SEARCH FOR BOUND NEUTRAL NUCLEI (Z=0)

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Abstract.

A search of indirect evidence for the production of bound neutral nuclei in the 24 GeV proton induced fragmentation of W is described. The enrichment by two neutrons of ^{70}Zn and ^{138}Ba in a shielded sample, which was looked for as an indication of the occurence of bound neutral nuclei, is observed. Among the many side reactions studied which could also account for the observed results, one is finally found to have a high enough yield. It is the (t,p) reaction induced by tritons from the p+W fragmentation process with an energy high enough to cross the shield which protects the sample.

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1. Introduction.

The neutron-neutron force is not known well enough to unambiguously predict whether polyneutron systems might have a bound state. The basic reason for this uncertainty lies with the fact that for lack of a target the nn interaction cannot be directly studied like the pp interaction. One has to rely upon indirect informations such as those derived from nn final state interactions.

For a long time theoretical estimates have yielded contradictory conclusions for the occurence of bound neutral nuclei. After tentative evidence was reported for a bound ^{3}n [Ajd 65], the adjunction of a moderately attractive ^{3}P to the nn force was found to bind three neutrons without binding two [Mit 66]. Other estimates of ^{A}n binding energies were derived from systematics. For instance, Goldanskii [Gol 73] used the variation of $\Delta_{TT'}$, the energy difference between the lowest states of different isospins, to predict that neutral nuclei could not be found for small mass numbers. At least 10^2 or 10^3 neutrons were found to be needed to form bound states [Baz 72, Ant 74].

Rather than relying on the systematics of binding energies, Vautherin [Vau 77] has recently used neutron neutron forces to make a Hartree-Fock calculation of the lowest configuration of a ^{A}n nucleus. In the most favourable, A=8, he observes that the tensor force nearly binds a cubic structure of 8 neutrons. However the changes in the nn force required to bind ^{8}n appear to be unrealistic.

When this work was undertaken, some three years ago, none of the theoretical arguments appeared compelling enough to definitely exclude

the occurence of bound neutral nuclei. The series of experiments reported here were intended to search for bound ^{A}n nuclei with $A > 4$. Indeed, most previous experimental results dealt with ^{3}n and ^{4}n. Most of them are reviewed by Fiarman and Hanna [Fia 75] for A=3, and Fiarman and Meyerhof [Fia 73] for A=4. All methods eventually led to negative results, strongly suggesting that neither ^{3}n nor ^{4}n are bound. More recently, the $^{7}Li + {}^{7}Li \rightarrow {}^{10}C + {}^{4}n$ again gave a very small upper limit (30 $nb.sr^{-1}$) for the ^{4}n formation cross section [Cer 74].

To our knowledge, only one attempt [Bri 64] had been made to look at heavier bound neutral nuclei, previous to our work. It consisted in bombarding ^{48}Ca targets with 72 MeV ^{12}C ions. Upper limits for the formation of ^{6}n were set at 1 $\mu b.sr^{-1}$.

Simultaneously with our work, and independently, Turkevich and his coworkers [Tur 73] proposed a method to look for neutral nuclei with $A > 4$. The negative results obtained [Tur 77] will be discussed in section 4.

2. Experimental method and results.

2.1. Means of producing neutral nuclei.

If bound neutral nuclei do occur, an experiment must be designed which produces them with a high enough yield to allow their detection.

The most favourable reaction is the fragmentation of heavy nuclei induced by high-energy protons [Hud 68]. Isotopes of light elements are emitted mostly isotropically with an energy spectrum which peaks some 10 to 20 MeV above the Coulomb barrier [Hyd 71, Ala 71, Pos 71, Zeb 75, Bog 76]. A remarkable feature of the fragmentation cross sections is their smooth variation with incident energy, mass of target nucleus and mass of fragmentation product [Sil 73]. The cross sections raise very rapidly when the incident energy increases up to 1 GeV or so. Above 1 GeV, the increase is much slower : typically the ratio $\sigma(20\ GeV)/\sigma(3\ GeV)$ is about 2. The smoothness of the variation of the cross section σ with the mass of the produced nuclide is best illustrated by the possibility of drawing lines

of equal σ through the chart of light nuclides [Pos 71, Thi 71].

On that basis, it was felt that if bound neutral nuclei did occur, their production cross section in proton-induced fragmentation could be extrapolated from existing results.

2.2. Means of observing neutral nuclei.

An experiment could be set up to directly observe neutral nuclei among all the nuclides and particles emitted in the bombardment of heavy target nuclei by 24 GeV protons from the CERN synchrotron.

An absorbant and an anticoincidence detector would be used to eliminate charged nuclei. The signal in a Si-detector of the remaining neutral products would provide two informations : 1) the time of flight, by making use of the time structure of the fast ejection beam ; 2) the energy deposited in the detector by a recoiling Si nucleus.

The combination of these two parameters would discriminate in particular between n and ^{A}n with a very sufficient efficiency in spite of the large number of neutrons.

In view of the beam time and equipment needed for such an experiment, it was decided to first look at a lower cost for an indirect evidence.

The aim of the study reported here is to search for the nucleus $^{N+Z+2}_{Z}X$ produced through the $^{N+Z}_{Z}X(^{A}n,(A-2)n)\,^{N+Z+2}_{Z}X$ reaction in a sample containing the $^{N+Z}_{Z}X$ nucleus located in the vicinity of a W target irradiated by 24 GeV protons. An absorbant is used to shield the sample from the W target. One geometrical arrangement is shown in figure 1.

Two $^{N+2}_{Z}X$ nuclei were used, ^{70}Zn [Dét 77] and ^{136}Ba, because they had all the following favourable properties :

1) the elements are available in large amounts with good purity at low cost.
2) the expected residual isotope $^{N+Z+2}_{Z}X$ is long lived ($T_{1/2}$ > 1 day).

3) its daughter $^{N+Z+2}_{Z+1}Y$ can be "milked out" by proper chemistry with high efficiency and selectivity.

4) it emits a very characteristic β-delayed γ-ray with large branching ratio and high energy.

5) the isotope $^{N+Z+1}_{Z}X$ which can be formed by (n,γ) neutron capture in the sample is short-lived so that it cannot accumulate.

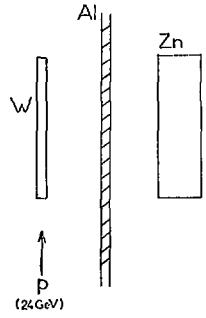

Fig.1. Sketch of the experimental arrangement. In some of the experiments, the Zn sample was replaced by a $BaCl_2$ sample.

2.3. Chemical procedure.

The chemical separation must be as selective and quantitative as possible for the element to be "milked out". It must be easy to perform on rather large amounts of material, several successive separations must also be possible. Solvant extraction appeared to be the best suited method.

2.3.1. "Milking out" Ga from Zn.

Ga is extracted as a chloro complex form in amyl acétate. Amyl acétate was prefered to the usual [Nor 57] ethylic and isopropylic ethers, because, contrary to the later, it is not soluble in aqueous phase for high concentrations of HCl and $ZnCl_2$. The 100 g Zn sample is dissolved in concentrated HCl. The resulting solution is brought to 6 normality by adding up more HCl. The concentration of $ZnCl_2$ at that point is about 2.5 M.

Gallium is extracted by shaking the solution with amylacetate.

The extraction efficiencies of Ga, Zn and other elements has been derived from the γ spectra measured. They are listed in table 1.

Table 1

Efficiency (in %) of the extraction of Ga and other elements by the method described in section 2.3.1.

Ga	Zn	Cu	Ni	Co	Fe[a)]	Mn	V	Ti
98.5	0.45	0.28	0.10	0.15	95.6	0.11	0.11	0.09

a) in the conditions of our experiment the presence of Fe isotopes did not complicate the search for the γ-rays from ^{72}Ga.

2.3.2. "Milking out" La from Ba.

The best conditions for this separation have been derived from the work of Dubuquoy et al. [Dub 67] who studied the partition of Cs, Ba, Eu between an aqueous phase and di-2-ethyl hexyl phosphoric (HDEHP) acid solutions.

The 30 g $BaCl_2$ sample is put into a 0.01 M hydrochloric acid solution (1 M for Ba). La is extracted by shaking that aqueous phase with a 0.1 M HDEHP hexane solution. The organic phase is washed twice by small volumes of 0.01 M HCl to decrease the extracted amount of Ba.

At last, La is recovered in a 2N HCl solution.

The extraction efficiencies are again derived from the measured γ-spectra. They are given in table 2.

Table 2

Efficiency (in %) of the extraction of La and other elements by the method described in section 2.3.2.

Ce	La	Ba	Cs	Xe[b]	I	Sb	In[b]
95 %	95 %	a	0.028	10.5	1.8	0.21	10.6

[a] unmeasurable

[b] in a second extraction the efficiencies decrease to 0.1% and 0.01% for Xe and In, respectively.

2.4. Experimental results.

The sample of natural Zn or Ba (as $BaCl_2$) is located some 8 cm away from a 10 cm long W target irradiated by 24 GeV protons (fig.1). This experiment is operated as a parasite and only requires to interrupt the beam for putting in and taking away the sample.

After the irradiation has lasted some two days in the case of Zn (since $T_{1/2}$ (^{72}Zn) = 46.5h) or two weeks in the case of Ba (since $T_{1/2}$ (^{140}Ba) = 12.79 days), the sample is shipped back to Orsay via air mail.

The Z+1 element -i.e. Ga for the Zn sample, and La for the Ba sample- is chemically "milked out" through the methods described in section 2.3. The extraction is repeated twice so that the abundance of Ga or La in the solution is reduced to a few 10^{-4} of the initial abundance.

If ^{72}Zn or ^{140}Ba have indeed been produced, they will yield ^{72}Ga or ^{140}La, respectively, by β decay. At the calculated time of the maximum abundance of these daughter activities, they are milked out in a third chemical extraction.

Their presence can be characterized by their β-delayed γ-rays observed by a Ge(Li) detector. As already reported [Dét 77], ^{72}Zn was indeed formed in the conditions of the experiment. Later on, the formation

of ^{140}Ba was even more clearly observed (fig.2). The branching ratios and half lives of the characteristic γ rays were checked to further establish their identification.

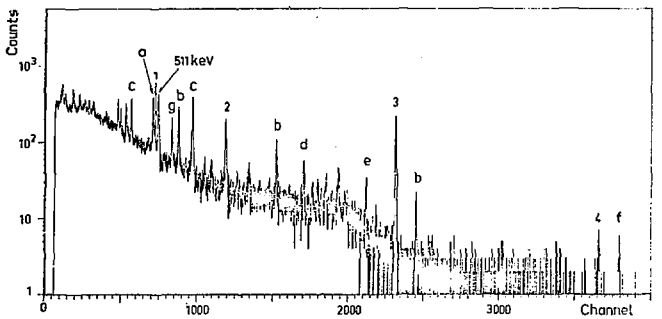

Fig.2. Energy spectrum of the γ activities of the third chemical extraction of La from the $BaCl_2$ sample (see text for the experimental procedure). The similar data for the Zn sample have been given in ref.[Dêt 77]. The peaks labelled I through 4 correspond to the γ rays from the β decay of ^{140}La with E_γ = 487.1 keV (46.7%), 815.7 keV (22.8%), 1596.4 keV (96%) and 2521.8 keV (3.4%), respectively. Some of the other activities are also labelled. They correspond to the β decay of : a : ^{135}La ; b : ^{124}I ; c : ^{126}I ; d : ^{120}Sb ; e : ^{40}K ; f : ^{208}Tl ; g : ^{121}Te.

After 1.6×10^{16} protons had irradiated the W target during 63 hours, 5×10^{6} ^{72}Zn nuclei were formed. For the Ba experiment, the corresponding numbers were : 6×10^{15} protons, 13.5 days and 4×10^{8} ^{140}Ba nuclei.

These results were found to be reproducible within expected uncertainties.

3. Interpretation of the results.

As explained in sections 2.1 and 2.2, the occurence of bound ^{A}n nuclei produced in the fragmentation of W and absorbed by ^{70}Zn or ^{138}Ba can qualitatively account for the observation of ^{72}Zn or ^{140}Ba, respectively. Yet one must closely examine all the possible side reactions which can enrich the Zn or Ba nuclei by two neutrons.

3.1. Assumption of a bound ^{A}n fragment.

From the number of ^{72}Zn or ^{140}Ba nuclei produced, the cross section for the $p + W \rightarrow {}^{A}n$ process can be derived if the cross section for the $(^{A}n, (A-2)n)$ reaction on ^{70}Zn or ^{138}Ba is known. It was calculated with the code ALICE [Bla 73] for the various values of A between 4 and 10. For ^{8}n, ^{9}n and ^{10}n, the reactions $(^{8}n,4n)$ on ^{68}Zn, $(^{9}n,5n)$ on ^{68}Zn and $(^{10}n,4n)$ on ^{66}Zn, respectively, were found to predict the largest yield for ^{72}Zn, at the expected energies of the ^{A}n fragments, around 5 to 15 MeV.

In view of the large uncertainty affecting the above calculations, probably one order of magnitude, the values of $\sigma(p+W \rightarrow {}^{A}n)$ determined from the Zn and Ba experiments (table 3) are not inconsistent between themselves for most values of A, nor with the values extrapolated from the systematics of fragmentation cross section [Sil 73, Thi 71, Pos 71].

3.2. Side reactions.

Many nuclear processes which are more conventional can also enrich by two neutrons the Zn and Ba nuclei, in the conditions of the experiment. Among the many processes examined, the most likely are discussed below.

3.2.1. Double neutron capture.

Simple geometrical considerations eliminate the possibility that two interacting neutrons emitted from W could be absorbed by the same Zn or Ba nucleus 8 cm away.

Two successive (n,γ) neutron captures can also produce ^{72}Zn and ^{140}Ba. But, as indicated in section 2.2, the short half-life of the intermediate nucleus, ^{71}Zn and ^{139}Ba, keeps the yield of that process very low.

Table 3

Production cross section of bound ^{A}n neutral nuclei in the proton-induced fragmentation of W at 24 GeV

Assumed mass of the neutral nucleus	4	5	6	7	8	9	10
Most favourable compound nucleus reaction forming ^{72}Zn and ^{140}Be	^{70}Zn / ^{138}Ba (^{4}n,2n)	^{70}Zn / ^{138}Ba (^{5}n,3n)	^{70}Zn / ^{138}Ba (^{6}n,4n)	^{70}Zn / ^{138}Ba (^{7}n,5n)	^{68}Zn(^{8}n,4n) / ^{138}Ba(^{8}n,6n)	^{68}Zn(^{9}n,5n) / ^{138}Ba(^{9}n,7n)	^{66}Zn(^{10}n,4n) / ^{138}Ba(^{10}n,8n)
$\sigma_{fragmentation}$(exper.) in μb							
from the Zn expert.	2800	200	85	45	70	10	300
from the Ba expert.	70000	3000	900	300	170	100	100
$\sigma_{fragmentation}$(predicted)* in μb	2500	1000	500	40	10	1	0.2

*For the method of prediction, see text.

The number of low-energy neutrons produced in W is about 10 per incident proton. It is calculated from the neutron production cross section [Hud 68]. It can also be deduced from the rate of the $^{142}Ce(n,\gamma)^{143}Ce$ reaction observed in an irradiation with a Ce sample (see section 3.2.4.).

The (n,γ) cross section is estimated as about 20 mb [Seg 53]. The resulting calculated yield of ^{72}Zn and ^{140}Ba is smaller than the experimental one by 4 to 8 orders of magnitude.

3.2.2. Secondary reactions in the beam halo.

The proton beam at the point of irradiation has a large geometrical cross section [Sim 77]. It was feared that enough protons in the beam halo could directly strike the Zn or $BaCl_2$ sample, 8 cm off the beam center line, to produce large quantities of n, α, t, etc... particles which, through appropriate reactions, could produce ^{72}Zn or ^{140}Ba.

A test was made, in the case of $BaCl_2$, by repeating the standard experiment for one day, but after taking away the W target. The upper limit for the formation of ^{140}Ba was 10 times smaller than observed with the W target in the beam.

3.2.3. Spallation from higher Z contaminants

A large number of energetic protons and neutrons emitted by the W target can reach the Zn or $BaCl_2$ sample through the Al shielding. They can induce spallation reactions [Hud 68] on possible contaminants of somewhat higher Z to produce ^{72}Zn or ^{140}Ba by reactions like (p,xpyn). Because of the large cross sections of such processes, small amounts of contaminants can be sufficient to account for the number of ^{72}Zn and ^{140}Ba nuclei observed.

To analyze this possibility, the Zn and $BaCl_2$ samples were replaced in one experiment by small samples of Ge, As, Se, Br, Rb and Sr, and in another one of Ce, Nd and Sm. The yield of ^{72}Zn in the first case, and ^{140}Ba in the second indicated the amount of each contaminant needed to account for the results obtained with the Zn and $BaCl_2$ samples, respectively. In some cases where ^{72}Zn or ^{140}Ba activities were not observed, only lower limits of contamination were derived (table 4).

Table 4

Effect of different chemical contaminants in the Zn and $BaCl_2$ sample on the observation of ^{72}Zn and ^{140}Ba, respectively

Contaminant in Zn		Ge	As	Se	Br	Rb	Sr
Needed amount (in μgram per gram) to account for the observation of ^{72}Zn		12	100	40	130	> 200	> 170
Real amount (in μgram per gram), as determined by methods[a] n°	1	< 10	< 9	< 100			
	2	< 11	< 0.1	< 3	< 0.15	< 16	
	3	< 0.1	< 0.1	< 0.3	< 0.3	< 0.1	< 0.1
Contaminant in $BaCl_2$		Ce	Nd	Sm			
Needed amount (in μgram per gram) to account for the observation of ^{140}Ba		2000	> 10^3	> 10^4			

[a] See text for the description of the methods.

The required levels of contamination in Zn are close to what can be expected, according to the indications of the manufacturer*. Three independent determinations of the actual levels of impurities were used, as reported before [Dêt 77] : 1) in the Zn sample experiment, the absence in the γ spectrum of some activities strongly produced in Ge, or As, or Se, etc... sets an upper limit on the amount of these contaminants ; 2) an

* pure zinc for analysis, from Merck Company.

activation analysis was done by neutron irradiation at the EL3 Reactor in Saclay ; 3) a spark spectroscopy analysis was performed at the CEA laboratory in Fontenay-aux-Roses.

These results excluded spallation on Ge, As, ... contaminants as the origin of ^{72}Zn.

As for Ba, irradiation of Ce, Nd and Sm samples indicates the amounts of contamination needed in the very pure $BaCl_2$ sample*. They far exceed any reasonable limits.

3.2.4. (α,2p) reactions with α from the W target

In the p+W fragmentation reaction, α particles are emitted with very large cross sections (4 barns in the case of p+U at 5.5 GeV [Pos 71]).

Since a small fraction of them are energetic enough to cross the 0.7 cm Al shielding, they might account for the observation of ^{140}Ba through the $^{138}Ba(\alpha,2p)^{140}Ba$ reaction.

An estimate of the yield of ^{140}Ba from this process was obtained in the following way. The energy spectrum of the α fragments [Hyd 71, Pos 71] indicated the percentage of these fragments which can reach the Zn or $BaCl_2$ sample. The (α,2p) cross section was calculated with the code ALICE [Bla 73] and was found to be very small ($\sigma < 1$ mb). Hence this process was unable to explain the observed number of ^{72}Zn or ^{140}Ba by three to five orders of magnitude. (A similar conclusion is reached for the effect of the ^{6}He fragmentation products which would induce the ($^{6}He,\alpha$) reaction in Zn or Ba). Two further checks were made.

First, the observation of Ce isotopes in the $BaCl_2$ experiment was attributed to $Ba(\alpha,xn)Ce$ reactions. From the ALICE estimate of the (α,xn) cross sections, the number of α particles incident on the $BaCl_2$ sample was deduced. It was within the order of magnitude calculated above.

*$BaCl_2$ High Purity Materials, from Johnson Matthey.

Second, a thick $BaCl_2$ target was irradiated with a 43 MeV α beam from the cyclotron of the Grenoble ISN. This irradiation does not exactly reproduce the conditions of the 24 GeV proton experiment, since the fragmentation α particles crossing the Al shielding are not monoenergetic. They are mostly low energy but it is believed that the 43 MeV α which are brought to rest by the thick $BaCl_2$ target can at least reproduce some of the low energy reactions which dominate the fragmentation CERN experiment.

No ^{140}Ba was observed from the 43 MeV α irradiation. As normalized through the yield of Ce isotopes observed in both experiments, the yield of ^{140}Ba from the (α,2p) reaction is at least four orders of magnitude two small to account for the 4×10^8 ^{140}Ba nuclei observed in the CERN experiment.

3.2.5. (t,p) reactions with t from the W target

There are fewer tritons than α particles emitted in high-energy fragmentation reactions. On the other hand, the Al shielding is less efficient for tritons than for α particles; the range of tritons in the sample at a given energy is longer, hence the effective target thickness is larger than for α particles; and the (t,p) cross section also appears to be larger than (α,2p).

Therefore, from the beginning of this study, the (t,p) reaction induced by tritons produced from W appeared as the potentially most effective side reaction to account for the observation of ^{72}Zn and ^{140}Ba.

However, as reported before [Dét 77], an estimate of the yield of this reaction appeared to exclude this possibility. The p+W→t cross section was taken at 700 mb, the same value as measured [Hyd 71] for p+Ag→t. From the measured [Pos 71] triton energy spectrum, it was estimated that about 20% of those tritons would be energetic enough ($E \geq 60$ MeV) to cross the 7 mm Al shielding and reach the Zn or $BaCl_2$ sample. It is felt that this estimate can yield the correct order of magnitude of the number of tritons on the Zn or Ba target.

The value of the (t,p) cross section is less free of uncertainty. First because the incident tritons have a broad energy spectrum. Second because the value of the (t,p) cross sections to bound states of the residual nucleus does not vary as systematically as e.g. a fragmentation cross section.

Several (t,p) or (p,t) reactions have been reported in the mass region of baryum. As compiled by Broglia et al.[Bro 73], the differential cross sections peak at forward angle and reach a few hundreds $\mu b\ sr^{-1}$ at most, for L=0 transitions. Recently (p,t) results on Te isotopes [Izu 75] at 52 MeV appear to confirm that trend. The integration of $d\sigma/d\Omega$ gives an estimate of 0.1 to 0.3 mb for the total cross section. At 25.5 MeV, W.Oelert et al.[Oel 74] have measured σ(p,t) for Sm isotopes. The angular distribution decreases less drastically with angle than at higher incident energy and the total cross section is somewhat larger, reaching as much as 1 mb.

The estimate of the number of ^{140}Ba produced in our experiment through this process has been estimated under the following assumptions :

1) $\sigma(p+U \rightarrow t) = 0.7$ b ;

2) 20% of the fragmentation tritons have $E_p \geq 60$ MeV ;

3) $\sigma(p+^{138}Ba \rightarrow ^{140}Ba) = 0.5$ mb.

Under the geometrical conditions of the experiment, 3×10^7 nuclei of ^{140}Ba should have been produced. As indicated in section 2.4, we observed 4×10^6 such nuclei.

It seemed unlikely that the error of the above estimate could reach more than one order of magnitude, hence that the fragmentation tritons could account for the observed production of ^{140}Ba.

However, it was felt desirable to check that conclusion by irradiating a $BaCl_2$ sample with tritons from the Los Alamos Van de Graaff facility. Tritons with 20 MeV energy were stopped in a thick $BaCl_2$ target to reproduce the conditions of the CERN experiment where energetic tritons have first to travel through the Al shielding before interacting with the $BaCl_2$ sample. The γ activity of ^{140}Ba was observed after irradiation and

the average cross section for the process $t + {}^{138}Ba \rightarrow {}^{140}Ba$ between $E_t = 20$ MeV and 0 MeV was measured as about 10 mb, a factor of 20 larger than the above estimate. It is enough to account for the observation of ^{140}Ba in our CERN experiment.

Although a similar test was not made for Zn, this result shows that the production of ^{72}Zn observed is probably within the possibilities of this side reaction.

4. Conclusion.

Under the geometrical conditions shown in fig.1, it was observed that both Zn and Ba nuclei contained in the shielded sample could be enriched by two neutrons with a high yield (section 2.4). For lack of a more conventional explanation that could quantitatively account for the data (section 3.2), this was first considered as indicating the possible existence of bound neutral nuclei (section 3.1). However, as reported in section 3.2.6, one side reaction was finally shown to produce ^{140}Ba with the experimentally observed yield. It involves the production of energetic tritons ($E_p \gtrsim 60$ MeV), in the 24 GeV proton induced fragmentation of W, which can cross the Al shield and interact with ^{138}Ba to produce the radioactive ^{140}Ba nuclei.

Therefore the production of ^{72}Zn and ^{140}Ba in the experiment does not at this point need the assumption that bound neutral nuclei might exist.

Although an experiment can be designed that would eliminate the side reaction involving fragmentation tritons, it has become of lesser interest since Turkevich has reported very low upper cross sections for the production of bound neutral nuclei in the fragmentation of U, first at 600 MeV [Tur 77] and more recently at 400 GeV [Tur 77a].

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References

[Ajd 65] V.Ajdacic et al., Phys. Rev. Lett. 14, 444 (1965).

[Ala 71] J.P.Alard, Thèse de Doctorat (Clermont-Ferrand, 1971).

[Ant 74] V.Ya.Antonchenko, V.N.Bragin and I.V.Simenog, Zh.E.T.F. Pis. Red. 19, 606 (1974) ; translated JETP Lett. 19, 314 (1974).

[Baz 72] A.I.Baz and V.N.Bragin, Phys. Lett. 39B, 599 (1972).

[Bla 73] M.Blann and F.Plasil, USAEC Report COO-3494-10 (1973).

[Bog 76] V.I.Bogatin, V.F.Litvin, O.V.Lozhkin, N.A.Perfilov and Yu.P.Yakolev, Nucl. Phys. A260, 446 (1976).

[Bri 64] O.D.Brill, N.I.Venikov, A.A.Kuraschov, A.A.Oglobin, V.M.Pankratov, V.P.Rudakov, Phys. Lett. 12, 51 (1964).

[Bro 73] R.A.Broglia, O.Hansen and C.Riedel, Adv. in Nucl. Phys. (M.Baranger and E.Vogt, edit.) vol.6, 287 (1973)(Plenum Press, N.Y.).

[Cer 74] J.Cerny, R.B.Weisenmiller, N.A.Jelley, K.H.Wilcox and G.J.Wosniak, Phys. Lett. 53B, 247 (1974).

[Dét 77] C.Détraz, Phys. Lett. 66B, 333 (1977).

[Dub 67] C.Dubuquoy, R.Guillaumont, G.Bouissières, Sonderdruck ans Radiochemica Acta 8, 49 (1967).

[Fia 73] S.Fiarman and W.E.Meyerhof, Nucl. Phys. A206, 1 (1973).

[Fia 75] S.Fiarman and S.S.Hanna, Nucl. Phys. A251, 1 (1975).

[Gol 73] V.I.Goldanskii, Zh. E.T.F. Pis. Red. 17, 56 (1973) ; translated JETP Lett. 17, 41 (1973).

[Hud 68] J.Hudis in Nuclear Chemistry (Academic Press, N.Y.,1968) vol.I, p.168.

[Hyd 71] E.K.Hyde, G.W.Butler and A.M.Poskanger, Phys. Rev. C4, 1759 (1971).

[Izu 75] T.Izumoto et al., Phys. Lett. 57B, 17 (1975).

[Mit 66] A.N.Mitra and V.S.Bashin, Phys. Rev. Lett. 16, 523 (1966).

[Mor 57] G.Morrison and H.Freiser, Solvant Extraction in Analytical Chemistry (J.Wiley and Sons Inc., edit. 1957).

[Oel 74] W.Oelert, G.Lindström and V.Riech, Nucl. Phys. A233, (1974).

[Pos 71] A.M.Poskanzer, G.W.Butler and E.K.Hyde, Phys. Rev. C3, 882 (1971).

[Seg 53] E.Segré, Experimental nuclear physics, vol.II (J.Wiley, N.Y., 1953) p.338.

[Sil 73] R.Silberberg and C.M.Tsao, NRL Report 7593 (Naval Research Laboratory, Washington, 1973).

[Sim 77] D.J.Simon, private communication ; D.Dumollard et D.J.Simon, note MPS/MU/EP 74.6 (1974).

[Thi 71] C.Thibault, Thèse de Doctorat (Orsay, 1971).

[Tur 73] A.Turkevich, T.E.Economou, H.R.Heydegger, LAMPF Users Group News Letter vol.5, n°3 (oct.1973) p.8.

[Tur 77] A.Turkevich, J.R.Cadieux, J.Warren, T.Economou, J.LaRosa and H.R.Heydegger, Phys. Rev. Lett. 38, 1129 (1977).

[Tur 77a] A.Turkevich, J.R.Cadieux, J.Warren, T.Economou and J.LaRosa, to be published.

[Vau 77] D.Vautherin, Lawrence Berkeley Laboratory Annual Report (1977) and private communication.

[Zeb 75] A.M.Zebelman, A.M.Poskanzer, J.D.Bowman, R.G.Sextro and V.E.Viola Jr., Phys. Rev. C11, 1280 (1975).