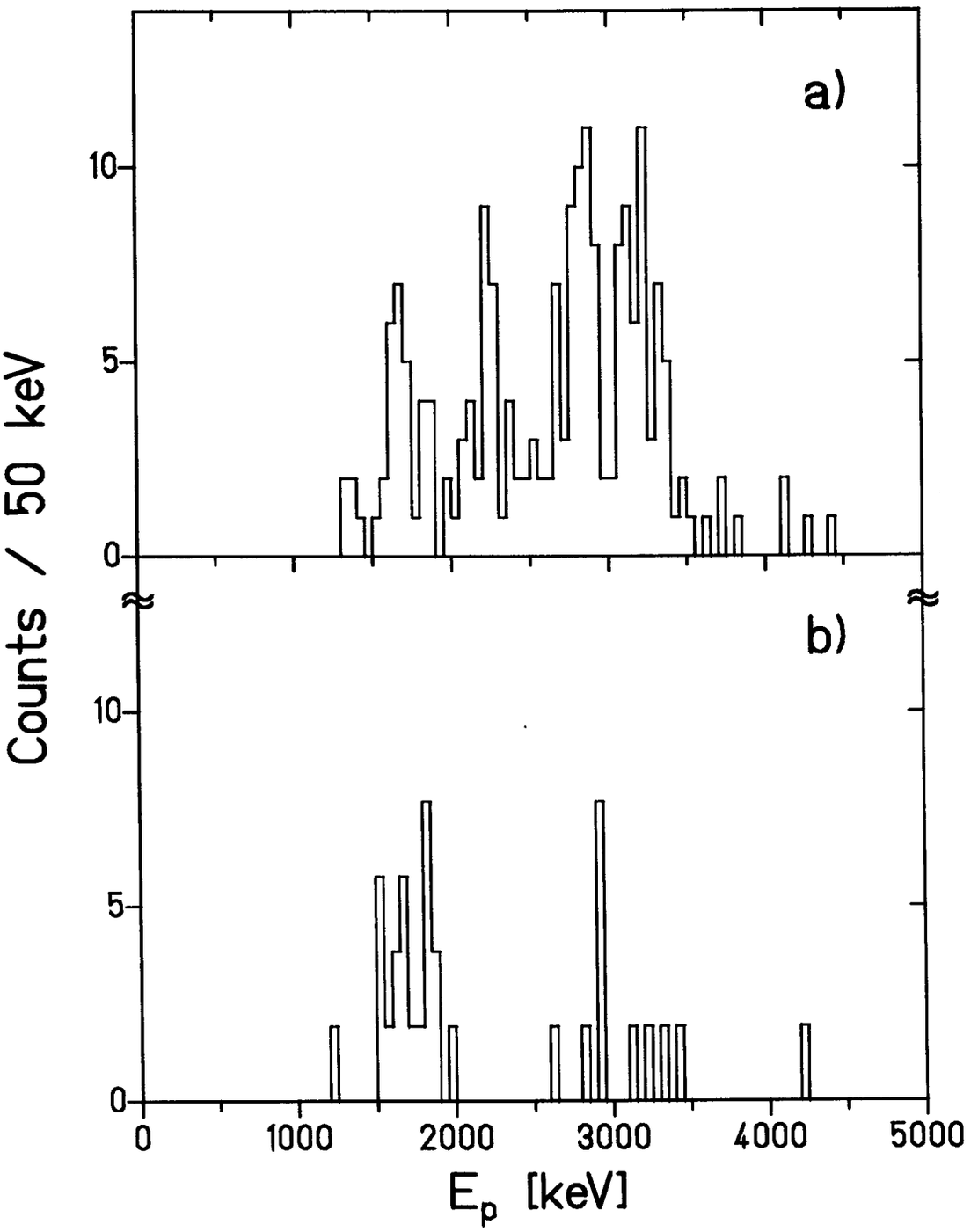

Fig. 2

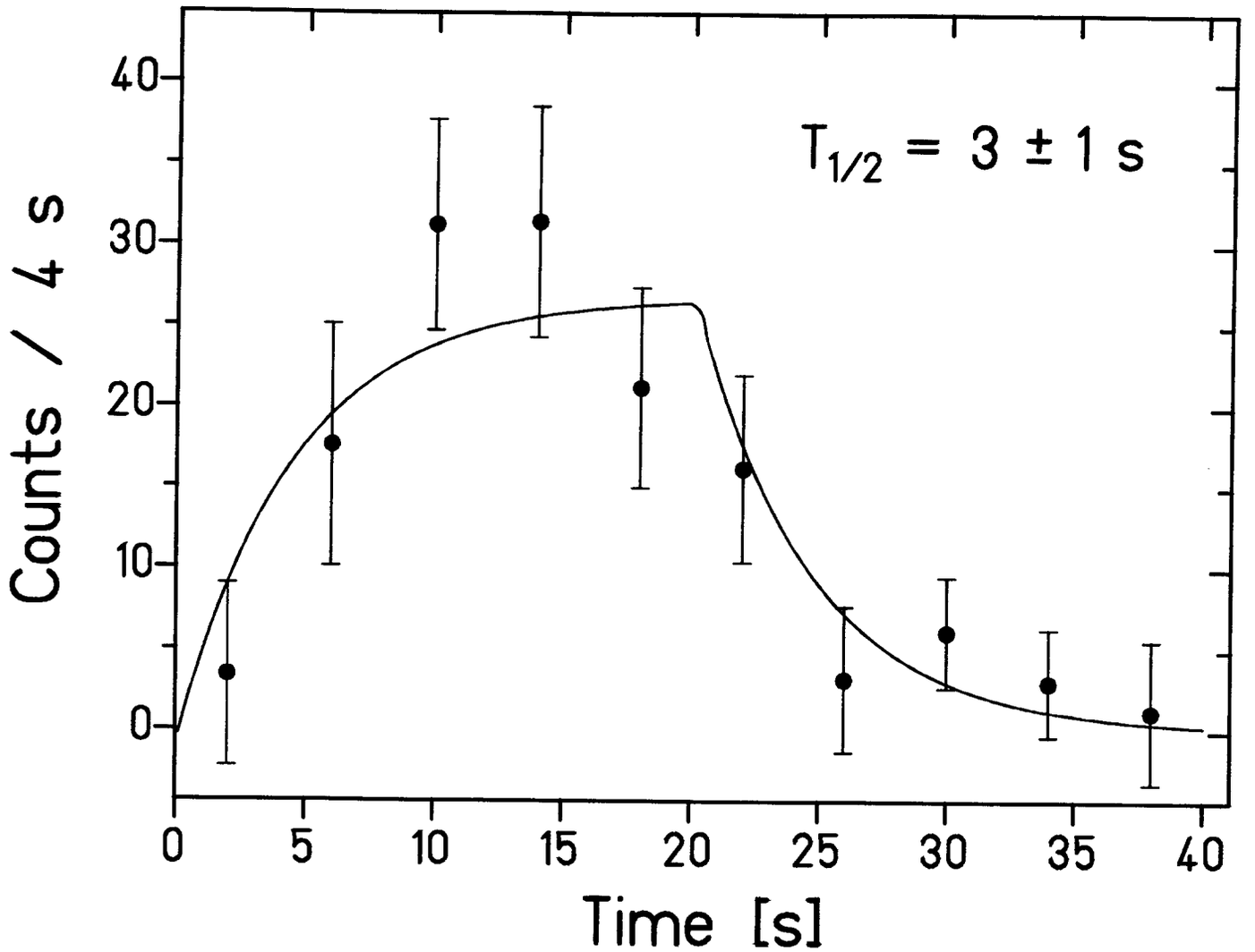

Fig. 3

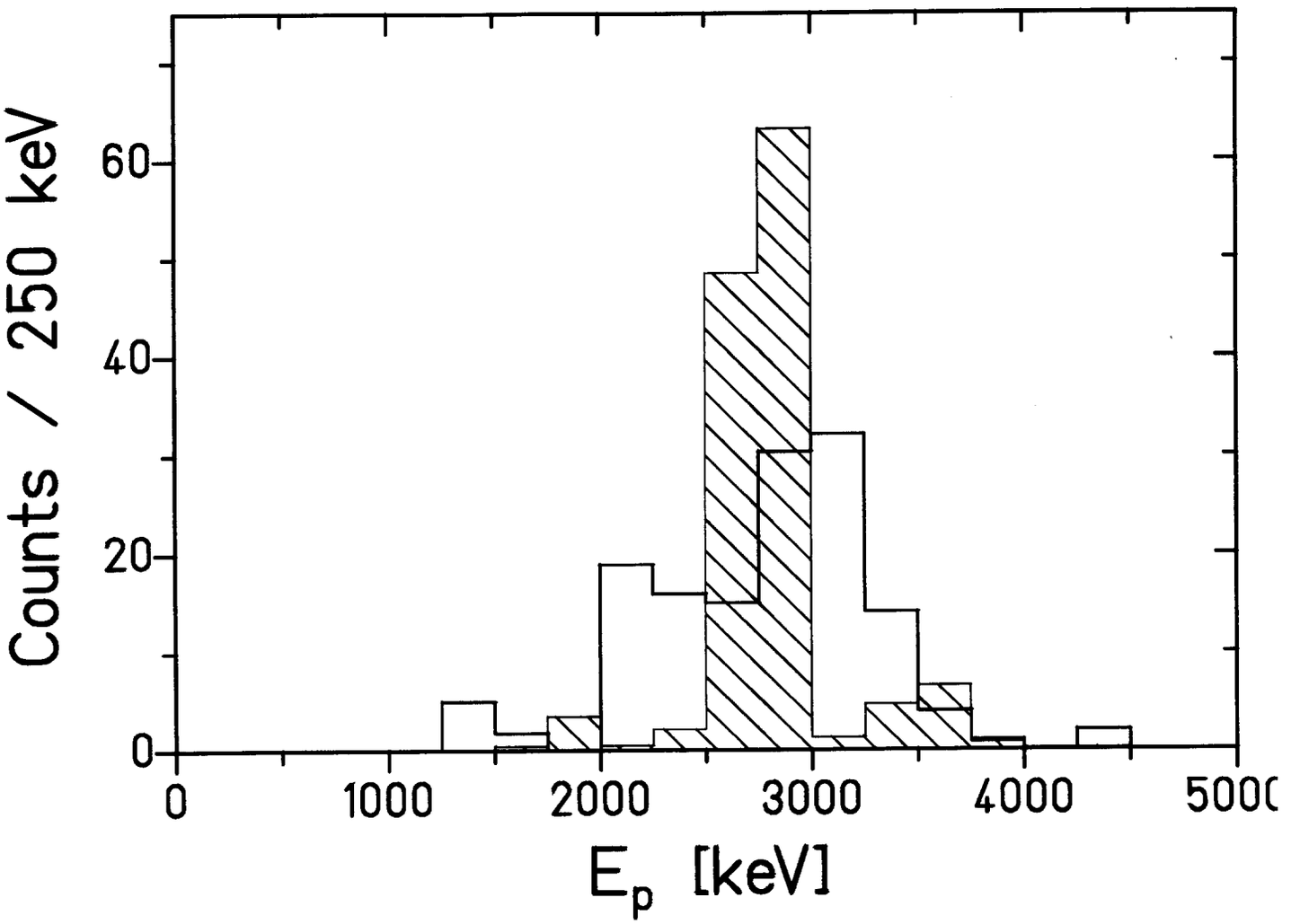

Fig. 4