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Low-Lying Level Structure of ^{73}Kr

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Abstract: We have used the ^{40}Ca(^{36}Ar, 2pn) reaction to study the low-lying level structure of ^{73}Kr. By utilizing a bombarding energy at the Coulomb barrier, the relative cross section for this channel was enhanced to a few percent of the total reaction cross section. Levels in ^{73}Kr were assigned based primarily upon observed neutron-gamma-gamma coincidences and upon comparisons of these newly assigned transition cross sections with those from known nuclei.

1. Introduction

The neutron deficient nuclei between the $1f_{7/2}$ and $1g_{9/2}$ shells have become the focus of much study in recent years. Although experimental studies have been hampered by the low production cross sections of nuclei near the proton drip line, the existence [1,2]) of an island of very deformed nuclei ($|\beta_2| > .3$) has created a number of possibilities for studying the effects of nuclear shape changes. Systematics for many traditional nuclear structure quantities have now been determined as a function of the shape changes within chains of isotopes and isotones. How these changes affect a very fundamental quantity in nuclear physics, the atomic mass, is not at all delineated, however. Although the paucity of reliable mass measurements in this region has contributed toward this knowledge gap, sorting out various known effects (e.g., the Wigner energy, volume energies, isospin effects, etc.) is not always straightforward. Two sets of studies have been performed in an attempt to obtain systematic mass measurements in this region. Originally, masses of all particle-stable, neutron-deficient rubidium isotopes were measured [3]) using a direct mass measurement technique. Subsequent measurements [4])attempted to derive masses (based upon these prior results) for several of the krypton isotopes by measuring the beta endpoints of the corresponding rubidium isotopes. A reevaluation of the original direct mass measurements [5]), however, required the utilization of direct transfer reactions to measure the masses of $^{74\text{-}77}$Kr [6,7]) because of revised uncertainties in the final values. Unfortunately, all of these measurements have raised additional questions rather than yielding a coherent set of answers. For instance, many formulae tend to correctly predict the masses of even-Z nuclei like Kr but seriously mispredict those of several odd-Z Rb nuclei (e.g., ^{76}Rb is much more stable than any prediction [4])).

The macroscopic-microscopic model of Möller and Nix [1]) gives the best overall results for deformed nuclei in the $N \approx Z \approx 40$ region. One could attribute this to the inclusion of shape dependences in the model. Checking this shape inclusion solely by examination of the mass surface is made difficult because to date, all nuclei whose masses have been measured have either

spherical or prolate ground states. Thus, to further check this and later mass models which include shapes (e.g., ref. [8]), it is important to measure the mass of a nuclide with an oblate ground state. Earlier predictions [9,10] suggested that Kr nuclei with A<74 could be excellent candidates for oblate ground states. Therefore, we decided to investigate the low-lying level structure in ^{73}Kr. Ideally one could use beta decay into the proposed nucleus for both the shape and mass measurements. Unfortunately, ^{73}Rb is proton unbound. Thus, we decided to divide the experiment into an in-beam gamma-ray study of ^{73}Kr and a beta-endpoint determination of the mass difference between ^{73}Kr and ^{73}Br. In this paper we report results of the former.

2. Experimental Technique

It was decided to utilize the cold fusion technique [11] used in the study of ^{77}Sr. By producing a compound nucleus just at the Coulomb barrier in a symmetrical nuclear reaction, one can limit the product channels to those with 2–3 evaporated particles. We chose to study products of the ^{36}Ar + ^{40}Ca (4 mg/cm^2 target) reaction at the Lawrence Berkeley Laboratory 88-Inch Cyclotron. First we performed the series of excitation function measurements shown in fig. 1 using a simple three-detector n-γ–γ technique which served to identify a few major transitions in ^{73}Kr. Subsequently, a preliminary measurement [13] by another group showed that our primary assignments were indeed in mass 73. We then used the HERA array [12] with the 0° gamma ray detector replaced with a small neutron detector to permit collection of n-γ-γ events in addition to the standard γ-γ coincidences with the remaining twenty Compton suppressed germanium detectors. The total projections of the γ-γ and n-γ-γ matrices obtained are shown in figs. 2a and 2b, respectively.

The 95 MeV ^{36}Ar bombarding energy was chosen to eliminate essentially all four-particle evaporation channels. This nuclear reaction, in conjunction with the neutron gate, almost solely selects the desired 2pn evaporation channel (two-particle-out channels are severely reduced at this energy) because the p2n channel leads to the unbound nucleus ^{73}Rb and the 3n channel (^{73}Sr) is at

least two orders of magnitude down in cross section. The α,n evaporation channel (^{71}Kr) should be produced in lower yield at this energy (x 1/20) and has not been directly identified. The efficacy of this neutron gating technique can be seen in fig. 2 by the strong presence of ^{49}Cr produced in the ^{16}O (^{36}Ar, 2pn) reaction (oxygen is an omnipresent contaminant of calcium targets).

3. Results and Comparisons

The strong transitions in fig. 2 which belong to ^{73}Br have been used to corroborate the evidence reported in ref. [14]. Principal transitions labelled in fig. 2 which do not belong to ^{73}Br or which we assign to ^{73}Kr are taken from various references and are listed in Table 1. Table 1 additionally gives the ALICE [15] prediction for the production cross sections (limited to $\sigma \geq 1$mb) and the percentage of events in the neutron-gated spectrum (ratio of net n-γ-γ/γ-γ events). This last criterion is extremely sensitive to the numbers of neutrons (if any) emitted and to the kinematic focusing in the ^{36}Ar + ^{16}O reaction. Using all of this information permitted the identification of several transitions which we attribute to ^{73}Kr. Figure 3 shows a typical coincidence projection from the n-γ-γ matrix for a transition assigned to ^{73}Kr. Subsequent generation of coincidence intensities from this n-γ-γ matrix at 95 MeV were utilized in constructing the preliminary decay scheme shown in fig. 4. The first two more strongly populated sequences are well-defined. However, due to the low intensities of its transitions, we could not decide with confidence that sequences 3 and 4 are even in ^{73}Kr; their crude excitation functions are also not inconsistent with that of the αn channel (^{71}Kr). Sequence 3 has been assigned, however, by recent work to ^{73}Kr [24]. In addition, because of the lack of connecting transitions between the bands, we do not know their relative positions. It is not, however, unreasonable to suggest that the two states at 1003 keV could indeed be the same state. The proposed spins for band 1 in fig. 4 are entirely based upon the $E = (A)(J)(J + 1)$ rule. Although many other transitions have been identified which may belong to ^{73}Kr, inconsistencies between the n-γ-γ and the hundred-fold greater data in the γ-γ spectra make it difficult to place them.

Results for the six lines seen at the Rochester RMS [13]) are in general agreement with our observations (statistics in their measurement were insufficient for coincidence work). Two notable exceptions exist for lines at 455 and 87 keV. Neither gamma ray is strongly coincident with any transition assigned to ^{73}Kr or ^{73}Br; the former is also extraordinarily close in energy to the main transition in ^{74}Kr and exhibits no enhancement in the neutron-gated spectrum, while the latter transition does exhibit a minor neutron-gate enhancement but in our spectrum is primarily attributed to ^{47}V from the ^{16}O(^{36}Ar, αp) reaction.

In the process of preparing this manuscript, another paper [24]) on the level structure of Kr has appeared. This paper utilized the same Rochester results [13]) in conjunction with a standard γ–γ experiment performed at Oak Ridge utilizing the same ^{40}Ca (^{35}Cl, pn) ^{73}Kr reaction. Although we agree with ref. [24]) on our sequence 3 for ^{73}Kr except for the last level at 1409 for which our statistics were inadequate, the omission of sequences involving gamma transitions in our first two bands is curious, particularly since they were initially reported [13]). Since these two bands are populated far stronger in our data than sequence 3 (see fig. 4), it is important to discuss why they are not reported in ref. [24]).

The most likely difficulties in their experiment arise from the different nuclear reaction chosen to produce ^{73}Kr and from the separation of the identification and production experiments. The Coulomb barrier in either the Ar or Cl reaction is so high that it is very difficult to prevent the evaporation of more than two particles. Thus we chose not to try by utilizing ^{36}Ar as the projectile. Thus although their γ–γ data has larger total statistics, the percentage belonging to ^{73}Kr is down by at least an order of magnitude. Furthermore, their neutron-gated data was only generated in conjunction with a small array and the Rochester recoil product separator [13]). Thus our neutron-gated spectra have ~5000 times more events than their mass 73-neutron gated spectra. These two facts in conjunction with the nearness and in some cases unresolvable overlap with ^{73}Br transitions easily explain their non-observations.

There is a second band listed in ref. [24]) with a crossover transition to what we call band 3. For some time we wondered why there exists zero evidence for any of these gamma rays in our data. After considerable thought had been given to what error could have been made (such as mass contamination during their initial identification), we came to the conclusion that the problem was probably due to a target contaminant. The most likely ^{40}Ca target contaminants are oxygen (ubiquitous in calcium targets) and ^{42}Ca. The former could be eliminated by the mass 73 gate, but ^{73}Se may be produced in the ^{42}Ca (^{35}Cl, 3pn) reaction (which is slightly open at their bombarding energy of 95 MeV). In fact, this second band is exactly the 3/2$^-$ band based upon the 39.8 min isomer [25]) in ^{73}Se. We must further assume that the 337.8-keV transition is an artifact. It is also important to note that ^{73}Se could not have been produced in our experiment because the ^{42}Ca (^{36}Ar, 4pn) ^{73}Se reaction is not open at our bombarding energy and because it cannot be reached by bombarding a ^{40}Ca target with an ^{36}Ar beam.

4. Conclusions

Prior predictions [9,10]) have shown that ^{72}Kr should be the first even Kr isotope to exhibit strong oblate deformation. Since ^{76}Kr and ^{74}Kr both have prolate ground states [26]) and exhibit shape coexistence with nearly spherical bands, results of studies of the odd neutron nuclei ^{77}Kr and ^{75}Kr may not extrapolate correctly to ^{73}Kr. A later prediction by Leander [27]) suggested that ^{73}Kr would also have an oblate ground state. Unfortunately, we feel that Leander's unpublished results must be independently verified before conclusions can be drawn from our data. Additionally, our total results for ^{73}Kr look similar to those for ^{75}Kr [26]); ^{75}Kr is prolate. Thus we do endorse the general conclusion of ref. [24]). It is hoped that these results near the proton drip line will initiate theoretical interest in solving this important shape dependence question.

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Table I. Nuclides produced in $^{36}Ar + ^{40}Ca$, ^{16}O reactions at $E_{Ar} = 95$ MeV

Nuclide	Production Channel	Relative[a] σ	Principal Transition(s) (keV)	Ratio[b] of Main Peaks in Neutron Gate	Reference
^{73}Kr	2pn	8	This study	~0.008	This study
^{73}Br	3p	40	177,188	~0.002	14
^{74}Kr	2p	2	456	~0.002	16
^{72}Se	4p	17	862	~0.002	17
^{72}Br	3pn	<1(3.5@100MeV)	654,583	~0.008	18, 22
^{71}Br	αp	1		—	—
^{70}Se	α2p	10	945	~0.002	19
^{49}Cr	2pn	132	272, 8.3	~0.013	20
^{50}Cr	2p	335	783, 1098	~0.002	21
^{49}V	3p	43	102	~0.002	20
^{47}V	αp	70	87.5, 58.2, 260	~0.002	23

[a]From the statistical compound nucleus evaporation code ALICE. [15])
[b]Ratio of n-γ-γ/γ-γ events. See text.

Figure Captions

Fig. 1 Excitation functions for several nuclides produced in the $^{36}Ar + ^{40}Ca$, ^{16}O reactions.

Fig. 2. Composite sum of 20 Compton suppressed Ge detectors with the following gating criteria: a) any gamma with any gamma; b) a) plus any neutron. The following numbers indicate the nuclide assigned to each transition. 1) ^{73}Kr, 2) ^{73}Br, 3) ^{74}Kr, 4) ^{72}Se, 5) ^{72}Br, 6) ^{70}Se, 7) ^{49}Cr, 8) ^{50}Cr, 9) ^{49}V, 10) ^{47}V.

Fig. 3. Coincidence spectrum projection from the n-γ-γ matrix for the 128.6 keV transition assigned to ^{73}Kr.

Fig. 4. Proposed partial level structure for ^{73}Kr. Transition energies and gamma ray intensities relative to the 128.6 keV transition are given.

References

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1) P. Möller and J.R. Nix, Nucl. Phys. A361 (1981) 117.

2) J.Eberth et al., Proc. of the Fifth Int. Conf. on Nuclei Far From Stability, Rossea Lake, Canada, AIP Conf. Proc. 164 (1988) 268.

3) M. Epherre, G. Audi, C. Thibault, R. Klapisch, G. Huber, F. Touchard, and H. Wollnik, Phys. Rev. C 19 (1979) 1504.

4) D.M. Moltz, K.S. Toth, F.T. Avignone III, H. Noma, B.G. Ritchie, and B.D. Kern, Phys. Lett. 113B (1982) 16.

5) G. Audi, M. Epherre, C. Thibault, A.H. Wapstra, and K. Bos, Nucl. Phys. A378 (1982) 443.

6) D.M. Moltz, K.S. Toth, R.E. Tribble, R.E. Neese, and J.P. Sullivan, Phys. Rev. C 26 (1982) 1914.

7) D.M. Moltz, A.C. Betker, J.P. Sullivan, R.H. Burch, C.A. Gagliardi, R.E. Tribble, K.S. Toth, and F.T. Avignone III, Phys. Rev. C 35 (1987) 1275.

8) P. Möller, W.D. Myers, W.J. Swiatecki, and J. Treiner, Proc. of the 7th Int. Conf. on Atomic Masses and Fundamental Constants (AMCO-7), Darmstadt-Seeheim, West Germany, 457 (1984).

9) W. Nazarewicz, J. Dudek, R. Bengtsson, T. Bengtsson, and I. Ragnarsson, Nucl. Phys. A435 (1985) 397.

10) I. Ragnarsson and R.K. Sheline, Phys. Scripta 29 (1984) 385.

11) C.J. Lister, B.J. Varley, H.G. Price, and J.W. Olness, Phys. Rev. Lett. 49 (1982) 308.

12) R.M. Diamond, in "Nuclei Off the Line of Stability", R.A.Meyer and D.S.Brenner, eds., ACS Symposia Series 324, American Chemical Society, Washington, D.C. (1986) p. 341.

13) M. Satteson, J. Boyle, T.M. Cornier, E. Dafni, A.V. Ramayya, and C.Y. Wu, University of Rochester Nuclear Structure Research Laboratory Annual Report, 78 (1987).

14) J. Heese, K.P. Lieb, L. Lühmann, S. Ulbig, B. Wörmann, D. Alber, H. Grawe, H. Haas, and B. Spellmeyer, Phys. Rev. C 36 (1987) 2409.

15) M. Blann and J. Birplinghoff, Lawrence Livermore National Laboratory, Report UCID-19614 (1976).

16) J.H. Hamilton, et al., Proc. of the 4th Int. Conf. on Nuclei Far From Stability, Helsingór, Denmark, 391 (1981).

17) H.P. Hellmeister, E. Schmidt, M. Uhrmacher, R. Rascher, K.P. Lieb, and D. Pantelica, Phys. Rev. C 17 (1978) 2113.

18) G. Garcia Bermudez, C. Baktash, A.J. Kreiner, and M.A.J. Maricotti, Phys. Rev. C 25 (1982) 1396.

19) A. Ahmed et al., Phys. Rev. C 24 (1981) 1486.

20) L.R. Medsker, L.H. Fry, Jr., and D.C. Wilson, Phys. Rev. C 18 (1978) 2584.

21) W. Dehnhardt, O.C. Kistner, W. Kutshera, and H.J. Sunn, Phys. Rev. C 7 (1973) 1471.

22) S. Ulbig, et al., Z Phys. A 329 (1988) 51.

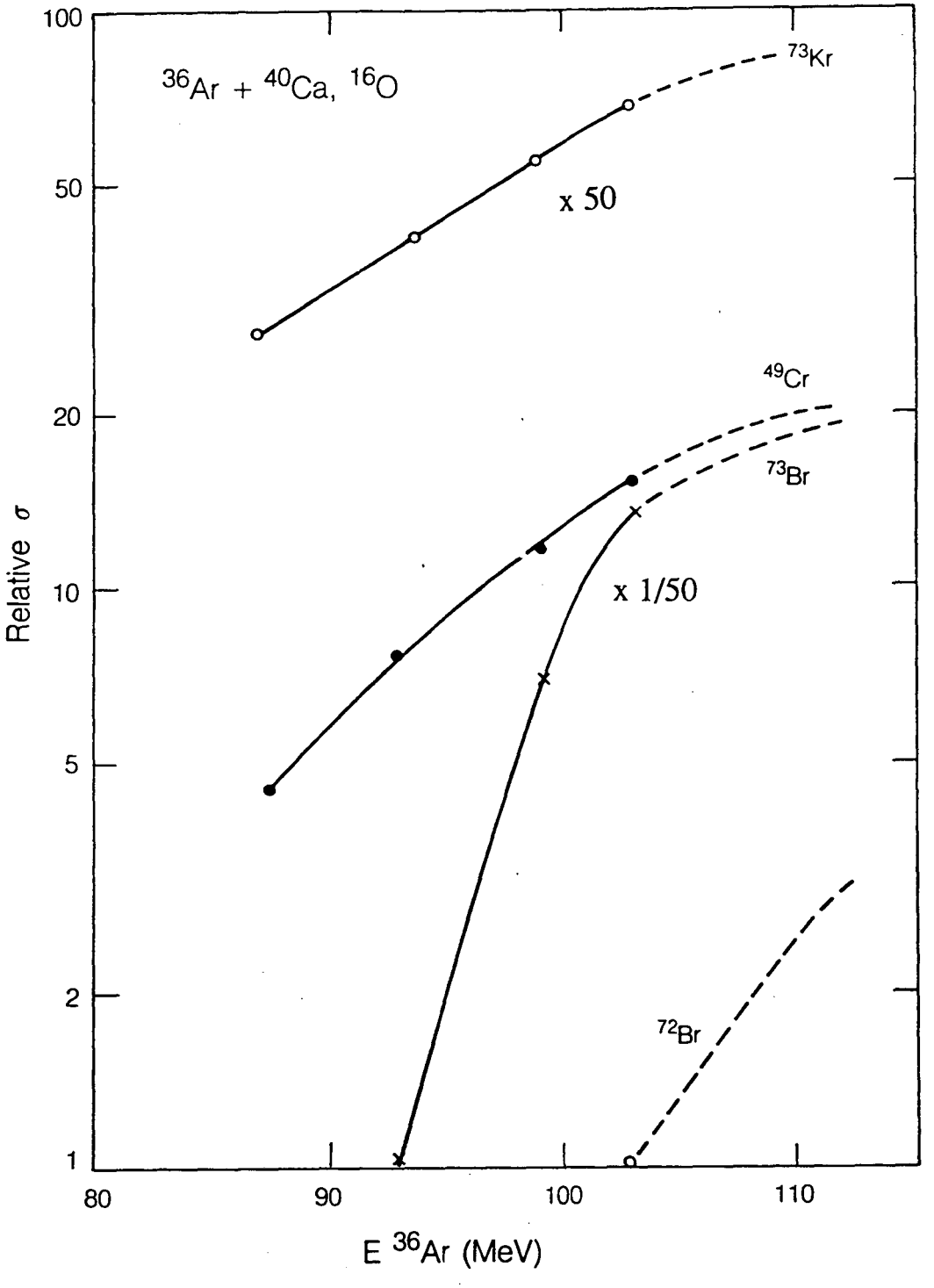
23) M. Schrader, K. Buccholz, and H.V. Klapdor, Nucl. Phys. A213 (1973) 173.

24) M. Satteson, *et al.*, J. Phys. G: Nucl. Part. Phys. 16 (1990) L27.

25) M. M. King, Nucl. Data Sheets 51 (1987) 161.

26) R.B. Piercey, et al., Phys. Rev. Lett. 47 (1981) 1514.

27) G. Leander, private communication.



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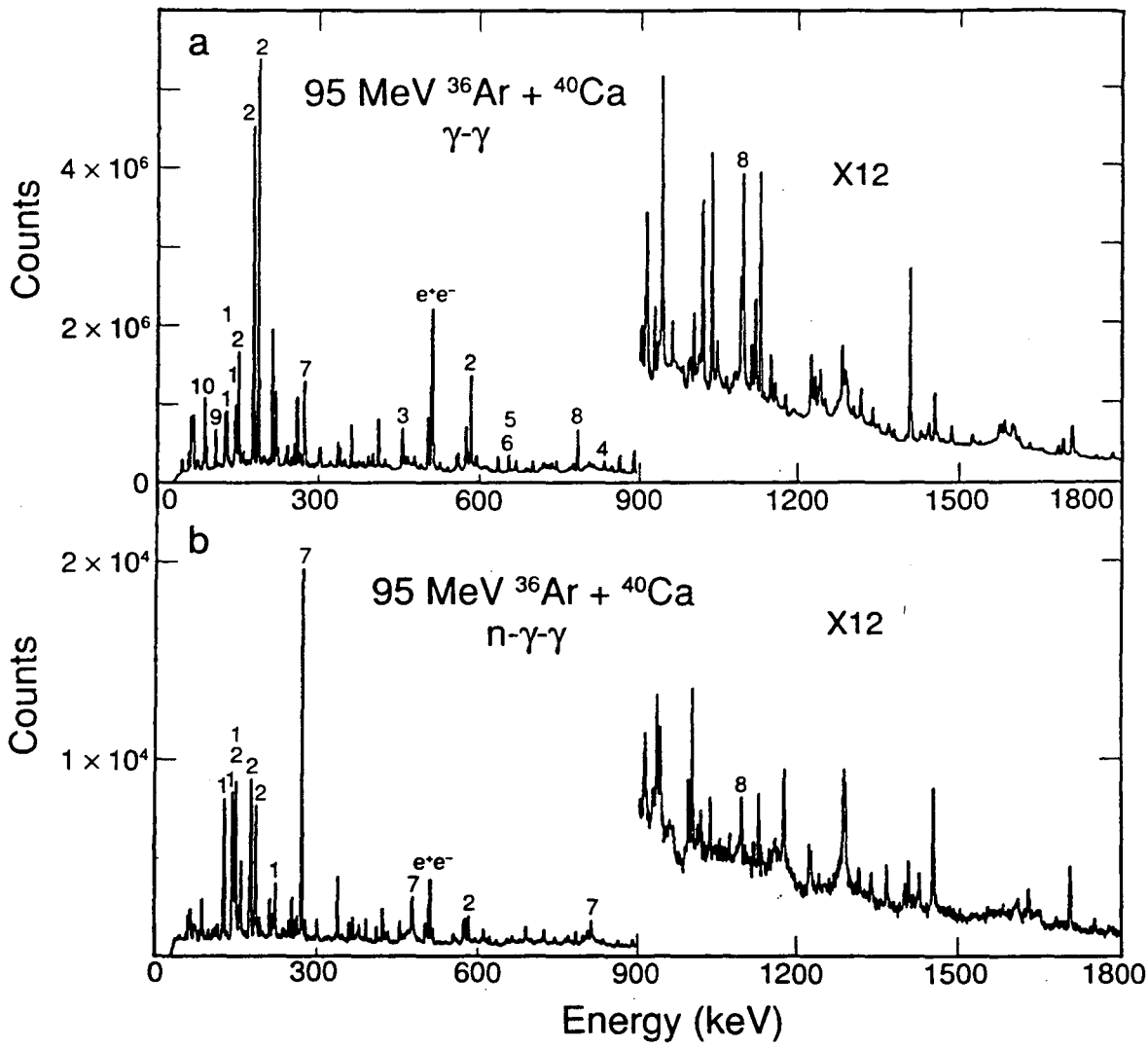
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95 MeV 36Ar + 40Ca
γ-γ
X12
Counts
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0
e+e-
b
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n-γ-γ
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Energy (keV)

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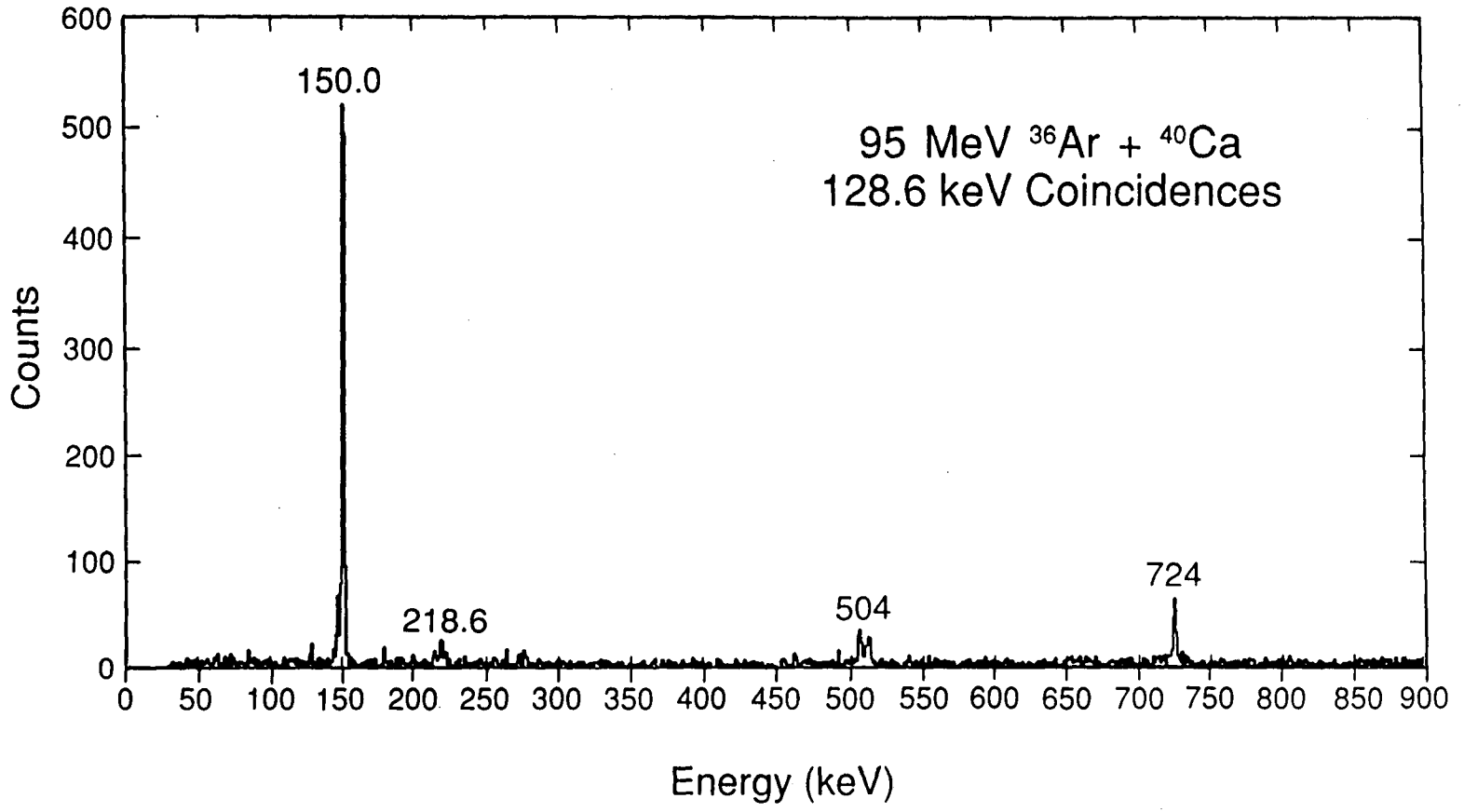

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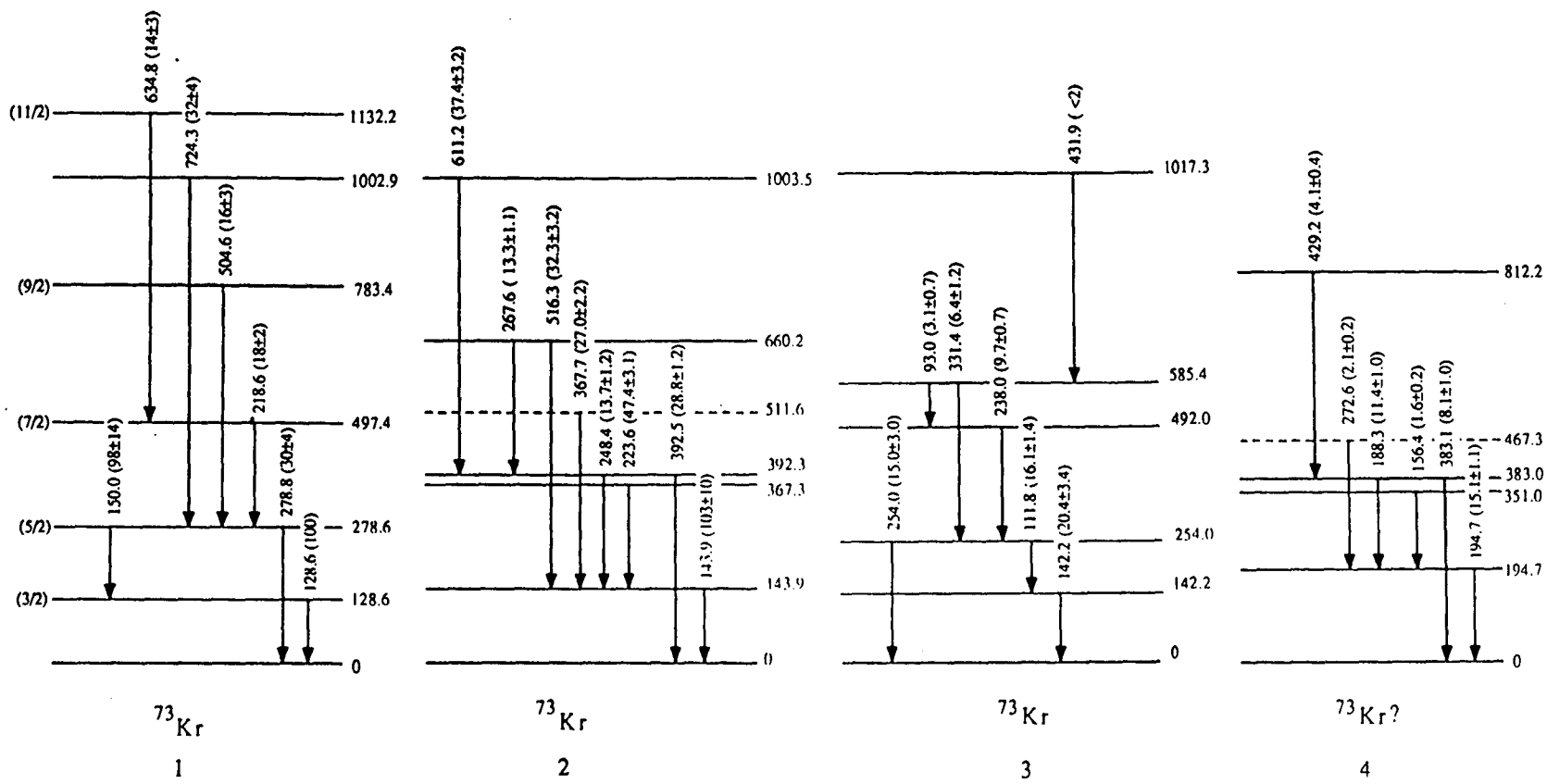
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724.3 (32±4)
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218.6 (18±2)
(7/2)
497.4
150.0 (98±14)
278.8 (30±4)
(5/2)
278.6
128.6 (100)
(3/2)
128.6
0
73Kr
1
611.2 (37.4±3.2)
1003.5
267.6 (13.3±1.1)
516.3 (32.3±3.2)
367.7 (27.0±2.2)
660.2
248.4 (13.7±1.2)
223.6 (47.4±3.1)
392.5 (28.8±1.2)
511.6
392.3
367.3
143.9 (103±10)
143.9
0
73Kr
2
431.9 (<2)
1017.3
93.0 (3.1±0.7)
331.4 (6.4±1.2)
238.0 (9.7±0.7)
585.4
492.0
254.0 (15.0±3.0)
111.8 (16.1±1.4)
254.0
142.2 (20.4±3.4)
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73Kr
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429.2 (4.1±0.4)
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272.6 (2.1±0.2)
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383.1 (8.1±1.0)
467.3
383.0
351.0
194.7 (15.1±1.1)
194.7
0
73Kr?
4

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