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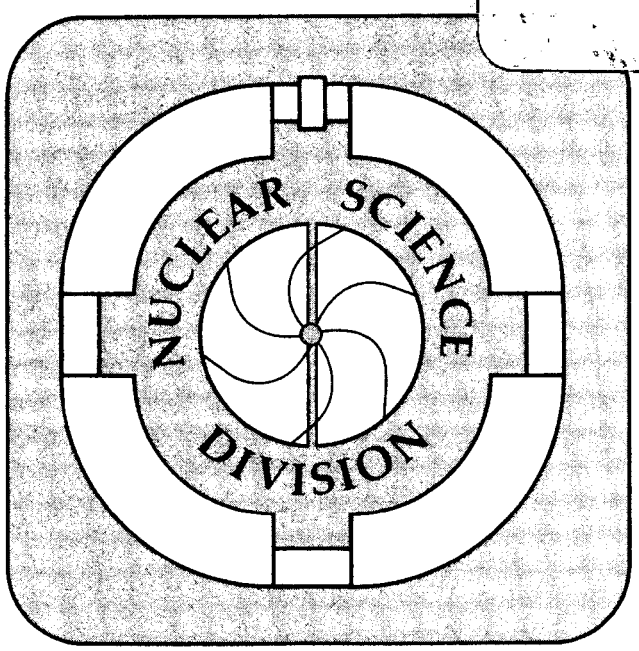

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Searches for Supermassive X^- Particles in Iron

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ABSTRACT

Two searches have been made for negatively-charged massive elementary particles (X^-) in iron nuclei by utilizing the fact that such systems would have the nuclear properties of iron but the chemical properties of manganese. We have looked for $^{56,58}FeX^-$ by searching for gamma rays emitted following the beta decays of $^{56}CoX^-$ and $^{59}FeX^-$ produced by (p,n) and (n,γ) reactions, respectively. No evidence of such particles was observed in either experiment, but a limit has been established on the possible concentration of X^- particles in iron of $< 1.2 \times 10^{-12}$ per nucleon.

As the energies available in accelerators have increased, new particles have been discovered with ever higher masses. At present, there is no reason to believe that the upper limit on the mass of elementary particles has been reached. In fact, there are theoretical reasons[1] to suspect that very massive (10 GeV — 100 TeV) particles do exist. Such particles would have been created in the Big Bang and, assuming that they carry some exotic quantum number (technicolor ?), may be sufficiently long lived to have survived to the present day. Among these may be the so-called $X^{\pm}$ particles which have only electromagnetic interactions with ordinary matter. The X^+ particles would capture an electron and then behave as a heavy isotope of hydrogen. The X^- particles would bind to atomic nuclei and thereby reduce the effective nuclear charge by one unit. Thus, the chemical properties of an atom of $(Z,N)X^-$ would be those of an ordinary atom of $(Z-1,N)$, while its nuclear properties would be nearly the same as those of the nucleus (Z,N) (Refs. 1,2). Calculations of the expected abundances of massive elementary particles depend sensitively on their assumed properites. If these objects are hadrons, then their abundances are estimated to be in the range of 10^{-10} — 10^{-12} per nucleon[3,4] . If they are leptons, however, their concentration may be as high as 10^{-5} per nucleon[4] .

Several previous searches have concentrated on looking for anomalously heavy isotopes of hydrogen, which in the present context would correspond to either X^+ particles or HeX^- bound states[5,6,7] . From the work of Smith et al.[7] , it is known that for masses $\lesssim$ 1 TeV the concentration of such objects in terrestrial water is less than about 10^{-29} per nucleon. While these limits seem to rule out the existence of X^+'s in anywhere near the abundance predicted for particles in this mass range, they do not necessarily preclude a much larger abundance of X^-'s. Such an asymmetry might be the result of the same sort of process that

led to the observed baryon excess in the universe. Searches in boron, nitrogen, fluorine, magnesium, and curium have established upper limits on the possible abundance of X^- particles in these elements to be in the range of $10^{-8} - 10^{-16}$ per nucleon[8-12] . However, as discussed by Turkevich et al.[9] , nucleosynthesis arguments suggest that these elements may not have been the most favorable places in which to look for X^- particles.

The presence of an X^- in a nucleus decreases the effective nuclear charge by one unit and hence lowers the Coulomb barrier for charged-particle-induced reactions on that nucleus. Furthermore, the Coulomb binding energy of an X^- to a nucleus grows with Z, so the Q-values for fusion reactions on a nucleus containing an X^- will be larger than those for reactions on ordinary nuclei. On the other hand, it should be pointed out that if the mass of an X^- is much greater than that of a typical nucleus, then in stellar environments nuclei containing such particles will have much lower thermal velocities than normal nuclei do. Nevertheless, the net result of these effects is that during each major stage of nucleosynthesis X^-'s will be preferentially concentrated in the heaviest element produced. Turkevich et al.[9] found that essentially all X^-'s will emerge from Big Bang nucleosynthesis bound to ^{7}Be. As a result of hydrogen-, helium-, carbon-, oxygen-, and silicon-burning in stellar environments, X^-'s should end up bound to carbon, oxygen, neon, magnesium, silicon, and iron nuclei. For example, we have calculated that in the nuclear statistical equilibrium which processes matter from silicon into the elements up to iron, virtually all of the X^-'s present will end up bound to iron nuclei. We have, therefore, undertaken two different searches for FeX^- systems, whose chemical properties would be those of manganese.

We have looked for evidence of both $^{56}FeX^-$ and $^{58}FeX^-$ by searching for

characteristic gamma rays emitted following the beta decays of $^{56}CoX^-$ and $^{59}FeX^-$ produced by (p,n) and (n,γ) reactions, respectively. The known[13] major decay modes of ^{56}Co and ^{59}Fe are shown in Figures 1a and 1b. Due to the variation in the Coulomb binding energy with Z, the presence of X^- particles in nuclei alters the relative masses of all members of a given isobar , which then changes beta-decay energies and, hence, half lives. The X^- is presumed to interact only electromagnetically with the nucleus. Thus, in the calculations discussed here, we assume that the log ft values for the beta decays of $^{56}CoX^-$ and $^{59}FeX^-$ are the same as those for ^{56}Co and ^{59}Fe, respectively. The presence of an X^- in a nucleus may also shift ,to some extent, the energies of the excited states of that nucleus. As a result of the collective nature of the excited states of ^{56}Fe, such shifts in the positions of these levels are expected to be quite small[14] and are neglected in our analysis. On the other hand, the low-lying levels in ^{59}Co are well described as proton single-particle states[15,16] and are thus more strongly affected by the presence of an X^- . Assuming the mass of the X^- is much larger than that of the nucleus, and using harmonic-oscillator wave functions, we have calculated the expected shifts in the A=59 system.

The results of our calculations for the $^{56}CoX^-$ and $^{59}FeX^-$ decay schemes are shown in Figs. 1c and 1d. We find that the beta-decay half life of $^{56}CoX^-$ is approximately 1 year, and that of $^{59}FeX^-$ is 1.5 days. The primary gamma rays from $^{56}CoX^-$ decay will be essentially the same as those of ^{56}Co, while those from $^{59}FeX^-$ will be shifted down in energy by approximately 120 keV with respect to those from ^{59}Fe.

In the first experiment, we attempted to produce $^{56}CoX^-$ via the $^{56}FeX^-$ (p,n) reaction. A thick disc containing 28 grams of 99.9%-pure manganese was bombarded for six hours with a 2-microampere beam of 10-MeV protons from

Lawrence Berkeley Laboratory's 88-Inch Cyclotron. After the sample was allowed to cool for one month, it was dissolved in 250 ml of concentrated HCl and passed through a column of AG1-X8 anion-exchange resin in order to isolate the iron fraction, which would contain any $^{56}CoX^-$ present. The iron fraction extracted from this sample was stripped from the column using water. The principal activity produced in the bombardment of the manganese target with the proton beam was ^{55}Fe. By measuring, both before and after the chemical separation, the yield of Mn K x-rays produced by the decay of this isotope, we determined that the chemical-recovery efficiency for iron was approximately 50%. The iron fraction was then counted in close geometry using a 110 cm^3 high-purity Ge detector shielded with 10 cm of lead. A portion of the gamma-ray spectrum observed in a period of sixty-three hours is shown in Figure 2a.

From this figure, it can be seen that clear peaks are observed at the positions expected from ^{56}Co and/or $^{56}CoX^-$ decay. This could either signal the presence of X^- particles in iron, or could be merely the result of imperfect chemical separation. These two possibilities can be distinguished by measuring the half lives of these gamma rays. We followed their emission rates over a period of approximately two months. The results of these measurements are shown in Fig. 2b. The composite decay curve obtained by summing together the yields of the 847- and 1238-keV gamma rays is consistent with that expected from a single activity with the known[13] 78.8-day half life of ^{56}Co. A least-squares fit to this decay curve allows an upper limit to be placed on a one-year component. This one-sigma limit was then combined with the measured chemical-recovery and counting efficiencies to set an upper limit on the number of $^{56}CoX^-$ nuclei present in the irradiated sample. In a separate experiment, we determined that the thick-target $^{56}Fe(p,n)$ yield for 10-MeV protons is $(3.1 \pm 0.5) \times 10^{-4}$ per

incident proton. The presence of an X^- in an ^{56}Fe nucleus should increase this yield due to the lowering of both the Coulomb barrier and the reaction threshold energy. However, in order to establish a conservative limit, we have assumed that this yield is unaffected by the presence of an X^- . We then establish a limit on the concentration of $^{56}FeX^-$ nuclei in manganese. Using the fact that the solar-system abundance of iron is ninety-seven times that of manganese[17] , we find that the concentration of X^- particles in iron is $< 1.1 \times 10^{-11}$ per nucleon.

In the second experiment, we attempted to produce $^{59}FeX^-$ via the $^{58}FeX^-$ (n,γ) reaction. A 58.2-gram sample of 99.995%-pure manganese was irradiated for two hours in a thermal flux of 8.4×10^{12} neutrons / cm^2 - second at the U. C. Berkeley TRIGA Mark III reactor. At the end of this irradiation, the sample contained approximately 800 Curies of the $t_{1/2}$ = 2.58-hour ^{56}Mn. After allowing this initial activity to decay for three days, the manganese was dissolved in 500 ml of concentrated HCl plus 5 ml concentrated HNO_3 and then passed through columns of hydrated antimony pentoxide and AG1-X8 anion-exchange resin in order to remove ^{24}Na, ^{59}Fe, and ^{60}Co activities (produced by neutron captures on parts-per-million impurities in the manganese sample). Six grams of lanthanum carrier were then added to the sample followed by 100 ml of concentrated HF. Unwanted rare-earth activities such as ^{140}La and ^{160}Tb were precipitated as fluorides, then centrifuged and discarded. The manganese solution was then boiled down to approximatley 100 ml for counting. A major product of the neutron irradiation of the manganese sample was ^{54}Mn, produced by fast neutrons via the $^{55}Mn(n,2n)$ reaction. By measuring, both before and after the chemistry, the yield of 835-keV gamma rays produced by the decay of this isotope, we determined that the manganese chemical-recovery efficiency was (62 $\pm$ 1) %. The chemical reduction factors for sodium, cobalt, and the rare earths were measured to be

>12,000, > 2600, and $\approx$ 15, respectively. The purified manganese fraction was then counted for 24 hours in close geometry using two 110 cm^3 and one 180 cm^3 high-purity Ge detectors, each shielded with 10 cm of lead. A portion of the gamma-ray spectrum observed in one detector over a period of twenty-four hours is shown in Figure 3.

Following this chemistry, the major peaks seen in the spectrum, aside from $^{54,56}Mn$ decay gamma rays, are due to the decays of $^{110}Ag^m$ nuclei which were produced by neutron captures on a < 1 part-per-million silver impurity in the manganese sample. Neither of the expected $^{59}FeX^-$ decay gamma rays were observed. From the observed widths of known gamma-ray peaks in this spectrum and from the measured background counting rates near the expected peak positions, one-sigma upper limits on the net numbers of counts attributable to such decays were extracted from the data. It should be noted that because there are no other peaks nearby, these limits are not very sensitive to the calculations of the energy shifts for the $^{59}FeX^-$ decay gamma rays. From these limits and the measured efficiencies, we place an upper limit on the number of $^{59}FeX^-$ nuclei present in the irradiated sample. Assuming that the 1.14-barn thermal-neutron capture cross section of ^{58}Fe (Ref. 13) is unaffected by the presence of an X^- particle, we derive, as described above, that the upper limit on the concentration of X^- particles in iron is $< 1.2 \times 10^{-12}$ per nucleon.

In conclusion, we have performed two different radiochemical searches for evidence of X^- particles in iron. No evidence of such particles was observed in either experiment. From these searches, however, we have established that the concentration of X^- particles in iron is $< 1.2 \times 10^{-12}$ per nucleon. This is at or below the level expected[3,4] if X^- 's were distributed uniformly in all matter. This is in spite of the enhanced concentration of X^- particles in iron suggested by

nucleosynthesis arguments.

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FIGURE CAPTIONS

1. Known principal decay modes of (a) ^{56}Co and (b) ^{59}Fe , and calculated decay modes of (c) $^{56}CoX^-$ and (d) $^{59}FeX^-$. Note that the spins shown for the levels in $^{56}CoX^-$ and $^{59}FeX^-$ neglect the possible spin of the X^- particle.

2. a) Relevant portion of the gamma-ray spectrum observed from the iron fraction isolated from the proton-irradiated manganese sample. The counting period was 63 hours. The positions of the known ^{56}Co gamma rays (which are expected to be essentially the same as those of $^{56}CoX^-$) are indicated by arrows. Unlabeled peaks are due to the decays of uranium and thorium contained in the shielding material. b) Composite decay curve of the 847 + 1238 keV gamma rays. The line is a least-squares fit assuming a single activity with the known 78.8-day half life of ^{56}Co.

3. Relevant portion of the gamma-ray spectrum observed following the neutron activation and chemical purification of a 58.2-gram sample of manganese. The counting period was 24 hours. The positions of the known ^{59}Fe gamma rays are indicated by solid arrows. The expected positions of the $^{59}FeX^-$ gamma rays are indicated by dashed arrows.

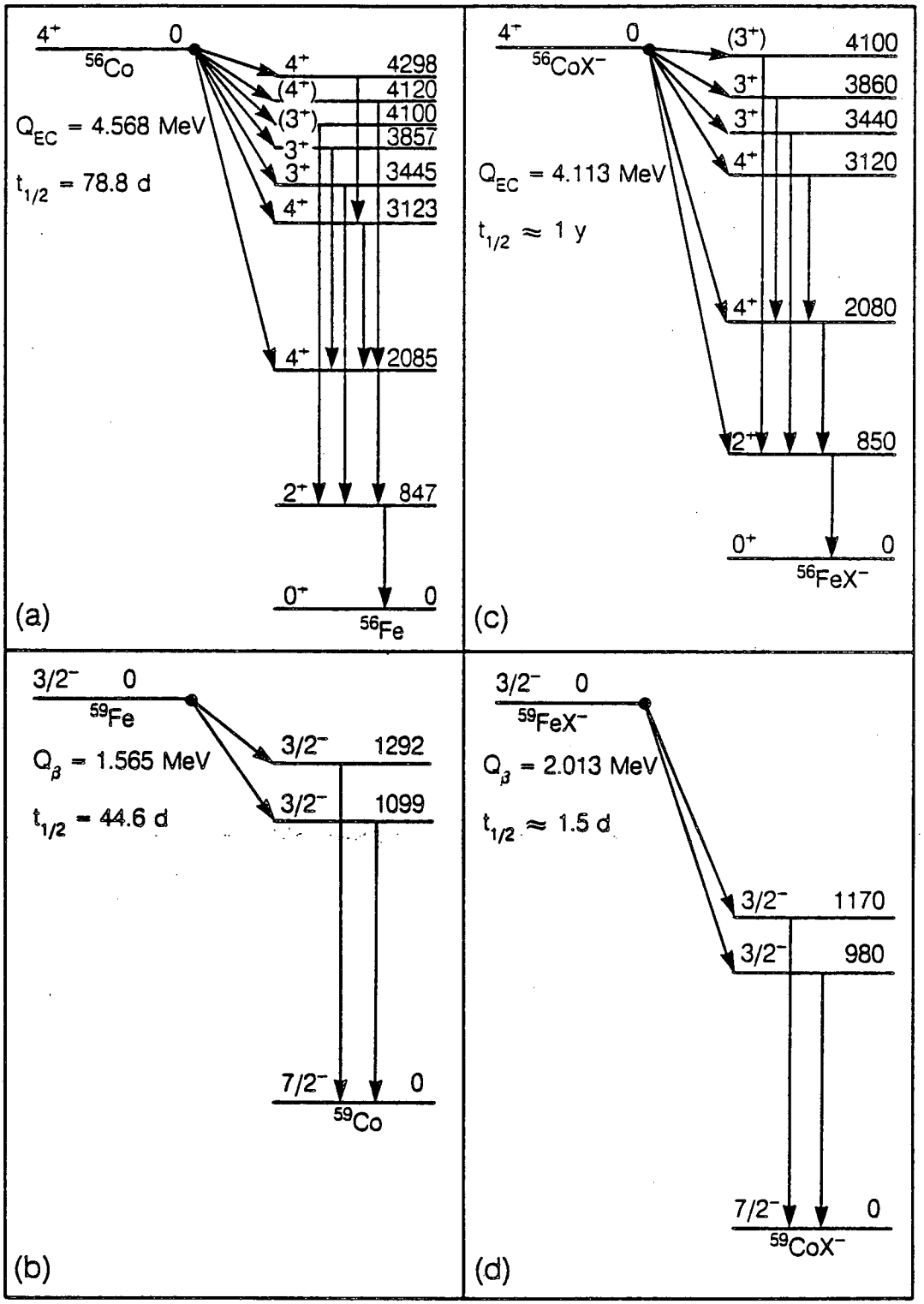

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Fig. 1

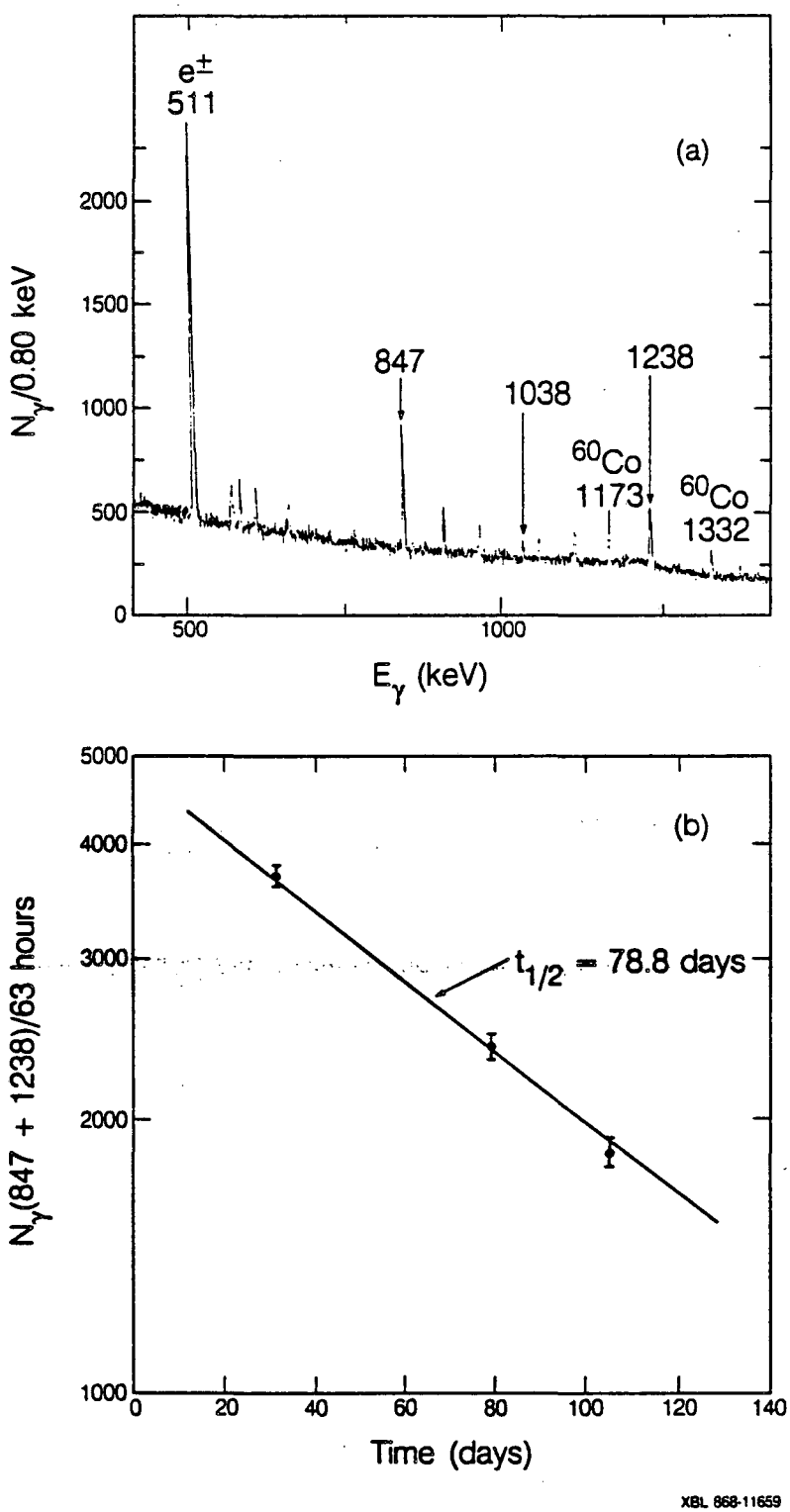
e±
511
(a)
2000
1500
1000
500
0
847
1038
1238
60Co
1173
60Co
1332
500
1000
Nγ/0.80 keV
Eγ (keV)
5000
4000
3000
2000
1000
(b)
t1/2 = 78.8 days
0
20
40
60
80
100
120
140
Nγ(847 + 1238)/63 hours
Time (days)
XBL 868-11659

Fig. 2

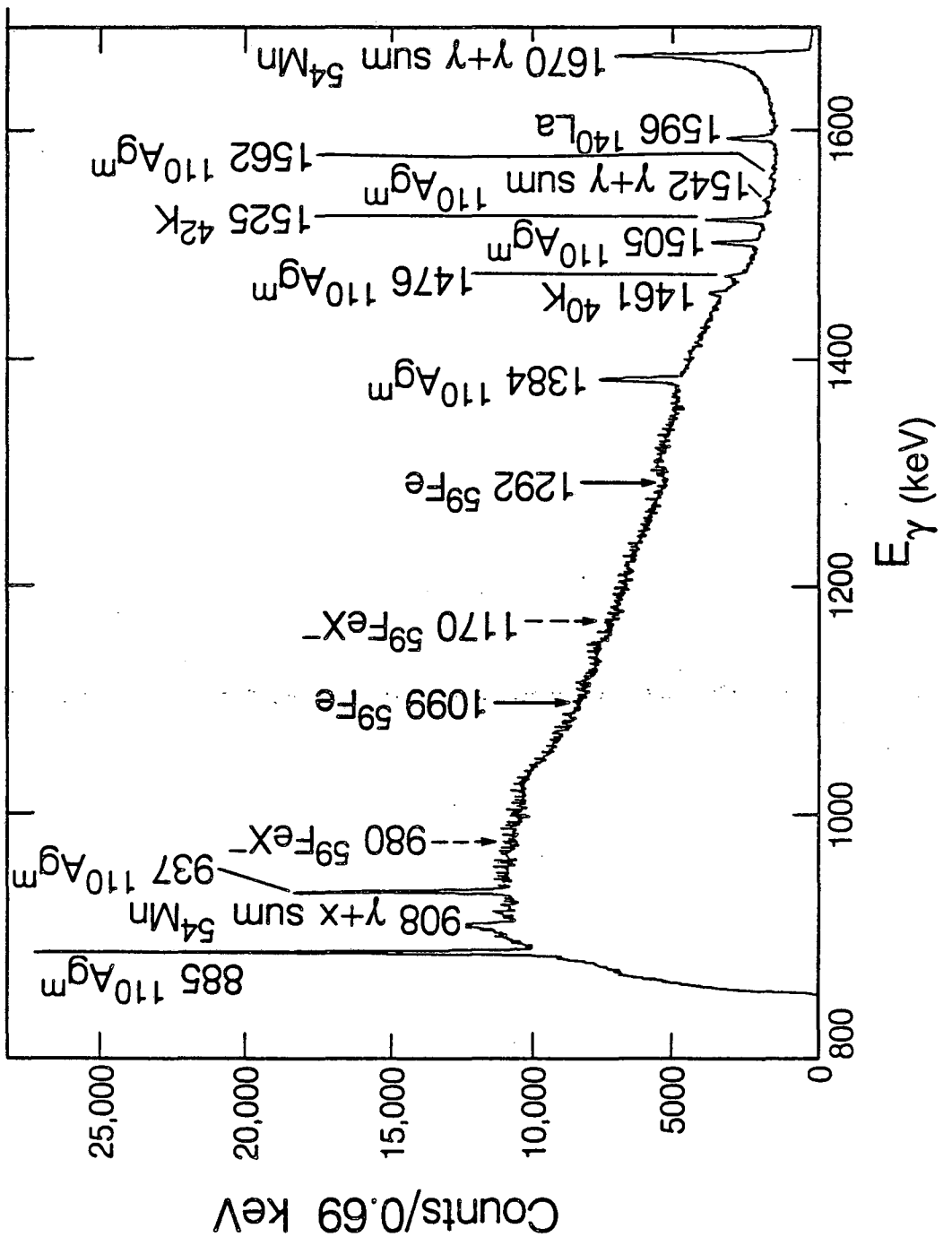

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Fig. 3

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